Preparing U.S. Workers and Employers for an Autonomous Vehicle Future

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Executive Summary

How will the introduction and diffusion of autonomous vehicles (AVs) affect U.S. workers? This highly fraught question promises soon to loom large in hometowns and policy realms across the nation. Given Americans' current reliance on cars and trucks for most of our transportation, the transition to self-driving vehicles will change many lives and livelihoods, likely for the better for the vast majority. But it will be costly for some. This study advances the national conversation about how to cope with the effect of AVs on workers in three ways: by setting forth a framework for discussion, presenting quantitative simulations and qualitative scenarios to help assess key impacts, and providing policy recommendations for mitigating negative impacts while also setting an agenda for research on policy. We hope that our report will help motivate policymakers and stakeholders to take steps now to reduce the likely negative effects of AV on U.S. workers.

To preview our results, we find that the introduction of autonomous cars and trucks could directly eliminate 1.3 to 2.3 million workers' jobs over the next 30 years, depending on the adoption scenario followed. While near-term effects are limited, the maximum impact we simulate (which occurs during the 2040s) could raise the overall annual unemployment rate by about 0.1 percentage points and lower labor force participation by about 0.1 percentage points for a number of years, with stronger effects in hard-hit communities or during a recession.

Using evidence from previous dislocations we find that each laid-off worker would likely lose on average about $80,000 in lifetime income due to the disruption, for a total loss of about $180 billion for U.S. workers. These adjustments take into account the probable age of workers being dislocated; on average these workers would have about 16 years of labor force participation left in their careers.

Most of the affected workers will eventually find new jobs or retire. However, this process will take time and may lead to wage increases or decreases. We do not provide specific estimates of job creation associated with AVs; instead we discuss the three general sources of these new jobs: growth in overall transportation, new labor inputs for the AV sector, and increased purchases of other goods and services by consumers who spend less on transportation.

In addition, when driving is no longer a requirement, the duties in many other jobs (such as many home health aides, building contractors, visiting nurses, real estate agents and other sales people, regional supervisors, automobile and vehicle insurance workers, and taxi dispatchers) will change substantially. In total, the jobs whose duties are very likely to change with the adoption of AV employed 7.7 million people in 2016. The change in duties could be associated with better or worse jobs from the perspective of pay or skills; we explore a range of possibilities.

Complacency, fatalism, or ignoring these serious consequences would be a mistake. There are numerous policy options for assisting workers in the affected occupations. As a country, we need to plan now so that the promise of AVs (cheaper and more efficient transportation, dramatic reduction in deaths and injuries from accidents, greater mobility for those who can't drive, freedom from tedium for those who can) either does not impose huge costs on those directly affected or compensates them for their loss. The economic benefits of AVs, which some have estimated at $800 billion to $1 trillion per year, should provide adequate resources for such policy intervention.[1] With advance planning, the task is manageable; according to our scenarios, employment disruptions won't start in large numbers until after 2030, and will be gradual (about 100,000 jobs disrupted per year, or 0.1 percent of the work force, at the time of peak impact).

Our estimates, like all estimates, have limitations. Our simulations for displacement and unemployment include adjustments for turnover (workers leaving occupations for reasons other than the rise of autonomous vehicles). However, we do not include multiplier effects (the fact that when people lose jobs, their spending drops, leading to additional temporary unemployment from reduced sales from those jobless workers), a clear source of underestimation. On the other hand, if the pace of AV diffusion is slower than our scenarios anticipate (e.g., due to delays in achieving fully autonomous capabilities, consumer hesitance about adoption, regulatory constraints, partial (vs. full) automation that preserves a role for a human driver) or if employers retain and retrain many workers in the eliminated jobs, we may have overestimated.

A. Lessons from the past

Recognizing that innovation is not new, we begin with seven examples of previous disruptive changes and their labor market impacts, each providing lessons for the current situation:

- The Industrial Revolution in England from 1750-1900
- Autopilot in aviation from 1912 to now
- Computer numerical control (CNC) in machine tools, 1960-1990
- Automation in auto assembly plants
- Automatic teller machines (ATMs)
- Trade expansion from 1990-now
- Self-driving trucks in the Australian strip mining industry, 2000-now

Together, these cases illustrate compellingly that while technological change leads to large social benefits in the long run, some benefits can be long-delayed and the change can result in significant uncompensated costs to those displaced and their communities. The direct effects of new technology on jobs and skill levels are easier to foresee in the short-term and may be primarily negative. The indirect effects are likely to be positive as productivity rises, but may take a long time to arrive—the pace is much harder to forecast explicitly. Accordingly, we focus our

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[1] See Securing America's Future Energy, "The Impact of Autonomous Vehicles on Consumers, the Economy and the U.S. Labor Force," (June 13, 2018) and Robert Atkinson, "The Coming Transportation Revolution," *Milken Institute Review*. 4th Quarter 2014. https://itif.org/publications/2014/10/17/coming-transportation-revolution. It is beyond the scope of this paper to estimate benefits from AV adoption. We take no stand on the size of benefits other than to reference two credible estimates and note that there is necessarily considerable uncertainty about these estimates, as is true for our estimates of costs. A key source of uncertainly concerns AVs' environmental impacts (in particular the impacts on vehicle miles travelled and on land use); policy choices will have a large impact on the size of net benefits.

simulations on quantitative calculation of jobs lost due to the disruption of the new autonomous technology. We address job creation in broader qualitative terms, sketching possible scenarios.

We predict that the transition from today's human-driven vehicles to the AV future will be long and marked by bursts of startling change in how people and goods are moved around, interspersed with times when diffusion slows due to technological complications, public resistance, regulatory caution, and efforts to clarify legal responsibility/liability. We know from other examples of disruptive change affecting jobs and skills that the length and difficulty of such transitions have varied greatly, depending upon the size of the changes in skills needed, investment requirements, stakeholder bargaining power, and institutions, even the geography.

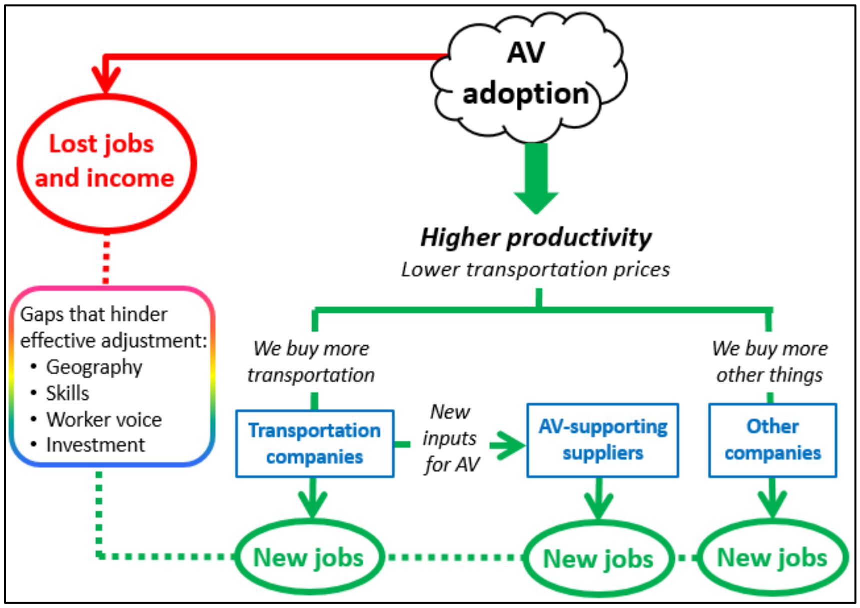
Hence, there are at least three reasons for concern about the impending adoption of AVs.

1. Losses tend to accumulate before widespread gains, substantially affecting certain individuals and geographic and demographic communities more than others.
2. Many benefits are difficult to predict and they may be very unevenly distributed. In particular, recent wage stagnation even in the face of significant productivity gains casts doubt on whether the benefits of a technology like AVs would, in fact, be shared, and causes worry among those who already feel they are just getting by.[2]
3. We cannot rule out the possibility that the advent of AVs and more generally, artificial intelligence (AI) technology, will result in a different mix of direct and indirect effects than in the past. In particular, AI may pose a more real threat to automating high-skilled work and hence adversely affect both jobs and skills at the high-skill (usually high-pay) end of the economy.

B. Framework

We set forth a framework (below) to help trace the labor market impacts of AVs. The framework draws on both historical experience and economic theory. It clarifies that a central risk from large disruptions stems not from some permanent decline in the number of jobs available in the economy, but from the costs imposed on displaced workers and the negative social reaction if adjustments to the disruption are too slow or costly. New jobs will be created through three effects: people will use more transportation when it becomes less expensive, suppliers of AV-related goods and services will expand to meet demand, and consumers will increase purchases of other goods and services with money left over when transportation becomes safer and cheaper. So, the economy will eventually return to full employment after AV-adoption layoffs.

[2] David Autor and Anna Salomons. "Is Automation Labor-Displacing? Productivity Growth, Employment, and the Labor Share." *Brookings Papers on Economic Activity*. March 8, 2018. https://www.brookings.edu/bpea-articles/is-automation-labor-displacing-productivity-growth-employment-and-the-labor-share/



Thus, if our report only estimated the number of workers likely to be displaced, we would miss the heart of the matter. The key questions concern the magnitude of losses to workers, how long the adjustments will take, and what we can do to mitigate the costs. The framework points to four gaps that make workers' adjustments slower and costlier. Displaced workers may not have the skills needed for the new jobs. They may not live in the same areas where new jobs arise. Lack of worker voice, bargaining power, and supportive institutions could mean that workers' losses are unnecessarily exacerbated. Finally, firms may not have the financing or incentives to invest because of poor economic conditions or other impediments. The historical cases reviewed demonstrate that technology alone does not uniquely determine many outcomes, including the quality of the new jobs. Instead, social policy and employer choices to address these gaps make a big difference.

C. Assessing impacts

Informed by the framework, we estimate the number of workers displaced and use that to simulate key impacts of AV adoption over the next few decades. First, we focus on how AV-adoption layoffs might raise unemployment, lower labor force participation, and reduce workers' earnings.

We consider four adoption scenarios developed by Securing America's Future Energy (SAFE):

- Passenger (light-duty) vehicles with household ownership: Households own most cars and light trucks, as is now the case. We call this scenario "Cars-Personal."
- Passenger (light-duty) vehicles with fleet ownership: A set of transportation service providers own and operate most cars and light trucks. Compared to household ownership, fleets imply more centralized maintenance, fewer vehicles per person, and more rapid adoption of electric vehicles. We call this scenario "Cars-Fleet."

- Trucking (heavy-duty) with slow adoption: Trucking takes about 30 years adapting to driver-assisted autonomous vehicles before it proceeds to fully autonomous trucks that do not need drivers. We call this scenario "Trucking-Slow."
- Trucking (heavy-duty) with aggressive adoption: Trucking proceeds to full autonomy much more quickly and completely than in the slow adoption scenario. We call this scenario "Trucking-Fast."

We base our simulations on the experiences of workers displaced in the recent past, data on the occupations likely affected, and estimates of earnings losses from displacement. We follow previous studies in identifying occupations likely to be affected directly and indirectly by AVs, building on occupational classifications identified as "driving related" by the Commerce Department's Economics and Statistics Administration (ESA) study.[3] In consultation with industry experts, we set the percentage of workers in each occupation who are at risk of layoff under each AV scenario. These include truck and bus drivers, taxi and other personal transport employees, and other drivers. In addition, we consider other job losses from the adoption of AVs, such as automobile insurance adjusters, auto repair mechanics, police patrol officers, and others. We adjust these job losses for projected occupational turnover (workers leaving occupations for reasons other than the rise of autonomous vehicles) to produce estimates of displacement.

From recent U.S. Bureau of Labor Statistics (BLS) Displaced Worker Surveys (DWS) we construct the likely path followed by a cohort of displaced workers. We quantify the path as shares of the cohort of displaced workers shifting between three possible labor force states (employed, unemployed, or out of the labor force) in the years after displacement. Although the DWS asks about only three years of experience post displacement, we extend the time covered by making assumptions about eventual convergence of the displaced workers to workforce averages. The path constructed is consistent with prior studies that find that displaced workers experience above average unemployment for a long time and are disproportionately likely to be out of the labor force after displacement.

With this information (post-displacement paths, numbers of workers in occupations affected, and the timing of transition phases) we simulate how many unemployed workers and labor force exits will be added due to AV adoption over the coming decades, as implied by the four scenarios.

Importantly, these simulations should be regarded less as highly specific forecasts, but rather as rough gauges of the potential size and nature of the disruption to the labor market posed by AV adoption. In order to place the effects in the easily-understood context of today's labor market, these simulations abstract from the many expected and unexpected changes in demographic and economic conditions that will occur over coming decades. When AV adoption actually takes place, its costs and benefits will undoubtedly be affected by conditions prevailing at the time (in particular the rate of growth of the overall economy), as well as employers' and policy choices.

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[3] David Beede, Regina Powers, and Cassandra Ingram. Office of the Chief Economist, Economics and Statistics Administration, U.S. Department of Commerce. (August 11, 2017). "The Employment Impact of Autonomous Vehicles" (*ESA Issue Brief* # 05-17). http://www.esa.doc.gov/sites/default/files/Employment%20Impact%20Autonomous%20Vehicles_0.pdf

Based on our simulations, we find the following unemployment impacts as the labor market absorbs the loss of 1.3 to 2.3 million jobs (adjusted for projected turnover), depending on the adoption scenario:[4]

- Job losses from AVs ramp up slowly and do not start adding noticeably (i.e., remain under 50,000 per year) to the ranks of the unemployed until 2030 or later.
- The Trucking-Fast scenario causes the most concentrated job losses of the four considered. At its peak, the rise in unemployment under this scenario is about four times higher than the peak impact of any of the other transition scenarios.
- Combining the Trucking-Fast adoption with either passenger car AV adoption swells the ranks of the unemployed by about 200,000 workers across the U.S. at the peak of impact, around 2046, enough to raise the U.S. unemployment rate by about 0.1 percentage points.
- The additional joblessness affects some demographic and geographic communities even more noticeably.
    - Men will lose many more jobs than women.
    - African Americans and people with lower levels of education will be disproportionately affected.
    - By region, the South and West will have the most workers displaced. Impacts may be most severe for the eight inland states that have disproportionate shares of Heavy and Tractor Trailer Truck Drivers: North Dakota, Arkansas, Nebraska, Iowa, Wyoming, Mississippi, Tennessee, and South Dakota.[5]

We also find the following labor force participation and earnings effects:

- AV adoption will increase the numbers of workers who exit the labor force for a considerable time. The number of workers not in the labor force after AV-induced displacement is on a par with the rise in unemployment and lasts longer. At peak impact (around 2049), it could lower the U.S. labor force participation rate by almost 0.1 percentage points.
- The lifetime wealth (present value of earnings) lost by workers will be very high, totaling $70,000 to $87,000 per AV-displaced worker and from $104 billion to $189 billion to the AV workforce and their families and communities as a whole.

[4] With no adjustment for occupational turnover, the figures are 1.4 to 2.6 million. According to BLS occupational turnover projections, turnover for the occupations affected by AV averages 10.5 percent per year for trucks and 9.9 percent per year for cars.

[5] See our in-depth case study on truck drivers in Section V.D. for more about the various factors that will affect job loss in that occupation.

It is important to note that in the context of a recession, all of these impacts would be much more severe. However, it is possible that a recession could also slow the diffusion of AVs, hence the overall levels of job loss or changed duties, as a partial offset.

It may be useful to compare our estimates of dislocation from AVs to that caused by the decline of manufacturing.[6] U.S. manufacturing has lost 6.7 million jobs since its peak in 1978, or about 1.7 million jobs per decade. We estimate AVs will disrupt 1.3 to 2.3 million jobs over 30 years, which is as much as 800,000 jobs per decade—**half** the size of the manufacturing job loss. The AV impact will be further weakened by the larger size of the U.S. labor force in the future, and the disruption will be less geographically concentrated than in manufacturing. However, given the large impact of manufacturing job loss on U.S. workers, the economy, and political system, a potential new disruption about half that size in another industry certainly merits serious attention.

D. Recommendations

In order to be sure that the country will reap the promised benefits of AVs, it will be important to ensure that transition costs and fear of them do not hinder progress. The short- to medium-term losses identified by these simulations likely won't be addressed adequately in the absence of active efforts to mitigate costs to those harmed. Anticipating that long-term gains in employment and skills may turn up in unexpected parts of the economy is insufficient to address these impacts for many reasons—including that those gains are not likely to accrue to those who suffered the losses. Indeed, it is imperative to avoid using the vision of a long-term post-adjustment future as an excuse not to deal with the dislocations caused in the short term by the adoption of AVs.

Previous major transformations in the United States have occurred without coordinated engagement of stakeholders to mitigate damage to those left behind. Failure to address the costs once again risks sidelining part of our national productive capacity and unleashing a full range of attendant social ills that accompany extended unemployment, including deteriorating health, shorter life spans, and intergenerational impacts on children.[7] The uncompensated losses from transformations have damaged many lives, families and communities and, thus, helped breed resistance to change. With research, advance planning, and conversation, the adoption of AVs offers an important opportunity to improve on the past.

There are many policy options, both existing and proposed, to mitigate losses to workers. The U.S. has a workforce development system composed of federal, state, and local partners that administer the Unemployment Insurance system, One-Stop centers to aid unemployed workers, training grants, community colleges, and other components. Increasing use of program evaluations provides evidence that many employment and training programs are effective and can help direct resources to their most productive uses. Despite its good work, there are many signs that this present system by itself will not be adequate to mitigate the large costs of the adoption

[6] Thanks to Michael Mandel for suggesting this comparison.

[7] Steven Davis and Till von Wachter. "Recessions and the Costs of Job Loss." *Brookings Papers on Economic Activity*, 2011 no. 2. https://www.brookings.edu/bpea-articles/recessions-and-the-costs-of-job-loss/

of AV, including falling coverage and take-up of Unemployment Insurance, declining funding for the Employment and Training Administration, and a rising sense of worker insecurity.

Addressing the costs to workers requires a multipronged approach to augment the existing system. While it is beyond the scope of this paper to take a stand on specific policies to pursue, we recommend an overall approach that includes the following:

1. Development of a forum for ongoing engagement by AV employers and stakeholders with the U.S. workforce development system in order to minimize disruptions from AV, perhaps via the Workforce Information Advisory Council. Such communication would educate members of the workforce system about upcoming challenges and opportunities, connect affected employers with local workforce system agencies, and help identify the best means to monitor labor market impacts of AVs.

2. Efforts to design new jobs created by AVs to take advantage of the skills that people in the disrupted occupations already have. For example, those who used to manually drive trucks might have skills well-suited for traffic monitoring, truck maintenance, or remotely piloting convoys of trucks (if this latter scenario becomes widespread).

3. An organized effort to conduct research with the goals of informing mitigation efforts for AV and future innovations. Key research topics beyond the scope of the current paper include measuring the impact of AVs on commuting times for employees, estimating the impact of a driving requirement on occupational wages, the potential of AVs to open more jobs to people with disabilities that prevent them from driving, and understanding the impact on workers and others of AV-induced changes in land use and vehicle miles traveled.

4. Active support for the development of good data to monitor developments via official statistics and private efforts. This includes support for:

    a. Recommendations by the recent Ryan-Murray Commission on Evidence-Based Policymaking (CEP) that point the way for the federal government to better harness administrative data for workforce development.

    b. Adequate funding for the Bureau of Labor Statistics to provide needed data including initiatives such as quick-response surveys of employers.

    c. Safe sharing of state Unemployment Insurance worker records for statistical and evaluation purposes and enhancing those records to include occupational titles and hours worked while retaining strict controls to maintain the confidentiality of individuals' data.

    d. Broadened access to data generated by AVs in the service of important public policy goals, e.g. supporting a viable insurance system or learning about safety violations and accidents in order to achieve system-wide improvements, again with controls to maintain confidentiality of individuals' data.

5. Active, ongoing consideration of directing some of the benefits from AV adoption toward support for major policy solutions that incorporate the following features:
    a. Programs that are large enough or scalable to handle multiple large scale disruptions, even during an economic downturn
    b. Multiple treatments that can be tailored to workers' situations, risks, and local conditions
    c. Increased ability of ordinary Americans to share in the gains from disruptions that help the overall economy
    d. Broad-based rather than applying narrow criteria for determining eligibility
    e. Engaged directly with employers and worker organizations
    f. Able to innovate
    g. Guided by evidence from program evaluations, robust labor market statistics, and research

There is no dearth of broad policy proposals that could meet these criteria, including works councils, worker training accounts, wage insurance, public sector employment, universal basic income, flexicurity, and place-based policies.

Going forward, we believe that establishment of a sound mitigation strategy must be recognized as an essential component of promoting any disruptive innovation like AVs in the U.S.

I. Lessons from Past Innovations

In this section, we explore what happened in the past when there were large changes in employment and job content. We look in detail at several cases, and also at more general studies of the issue. Our seven main cases, in rough chronological order, are:

- The Industrial Revolution in England from 1750-1900
- Autopilot in aviation from 1912 to now
- Computer numerical control (CNC) in machine tools 1960-1990
- Automation in auto assembly plants, 1980s to now
- Automatic teller machines (ATMs), 1980s to now
- Trade expansion from 1990 to now
- Self-driving trucks in the Australian strip mining industry, 2000 to now

All but one of these cases involves a major change in technology. The exception is the impact of trade with China, which we include because it is both well-studied and recent. Also, much of the current fear about the potential impact of autonomous vehicles and other forms of automation stems from this recent shock, which imposed large uncompensated losses for workers and communities.

Below, we summarize the lessons from these cases and their potential lessons for the case of autonomous vehicles. More detail on each case appears in Appendix A.

A. Summary of labor market impacts from past innovations

The introduction of almost all technologies has both positive and negative impacts. In general, the direct effect of automation is that fewer jobs are needed to make a certain amount of product or service. Typically, demand then rises for that product or other products. In the long run, the demand effects more than offset the productivity effects, and employment and living standards increase. A recent McKinsey report provides several examples of this process.[8] For example, in the first half of the 20th century, the growth of the auto industry destroyed jobs in the carriage industry and railways, but created new jobs in automobile manufacturing and trucking; the number of jobs created over this period was more than 10 times the number destroyed, McKinsey estimates.

Although the new technology almost always creates enough new wealth to leave everyone better off, actually distributing this income widely sometimes takes a very long time. For example, the Industrial Revolution began in England in the late 18th century. The mechanization of industries such as agriculture and weaving led to dramatic increases in output. However, wages stagnated for half a century, from about 1790-1840, and workers' living standards declined. The Enclosure Movement removed small farmers' and grazers' access to land, enabling agriculture to be mechanized on the resulting large holdings; the mechanization also reduced the skills needed for farming. Similarly, skilled hand-loom weavers were replaced by unskilled factory workers (including children), and the weavers' wages fell dramatically. Eventually, wages did grow at a rate commensurate with (and sometimes exceeding) productivity growth, thus enabling workers to share in prosperity. But these changes did not occur automatically. As the McKinsey report notes, "The turnaround in the relationship between wages and output came at a time of substantial reform of existing structures including the right to unionize, limitations on child labor, the introduction of public high schools, urban planning to improve public health, elimination of debtors' prison, and the extension of the right to vote to landless workers."[9]

Technology is not deterministic of any particular outcomes, and examples are abundant of how the same technology can be implemented in very different ways with very different consequences, certainly for jobs and skills. For example, the U.S. Air Force subsidized development of computer numerically controlled (CNC) machine tools with the goal of enabling complex products to be

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[8] James Manyika, Susan Lund, Michael Chui, Jacques Bughin, Jonathan Woetzel, Parul Batra, Ryan Ko, and Saurabh Sanghvi. "Jobs Lost, Jobs Gained: Workforce Transition in a Time of Automation." McKinsey Global Institute. December 2017. https://www.mckinsey.com/global-themes/future-of-organizations-and-work/what-the-future-of-work-will-mean-for-jobs-skills-and-wages

[9] James Manyika, Susan Lund, Michael Chui, Jacques Bughin, Jonathan Woetzel, Parul Batra, Ryan Ko, and Saurabh Sanghvi. "Jobs Lost, Jobs Gained: Workforce Transition in a Time of Automation." McKinsey Global Institute. December 2017, p. 47. https://www.mckinsey.com/global-themes/future-of-organizations-and-work/what-the-future-of-work-will-mean-for-jobs-skills-and-wages.

produced without companies having to depend on skilled labor. The Air Force and defense contractors ended up with a highly abstract programming method which initially was quite complex, expensive, and fault-prone. They rejected a simpler technology, "record playback," which would have simply recorded the actions of skilled machinists to make a repeatable process. The result was a technology that after much tribulation could make more complex parts than even the most skilled machinist could make—but which continued to require input of skilled technicians. The most effective operation of the technology involves both specialized programmers and skilled technicians on the shop floor who can modify programs to take into account ever-changing variables such as tool wear.[10] The goal of a "lights out factory" (one with no workers) remains elusive.

Automation sometimes leads to de-skilling, and sometimes to upskilling. For example, automation in banking in the U.S. in the 1990s had both effects, leading to "job polarization."[11] Computerization made it easier to divide up the relatively low-level tasks performed by "check processors" into four jobs. One of these jobs was done by computers; the other three were narrower jobs doing relatively tedious tasks that are hard for computers to do. (One of the jobs was removing staples and orienting checks so the computer could scan them; this job was paid less than the original check processor job.) In contrast, the more tedious parts of jobs performed

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[10] David Noble. "Social Choice in Machine Design: The Case of Automatically Controlled Machine Tools, and a Challenge for Labor." *Politics and Society* 8, nos. 3-4 (September 1978): 313-347. http://journals.sagepub.com/doi/10.1177/003232927800800302

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Maryellen R. Kelley. "Productivity and Information Technology: The Elusive Connection." *Management Science* 40 (1994): 1406–1425. https://pubsonline.informs.org/doi/abs/10.1287/mnsc.40.11.1406

Maryellen Kelley and Susan Helper, 1999. "Firm Size and Capabilities, Regional Agglomeration, and the Adoption of New Technology," *Economics of Innovation and New Technology* 8, no. 1-2 (1999): 79-103. https://pdfs.semanticscholar.org/3d40/ebf41076da32747f48d4fbbcd078ffc04b60.pdf

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P. Timothy Bushnell. *Transformation of the American Manufacturing Paradigm*. New York: Garland, 1994.

[11] David H. Autor, Frank Levy, and Richard J. Murnane. "Upstairs, Downstairs: Computers and Skills on Two Floors of a Large Bank." Cornell *Industrial and Labor Relations Review* 55, no. 3 (2002). http://journals.sagepub.com/doi/pdf/10.1177/001979390205500303; David H. Autor, "Why Are There Still So Many Jobs? The History and Future of Workplace Automation." *Journal of Economic Perspectives*, 29, no. 3 (2015): 3-30. https://www.aeaweb.org/articles?id=10.1257/jep.29.3.3 ; Lawrence Mishel and Heidi Shierholz. "A Decade of Flat Wages: The Key Barrier to Shared Prosperity and a Rising Middle Class." Economic Policy Institute. Briefing Paper 365. 2013. http://www.epi.org/publication/a-decade-of-flat-wages-the-key-barrier-to-shared-prosperity-and-a-rising-middle-class/. Lawrence Mishel, Heidi Shierholz, and John Schmitt. "Don't Blame the Robots: Assessing the Job Polarization Explanation of Growing Wage Inequality." Economic Policy Institute-Center for Economic and Policy Research Working Paper. 2013. http://www.epi.org/publication/technology-inequality-dont-blame-the-robots/

by higher-level workers were automated, and these workers took on tasks involving more judgment and higher pay.

In some cases, introduction of the same type of equipment led to upskilling in some cases and deskilling in other places, depending upon characteristics of both product and labor markets. Once CNC had been adopted, rather than record playback, machinists in some plants gained computer programming skills while computers took over the direct determination of "feeds and speeds." More often, however, machinists became less skilled, mostly watching for errors by the automated equipment, while firms gave programming and problem-solving duties to engineers.

Sometimes a new general purpose technological capability follows very different implementation trajectories when applied to different tasks. For example, the 1980s saw the beginning of a huge campaign to invest in automation at automotive assembly plants as multi-axes, programmable robots became available. These robots' flexible capabilities came at a price that incentivized efforts at labor cost displacement.

Automation in both welding and paint departments did increase substantially due to investment in these new robotic capabilities. However, automakers worldwide all failed in their attempts to apply these same robots to final assembly tasks, for three reasons:[12] 1) the capital equipment was expensive; 2) the equipment broke down a lot, making production schedules unreliable and requiring frequent maintenance; and 3) the equipment, while hypothetically programmable and able to handle a high degree of product complexity, was mostly unable to accommodate a high level of variety in actual operating conditions. With these barriers to implementation, many assembly automation initiatives were unwound.

The alternate path eventually adopted by virtually all automakers could be called "automation assist." These days, simple, inexpensive robots that can lift heavy parts and hold them in place while human workers carry out assembly tasks and quality checks have proved a winning combination in terms of lower capital investment, better labor productivity and product quality, and fewer workplace injuries. Custom-designed carts to hold tools, parts, and fasteners, connected to move in synchrony with the assembly line, are another low-cost "automation assist" application that has had the additional benefit of involving line workers, within teams, in their design. The lesson is that automation often does not completely eliminate jobs. Many times, automation has a partial impact in which tasks are shared between the human and the machine – and creative approaches to managing the human-machine interface are often possible in this partial automation state. Indeed, when humans work in close proximity to machines, their

[12] The assembly automation case is supported by research carried out under auspices of the International Motor Vehicle Program at MIT, involving data collected from 70 assembly plants from 20+ countries and companies in 1989, 1995, and 2000. See John Paul MacDuffie and Frits K. Pil, "From Fixed to Flexible: Automation and Work Organization Trends from the International Assembly Plant Survey," 1996, IMVP working paper. https://dspace.mit.edu/handle/1721.1/1623

observations can yield improvement ideas that "give wisdom to the machine"[13], which can help capital equipment appreciate (rather than depreciate) in value.

The pace of change has a large impact on the size of the dislocation. Rapid implementation of AV could lead to sudden dislocation. This suddenness is typically difficult for individuals, communities, and government policies to adjust to and/or ameliorate. In contrast, slow change, interrupted diffusion, and/or equifinal paths to implementation could allow for better anticipation and better adjustment, smarter policies, less negative framing, and more creative discovery of positive scenarios for joint gains.

For example, the sudden entry of China into the World Trade Organization caused widespread dislocation in U.S. manufacturing communities. Autor, Dorn, Hanson, and Song found that one quarter of recent U.S. manufacturing job loss could be attributed to this cause.[14] The impact was not limited to the manufacturing sector; they estimate that the median working-age American lost $1,200 in annual income from 2000 to 2007 as a result of China's entry into the WTO.[15]

Future analysts will continue to debate exactly which factors caused which outcomes. This is because assigning causality to any particular impact is always difficult and technological transformations do not follow a rigid pattern. For example, in the trade example above, economists used to think in general that dislocations due to various types of economic change were temporary. Recent research is upending this conclusion, as we noted above. A recent example, automated mining in Australia, shows that some technologies have immediate benefits for many workers. There, AV technology has eliminated long commutes by miners to remote areas and dangerous work in dusty and hot conditions, and has led to increased pay for remotely directing automated mining machines. However, jobs near the mines supplying food and goods to the remote miners (often among the few available in these remote communities) were permanently eliminated, to the detriment of many local workers.

Economic historians also believed that the gains from the Industrial Revolution were so unequally distributed that malnutrition (as measured by average heights) rose in the ensuing decades. But more recent scholarship casts some doubt on this conclusion, suggesting that sample selection biased the results. (For example, much height data comes from recruits to the military; if times are better, those interested in joining the military are a less-wealthy stratum of the population than before. Thus paradoxically, improved welfare could lead to shorter stature in the army.) Still, as we noted above, it does seem clear that wages stagnated during the early years of the Industrial Revolution (and fell sharply for many), with disputed indications that average heights fell significantly during this period.

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[13] Haruo Shimada and John Paul MacDuffie. "Industrial Relations and 'Humanware': Japanese Investments in Automobile Manufacturing in the United States," in Schon Beechler (ed.), *The Japanese Enterprise* (1998). London: Routledge.

[14] David Autor, David Dorn, Gordon Hanson, and Jae Song. "Trade Adjustment: Worker Level Evidence." *Quarterly Journal of Economics* 129, no. 4 (2014): 1799–1860. https://economics.mit.edu/files/11606

[15] Some, but not all of this loss was offset by the benefit of lower consumer prices in the U.S. of Chinese-produced goods.

Forecasters can typically anticipate the direct impacts that automation will have in eliminating specific jobs. However, analysts have been very poor at predicting how indirect effects of automation will change input costs, thus creating new economic activity and creating new jobs to deal with higher demand or new types of goods and services, etc. Yet with benefit of historical hindsight we can see that the number of indirect jobs created vis-à-vis a given type of automation is virtually always greater than the number of direct jobs lost.[16]

Fifty years of experience with automated teller machines (ATMs) testify to the difficulties of predicting these indirect effects, particularly during a long transition to ubiquitous application of the technology. ATMs were launched in 1967, almost simultaneously (and independently) in the U.S., UK, and Sweden. Early diffusion was slowed by operational problems, some created by ATM exposure to harsh weather and temperature extremes.[17] The pace of diffusion picked up by the mid-1980s and the direct effect of eliminating bank teller jobs showed up immediately; a 1996 Bureau of Labor Statistics (BLS) study found a decline of 41,000 bank teller jobs from 1986 to 1996, out of an overall employment drop of 70,000 to the level of 1.5 million commercial banking jobs, despite an expanding economy.[18]

But this pattern reversed beginning in the mid-1990s. According to Bessen,[19] the number of full-time equivalent bank tellers grew from the late-1990s to 2014 even as the number of ATMs deployed grew dramatically. How was this possible? Since ATMs allowed banks to operate branch offices at lower cost, they chose to open many more branches for easier access and a stronger community presence, expanding the number of people served and services offered by banks. Job losses from fewer tellers per branch were offset by the larger number of branches, resulting in net growth for bank tellers. Furthermore, with the emphasis on cross-selling new financial products to bank customers, new types of jobs were created at these branches, requiring customer-facing interpersonal skills, product knowledge, and aptitude for sales. In the last few years, with a decline in the use of cash, the trend is again reversed, with expectations that some bank branches will close. At the same time, the newest ATM feature at some banks is a two-way video connection to a bank employee in a call center to handle any non-routine transactions. ATMs as portals for new services could spur yet another phase of expected and unexpected consequences for jobs and skills.

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[16] James Manyika, Susan Lund, Michael Chui, Jacques Bughin, Jonathan Woetzel, Parul Batra, Ryan Ko, and Saurabh Sanghvi. "Jobs Lost, Jobs Gained: Workforce Transition in a Time of Automation." McKinsey Global Institute. December 2017. https://www.mckinsey.com/global-themes/future-of-organizations-and-work/what-the-future-of-work-will-mean-for-jobs-skills-and-wages

[17] Bernardo Bátiz-Lazo. "A Brief History of the ATM," *The Atlantic*, March 26, 2015 https://www.theatlantic.com/technology/archive/2015/03/a-brief-history-of-the-atm/388547/ and Linda Rodriguez McRobbie. "The ATM is dead. Long live the ATM!" *Smithsonian Magazine*, January 8, 2015: 1–11. https://www.smithsonianmag.com/history/atm-dead-long-live-atm-180953838/

[18] Teresa Morisi. "Commercial Banking Transformed by Computer Technology," *Monthly Labor Review*, August 1996, pp. 30-36. https://www.bls.gov/opub/mlr/1996/08/art4full.pdf

[19] James E. Bessen. "Toil and Technology," *Finance and Development,* June 2015, pp. 16-19. http://www.imf.org/external/pubs/ft/fandd/2015/03/bessen.htm

Some implementations of big new technologies have gone relatively smoothly. In the U.S. for example, the 1990s computerization of white-collar work affected the jobs of people with college degrees; they were able to use computers as a complement to their work, rather than as a substitute for it. In other cases, the co-existence of people doing jobs that overlap with what technology could do on its own becomes institutionalized, not least because this arrangement keeps a responsible (and liable) human being "in the loop."

For example, the autopilot function in aviation has a long history, going back to 1914 when gyroscope technology was shown capable of keeping a plane's flight path stable even in the absence of an active pilot at the controls. Yet pilots still routinely staff all commercial airline flights. The minimum required staffing level for a flight crew has shifted down; it was once three (two pilots and a flight engineer) and now only the two pilots are required by FAA regulations. This status quo is, by most accounts, securely maintained under the current regulatory regime.[20]

Are human pilots headed for elimination? Perhaps, since in a recent survey, airline pilots reported spending only 4 to 7 minutes per flight in manual control mode. And NASA is investing heavily in a "safe autonomous system operations" project that could potentially remove the on-board co-pilot and substitute a remote ground controller who could serve as co-pilot for multiple flights.[21]

Yet, even with what autopilot technology is capable of doing, accounts from pilots reveal how misleading the "seven minutes of hands-on flying" statement is.[22] Pilots always have hands-on control during taxiing for takeoff and after landing. Pilots also make the choices among a set of operating parameters that go into a given autopilot configuration. Pilots respond to queries and directives from air traffic controllers and, of course, take over in the case of extreme weather conditions, equipment failures, and other emergencies.

But perhaps the most important point about the continued presence of pilots in the cockpit is that they are there to reassure both passengers and the society at large that a responsible, competent professional is in charge and monitoring the technology for their safety. Legal philosophers and ethicists, observing this phenomenon, speak of the importance of having a "moral crumple zone" for certain activities that are dangerous and occur in public space.[23] Just as the crumple zone in an automobile provides protection for the occupant in the event of a crash, the presence of a pilot

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[20] In the summer of 2016, National Transportation Safety Board Chairman Christopher Hart reiterated the necessity of human pilots, saying "[o]n the one hand, the human operator is the least predictable part of the system… But a highly trained, proficient human operator can save the day by being the most adaptive part of the system." https://www.c-span.org/video/?411934-1/ntsb-chair-christopher-hart-discusses-driving-cars

[21] John Markoff. "Planes Without Pilots," *New York Times*, April 6, 2015 https://www.nytimes.com/2015/04/07/science/planes-without-pilots.html and "Towards the End of Pilots," *The Atlantic*, March 3, 2016. https://www.theatlantic.com/technology/archive/2016/03/has-the-self-flying-plane-arrived/472005/

[22] Patrick Smith. "Cockpit Confidential: The Autopilot Myth," 2011. http://freakonomics.com/2011/12/12/cockpit-confidential-the-autopilot-myth/

[23] Madeleine Clare Elish. "Letting Autopilot Off the Hook," *Slate,* June 2016. http://www.slate.com/articles/technology/future_tense/2016/06/why_do_we blame_humans_when_automation_fails.html

who is responsible for safety provides a kind of moral protection against anxieties that could otherwise render the aviation system less effective as a transportation service open to all.

Thus, it appears unlikely that "planes without pilots" are coming to our airports anytime soon. We might find that similar sentiments will preserve a driver role for autonomous trucks, perhaps particularly the big tractor-trailers that can pose such a danger in case of accidents in uncontrolled environments, even when the technology is hypothetically able to function without any human intervention.

Although in some situations, automation can be implemented without the need for dramatic adjustments in jobs or skills, this is by no means the norm—or even the dominant case. And even when indirect effects over the long term add more jobs and skills than are lost in the short term, limitations in the effectiveness of short-term adjustments can have negative consequences for the individuals and communities first affected. Several types of gaps slow adjustment:

1) The new jobs may be located in different places from existing jobs. In this case displaced workers may have to move to find new employment, slowing the process of re-employment. An example here would be trade, where manufacturing-intensive communities lost jobs, while others gained.[24]

2) The new jobs may require different skills from the old jobs. For example, computerized machine tools were designed in such a way as to require sophisticated programming skills, making it hard for existing machinists to use their skills.

3) Incentives or access to capital for investments that create new jobs may be lacking. For example, if the major adoption of a technology occurs during a recession or in a region with low access to capital, the creation of new jobs may be slowed. In contrast, this process may occur relatively quickly during a boom time, such as during the rapid diffusion of ATMs from the mid-1980s to mid-1990s.

4) Institutions and regulations that facilitate the sharing of productivity gains may be lacking. Examples of these mechanisms include unions and some labor market regulations. Unions can work with employers to implement transition plans that reduce the need for layoffs and new hires. The automation of welding and stamping in the auto industry was facilitated by clauses in UAW contracts that required retraining and reassignment when jobs were eliminated due to new technology. The union recognized that the viability of the "Annual Improvement Factor" (an annual wage increase received by all members) in fact depended on the introduction of new technology.[25] In contrast, where workers do not have the power to enforce an efficient agreement, they may try to protect their right to perform the duties of their individual job, preventing efficient reallocation of resources. For example, some states'

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[24] David H. Autor, David Dorn, and Gordon H. Hanson. "The China Shock: Learning from Labor-Market Adjustment to Large Changes in Trade." *Annual Review of Economics* 8 (2016):205–40. https://www.ddorn.net/papers/Autor-Dorn-Hanson-ChinaShock.pdf

[25] Frank Levy and Peter Temin. "Inequality and Institutions in 20th Century America," NBER Working Paper No. 13106, May 2007. http://www.nber.org/papers/w13106

occupational license requirements impose barriers that slow occupational switching but do not appear to contribute much to the quality or safety of the service provided.[26] Other regulations can improve transitions, such as requiring early warnings for mass layoffs to allow workers more time to search or retrain while on the job to shorten or avoid unemployment spells.[27]

B. Implications of past changes for likely labor market impacts of AVs

Taken together, our review of historical cases suggests that technological change in the long run leads to large social benefits, but that in some cases these benefits are long-delayed and/or impose significant costs to those displaced.[28] The length and difficulty of the adjustments varied greatly, depending upon the size of the changes in skills needed, the geography, investment, bargaining power, and institutions.

For example, the pace and pattern of diffusion of AVs will likely be affected by many factors, including the capability of the technology itself (e.g., extreme weather conditions are still challenging for most AV hardware to handle), customer receptiveness (e.g., how much customers are ready to trust a driverless vehicle, particularly where there is no potential for human backup), regulatory and legal requirements (e.g., at what level of safety will regulators allow (or demand) a rapid move to a fully-AV transportation network? who is liable when AVs cause accidents?), and economics (e.g., what level of density of demand is needed to make fleets of AV cars economically viable, particularly in suburban and rural areas; what cross-subsidies might be needed to insure universal access to new modes of transportation?). An additional factor is the interaction of AV diffusion with efforts to regulate carbon that might lead to significant increases or decreases in vehicle miles travelled. At any given rate of diffusion, there will be immediate direct effects and longer-term, difficult-to-predict indirect effects; there is no scenario in which negative direct effects can be completely avoided.

Still, when viewed in retrospect and across the entire economy, it is clear that automation has not shrunk the total number of jobs and has delivered a higher standard of living. This is such a positive scenario that one might ask "why worry?"

So, why worry?

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[26] Morris M. Kleiner and Alan B. Krueger. "Analyzing the Extent and Influence of Occupational Licensing on the Labor Market." *Journal of Labor Economics* 31:S1 Part 2, April 2013. http://www.journals.uchicago.edu/doi/10.1086/669060

[27] See Christopher J. Ruhm. "Advance Notice and Postdisplacement Joblessness." *Journal of Labor Economics* 10: 1 (January 1992), pp. 1-32. http://www.journals.uchicago.edu/doi/pdfplus/10.1086/298276; and Paul Swaim and Michael Podgursky. "Advance Notice and Job Search: The Value of an Early Start." The *Journal of Human Resources* 25, no. 2 (Spring, 1990): 147-178. http://www.jstor.org/stable/pdf/145752.pdf

[28] This conclusion is also reached by other studies of this topic; for McKinsey's recent review, see James Manyika, Susan Lund, Michael Chui, Jacques Bughin, Jonathan Woetzel, Parul Batra, Ryan Ko, and Saurabh Sanghvi. "Jobs Lost, Jobs Gained: Workforce Transition in a Time of Automation." McKinsey Global Institute. December 2017. https://www.mckinsey.com/global-themes/future-of-organizations-and-work/what-the-future-of-work-will-mean-for-jobs-skills-and-wages

First, the direct losses that occur right away can impose substantial costs on certain individuals and communities. In particular, for the reasons listed above, re-employment may be delayed substantially. Indeed, recent declines in U.S. business expansions and startups suggest that the capacity of the U.S. economy to respond quickly to shocks has diminished.[29]

Second, the broader indirect impacts may be very unevenly distributed and increasingly so. While the U.S. has historically seen wages rise in tandem with productivity, institutions for achieving this have broken down since the 1980s, as shown in Figure I-1 on the next page. As a result, despite significant U.S. productivity gains, the bottom 90 percent of American adults have not seen any income gains since 1999, even when government payments are included.[30] The President's Council of Economic Advisors provides more evidence, reviews possible causes, and advances the idea that employer bargaining power (also called monopsony power) has been growing in the U.S.[31] This real wage stagnation, which has persisted since the mid-1970s in the face of significant productivity gains, casts doubt on whether the promise of a technology like AVs would in fact be shared, and causes worry among those who already feel they are just getting by.

Third, we cannot rule out the possibility that the technology behind the current wave of automation—artificial intelligence (AI)—will have a different mix of direct and indirect effects than in the automation scares of the past. In particular, due to a capacity for "machine learning" via mimicking what humans do in their jobs (rather than programmers having to figure out how to reduce those human activities to programmable rules), AI may pose a more real threat to high-skilled workers and hence adversely affect both jobs and skills at the high-skill (usually high-pay) end of the economy. Future technologies may differ from past technologies in important ways that could render what we know about past patterns to be worth little. Many heralding the importance of artificial intelligence (AI) are making exactly the claim that "this time it's different."

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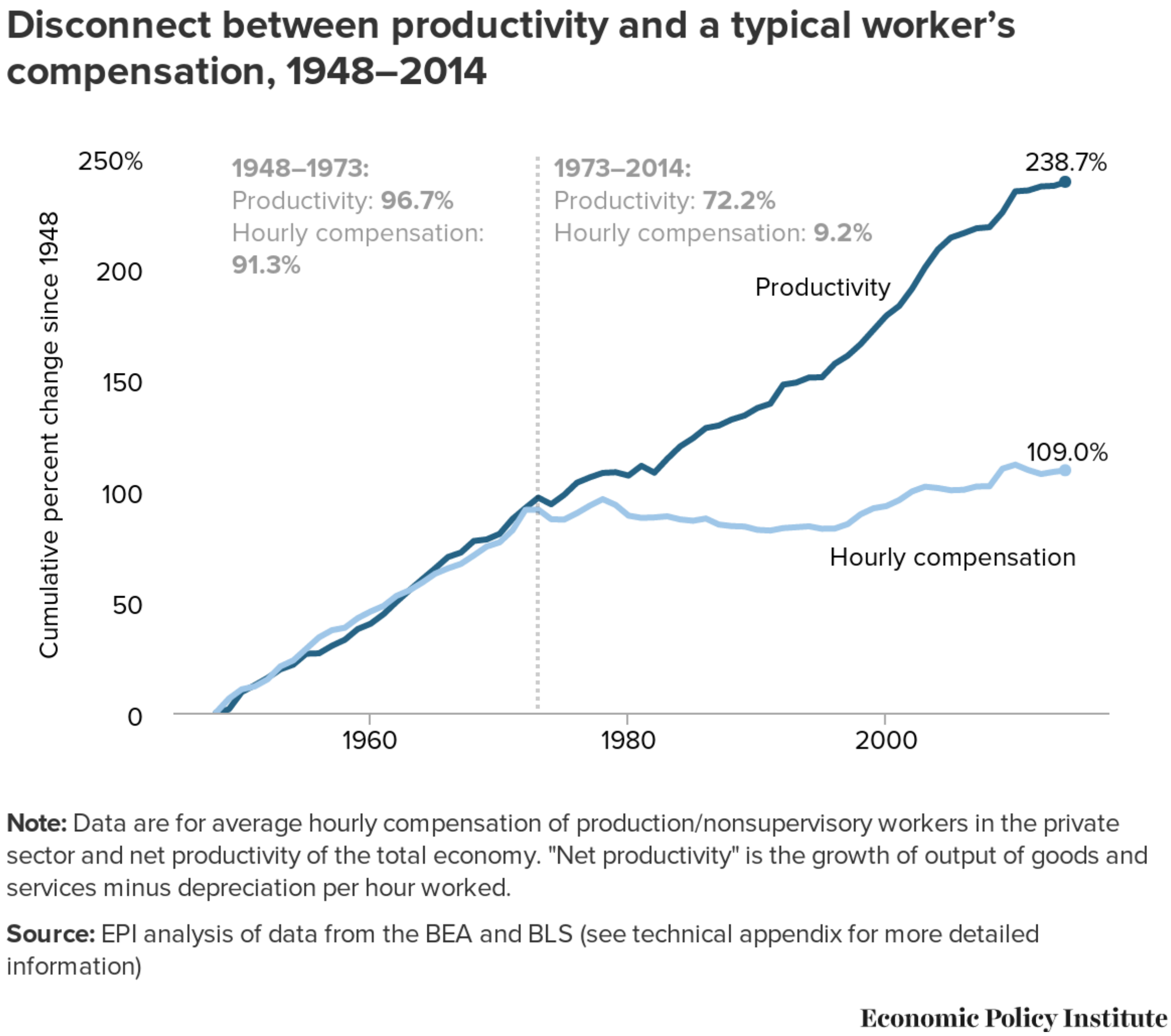
[29] Raven Molloy, Christopher L. Smith; Riccardo Trezzi, and Abigail Wozniak. "Understanding Declining Fluidity in the U.S. Labor Market." *Brookings Papers on Economic Activity*. Spring 2016, p. 183-237. https://www.brookings.edu/wp-content/uploads/2016/03/molloytextspring16bpea.pdf; Steven Davis and John Haltiwanger. "Re-Evaluating Labor Market Dynamics," Federal Reserve Bank of Kansas City, Jackson Hole Symposium, August 21-23, 2014, pp. 17-107. https://www.kansascityfed.org/~/media/files/publicat/sympos/2014/2014davis_haltiwanger.pdf

[30] Figure 7 in Emmanuel Saez. "Income and Wealth Inequality: Evidence and Policy Implications." *Contemporary Economic Policy* 35:1, January 2017, 7–25. https://eml.berkeley.edu/~saez/SaezCEP2017.pdf. This figure shows that for the bottom 90% of adults, income has essentially stagnated since 1999, even including post-tax transfers and using a conservative inflation measure (national income deflator instead of CPI). See also David Autor and Anna Salomons. "Is Automation Labor-Displacing? Productivity Growth, Employment, and the Labor Share." *Brookings Papers on Economic Activity*. March 8, 2018. https://www.brookings.edu/bpea-articles/is-automation-labor-displacing-productivity-growth-employment-and-the-labor-share/

[31] Council of Economic Advisors. "Labor Market Monopsony: Trends, Consequences, and Policy Responses." *Issue Brief*. October 2016. https://obamawhitehouse.archives.gov/sites/default/files/page/files/20161025_monopsony_labor_mrkt_cea.pdf

Others disagree, expecting that consequences of the current automation scare will not differ substantially from the patterns of past waves of technological disruption.[32]

FIGURE I-1: Disconnect Between Productivity and a Typical Worker's Compensation, 1948-2014



Source: Josh Bivens and Lawrence Mishel. "Understanding the Historic Divergence Between Productivity and a Typical Worker's Pay: Why It Matters and Why It's Real." Economic Policy Institute. September 2, 2015. https://www.epi.org/publication/understanding-the-historic-divergence-between-productivity-and-a-typical-workers-pay-why-it-matters-and-why-its-real/

Since people's experience with previous innovation is likely to strongly inform their attitude to future changes, we ignore these worries at our peril. All three of these concerns have the potential to fuel local and national resistance to innovation, via adverse policy or shop-floor disruptions. If so, they could slow productivity growth, reduce international competitiveness and retard

[32] For more on this debate, see Robert Atkinson, " 'It's Going to Kill Us!' and Other Myths about the Future of Artificial Intelligence," *Information Technology and Innovation Foundation Report*, June 2016. https://itif.org/publications/2016/06/06/its-going-kill-us-and-other-myths-about-future-artificial-intelligence. Frank Levy, "Can Robots be Lawyers?" *Georgetown Journal of Legal Ethics*, Vol. 30, pp. 501-558, https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2701092

improvements in our standard of living. Proponents of innovation need to take these risks seriously.

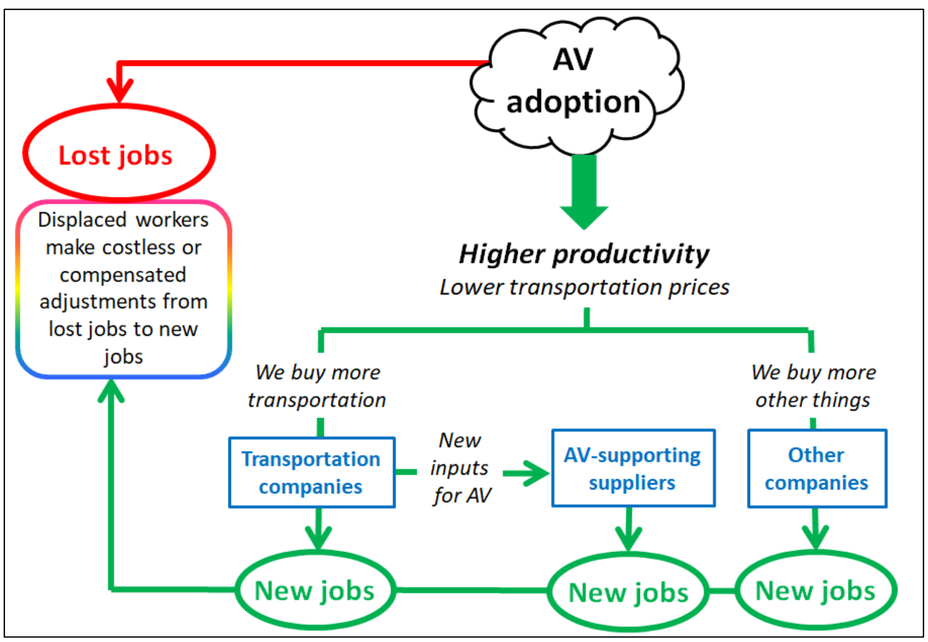
II. Framework for Labor Market Impacts

This section sets forth a framework that allows us to consider comprehensively the labor market impacts of AV. First, we describe how an ideal, well-functioning labor market works and how the adoption of autonomous vehicles would affect such an ideal market. Then, we discuss the impact of key ways in which the actual U.S. labor market differs from the ideal.

A. How an ideal labor market would adapt to AVs

Economists often use simple models as baselines from which they can systematically examine factors that alter outcomes from the ideal. That is, an understanding how the ideal market works during a transition provides us with a clarifying starting point for assessing an actual event. Figure II-1 presents a diagram of this ideal system.

FIGURE II-1: Impact of Adoption of AVs on the Labor Market—Ideal (Frictionless) Adjustment Process



Source: Authors, inspired by Joss Fong, "Why the rise of the robots won't mean the end of work," *Vox*, November 13, 2017. https://www.vox.com/videos/2017/11/13/16635360/automation-robot-jobs-unemployment-debate.

In a nutshell, adopting productivity-boosting AV in a model competitive economy with a perfect labor market can be beneficial for all parties. Here's how that works, starting with the employers. At the beginning, all employers are making the same, normal profits. When the first employers adopt AV, the cost of making their goods or services falls, which enables them to earn higher profits and to lower their prices to grab market share. Seeing that, other employers adopt AV in order to stay competitive. The ones that don't adopt AV close down because they see better uses for their investments elsewhere. When the dust settles, a new lower price level for AV-enabled goods and services prevails. And the total amount of those goods and services produced (now using AV) will rise in accordance with how price-sensitive the customers are. The increase in production can range from substantial (if the customers are very price-sensitive—think about bank customers using ATMs much more than they did tellers) to zero (if customers' demand is unresponsive to prices). The early adopting firms make abnormally high profits briefly, until their competition catches up. Then all revert to making normal profits at the new AV-enabled lower prices and higher productivity.

How do workers fare in this perfect world? They start off with wages that reflect their productivity without AV, and everyone who wants to work is fully employed, except for those who are in brief transitions between jobs: full employment. As employers adopt AV, two related things happen: (1) job churning rises temporarily; and (2) firms' skill needs change permanently.

Job churning rises as some firms grow or shrink while others are born or close. As firms adopt AV, they need fewer workers in some occupations, such as truck drivers. Meanwhile, workers are attracted to higher productivity firms (with AV or in other sectors) that pay higher wages and are expanding. At the same time, firms without AV lose market share and thus lay off workers as they shrink or close. The unemployment rate rises temporarily while the churn is higher.

As new skills are needed to adapt to AV, employers or external parties can use savings they have garnered from lower transportation prices to attract and train workers accordingly. Some of the reallocation and retraining takes place within firms. Employers adjust worker training to fit redesigned jobs and to move workers from jobs being cut to new vacant slots. In other cases, laid-off workers are unemployed while they search for new jobs. To ensure that no one loses from AV adoption, a tax or surcharge paid by the beneficiaries of lower transportation prices funds retraining or other benefits for laid-off workers. Eventually, the economy adjusts back to full employment with employment churning returning to its normal level.

Where do the new jobs for all the displaced workers come from? There are three sources.

1. More transportation services. As firms implement AV, mobility will become more affordable, so use of personal mobility (including by the young, disabled, and poor) will rise, perhaps a lot. Similarly, as road transport costs fall, more goods carried by trucks or delivery vans will be consumed. So, transportation services and trucking companies will expand their output and add jobs to handle the new volume. Firms will need to expand and hire workers to meet this new demand, as banks did with tellers after the introduction of ATMs.
2. More AV support jobs: AVs will expand employment in jobs that support AVs in transportation services firms and elsewhere, such as AI specialists and programmers. In addition, some new products and services will be enabled by AVs, such as expanded in-automobile entertainment systems or Wi-Fi-enabled applications that occupants who are no longer driving can utilize, which will lead to new jobs.

3. More spending on other goods and services. When consumers see cheaper and safer transportation, some will have more income remaining to use for non-transportation expenditures. Capital will be invested in the firms that produce these goods and services, so more workers will be hired to produce, distribute, and sell these additional goods and services, whether in health, education, computer games, home repairs, vacations, or toys. Indeed, this final source of demand closes the loop and leads to full employment in the long run.

With flexible wages, these new jobs, in aggregate, will absorb all the workers displaced by AV because their expansion is funded by the savings from the productivity gains from AV. These workers' wages will not necessarily be higher than before. However, the efficiency gains from introducing AV make it possible to compensate these workers and leave everyone better off than they were before.

In the next section, we draw on our historical cases to add two real-world complications to this story and present the framework that guides our estimation.

B. Real-world complications

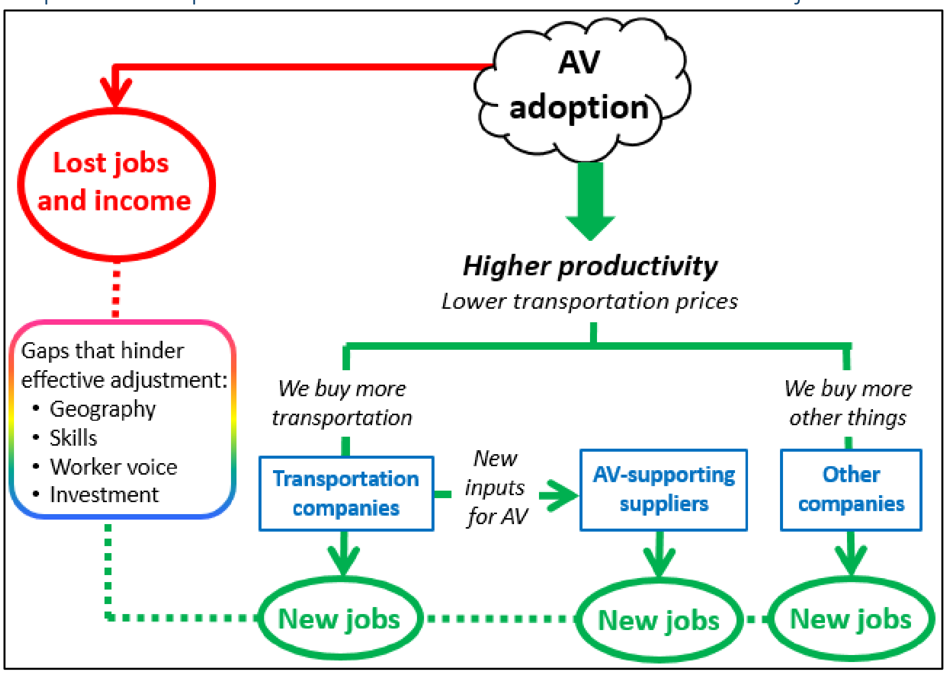
Above, we showed how the economy could return to full employment with everyone better off after some jobs are permanently eliminated by AVs. Two key real-world complications have frustrated the achievement of this happy scenario in the past: a) barriers to moving resources (such as people and equipment) to the new opportunities, and b) lack of institutions or mechanisms to enable or force the winners from the new technology to compensate the losers.

Figure II-2 illustrates a framework that incorporates the potential for adjustment shown in Figure II-1 and the two real-world complications we just introduced. Figure II-2 captures the fact that four types of gaps make workers' adjustments from the old jobs to the new ones more difficult:

1) **Geography**: New jobs may be located in different places from existing jobs (as occurred during the industrial revolution and trade expansion).
2) **Skills**: New jobs may require different skills from the old jobs (as occurred in the automation of auto assembly plants).

3) **Worker voice**: Institutions and regulations that surface workers' perspectives and facilitate the sharing of productivity gains may be lacking (as during the recent trade expansion in the U.S.).[33]
4) **Investment**: Incentives or access to capital for investments to create new jobs may be too low (such as transitions during a recession and the impact on local indigenous workers near Australian mines).

FIGURE II-2: Impact of Adoption of AVs on the Labor Market—Realistic Adjustment Process



Source: Authors, inspired by Joss Fong, "Why the rise of the robots won't mean the end of work," *Vox*, November 13, 2017. https://www.vox.com/videos/2017/11/13/16635360/automation-robot-jobs-unemployment-debate.

The larger these gaps are, the longer laid off workers will spend unemployed while they search or prepare for their next job. And if many workers lose their jobs, unemployment rises substantially

[33] The broad concept of worker voice covers any format (including, but not limited to, formal unionization) that can channel workers' perspectives to influence outcomes and provide some measure of bargaining power. Such institutions tend to raise productivity as well as lead to more equitable distribution of returns. The seminal work on the importance of stakeholder voice appears in Albert O. Hirshfeld's "*Exit, Voice, and Loyalty Responses to Decline in Firms, Organizations, and States*," Harvard University Press, 1972. For recent research on the rationale and options for restoring a voice for U.S. workers see Thomas Kochan, William Kimball, Duanyi Yang, and Erin L. Kelly, "Worker Voice in America: A Current Assessment and Exploration of Options," Massachusetts Institute of Technology, draft, January 17, 2018 http://iwer.mit.edu/wp-content/uploads/2018/01/worker-voice-paper-1_16_18_tablesintext12pt.pdf. Another relevant study is Jeremy Avins, Megan Larcom, Jenny Weissbourd, "New forms of worker voice in the 21st century," Harvard Kennedy School of Government and MIT Sloan School of Management, January 2018. http://iwer.mit.edu/wp-content/uploads/2018/01/New-Forms-of-Worker-Voice-IWER.pdf.

for a long time and displaced workers' new jobs pay far less than they received before. Particularly large gaps raise the possibility that low wages for many are not just a transition problem, but also a persistent feature of new economic arrangements.

Thus, in Figure II-2, AV adoption causes lost jobs and incomes because unemployment durations are longer and/or uncompensated. This impact is shown in red. The three general sources of job increases (shown in green) remain: more transportation will be used, requiring some new jobs, new companies and jobs will spring up to provide AV services and new products enabled by AV (for example new forms of in-car entertainment); and consumers will have more money to spend on other things with the money and time they are saving on transportation. And, as we have seen in the past, the "green" new jobs usually eventually come to balance the "red" job losses. However, the dotted green lines show that connecting the displaced workers to the new jobs quickly (or ever) is not guaranteed.

As before, the model also shows how consumers benefit as AV lowers the price of transportation, allowing them to travel more and buy other things with their AV-enabled savings. In essence, the benefits of the transition will go to the AV-adopting companies and to consumers overall, while the costs are borne most severely by the displaced workers.

Figure II-2 shows that, in order for everyone to be at least as well off as before, there must be mechanisms for job placement, retraining, or other benefits for the displaced workers. With these mechanisms we can achieve the outcome illustrated in Figure II-1. Without such mechanisms, the rise in unemployment can be prolonged and earnings-decreases more likely. So, workers at high risk of displacement (along with those who support and represent them) have a strong reason to resist or slow the transition. Furthermore, even workers who are not displaced may have reason to resist if changes in their duties that increase productivity are not reflected in their wages or they fear future displacement. Policy options for these issues are discussed in Section V.

The framework also invites investigation of other topics related to the adoption of AVs, many of which are discussed in Section IV.

- Future research will be needed on likely benefits of AVs to workers and employers. These benefits include lowering the risk of occupational injury or deaths (a crucial feature of working conditions) and reduced time spent actively driving, which should allow workers more time for non-driving duties, raising the productivity of any worker whose job now requires driving.
- New jobs will also be created, as noted above. Even though much is unknown about the timing, price effects, and consumer response, the three categories of new jobs provide a route for conjecture about what form these new jobs may take.

C. Adoption scenarios

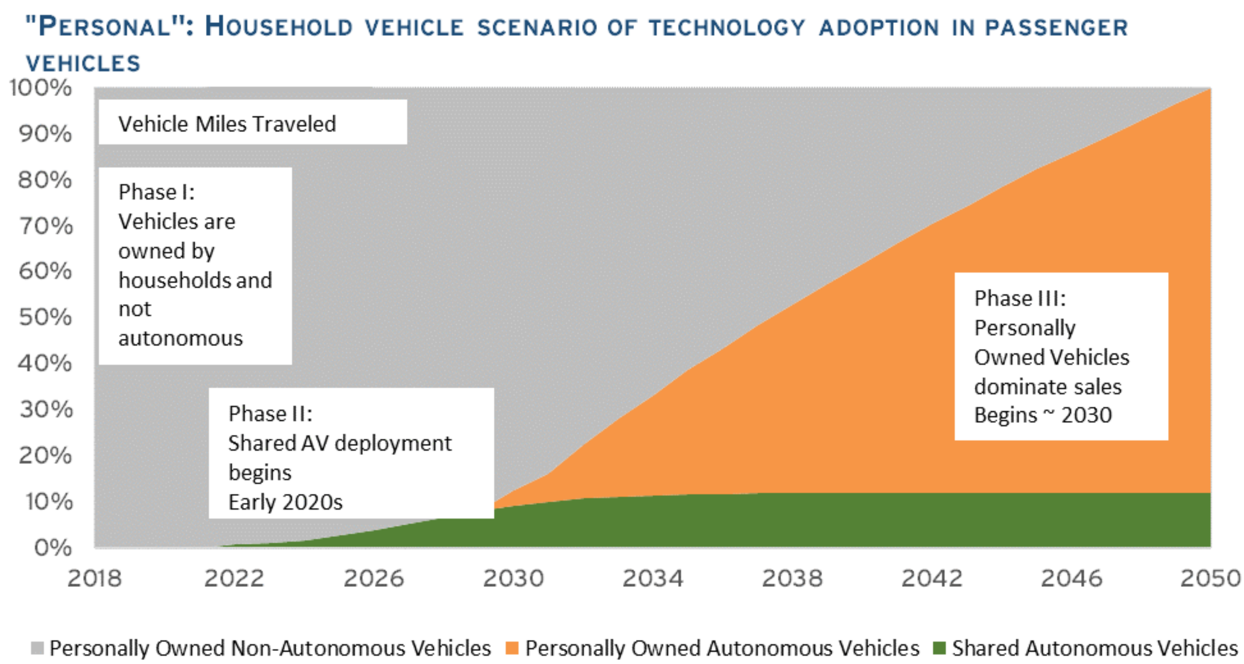
To understand the magnitude of the labor market challenges posed by the transition to AVs, we construct quantitative simulations of job loss. These simulations use four high-level AV adoption scenarios developed by Securing Americans' Future Energy (SAFE) to help ground projections within the context of technological development and deployment. The scenarios also inform our qualitative treatment of job creation.

Labor market and policy dynamics make it useful to look separately at “light-duty” and “heavy-duty” vehicle sectors. Light-duty vehicles are mostly cars. They weigh less than 10,000 pounds and primarily serve personal mobility needs, moving people from place to place. Heavy-duty vehicles are mostly trucks and buses. They weigh over 10,000 pounds and are primarily used for the movement of goods as well as for mass transit.

SAFE has developed two scenarios for each sector to explore different technology development and deployment trajectories. For the purposes of this study, we treat the car and truck sectors as fully independent of each other. The scenarios are illustrated in Figures II-3 and II-4. They can each be considered individually or combined into four car-truck combinations.

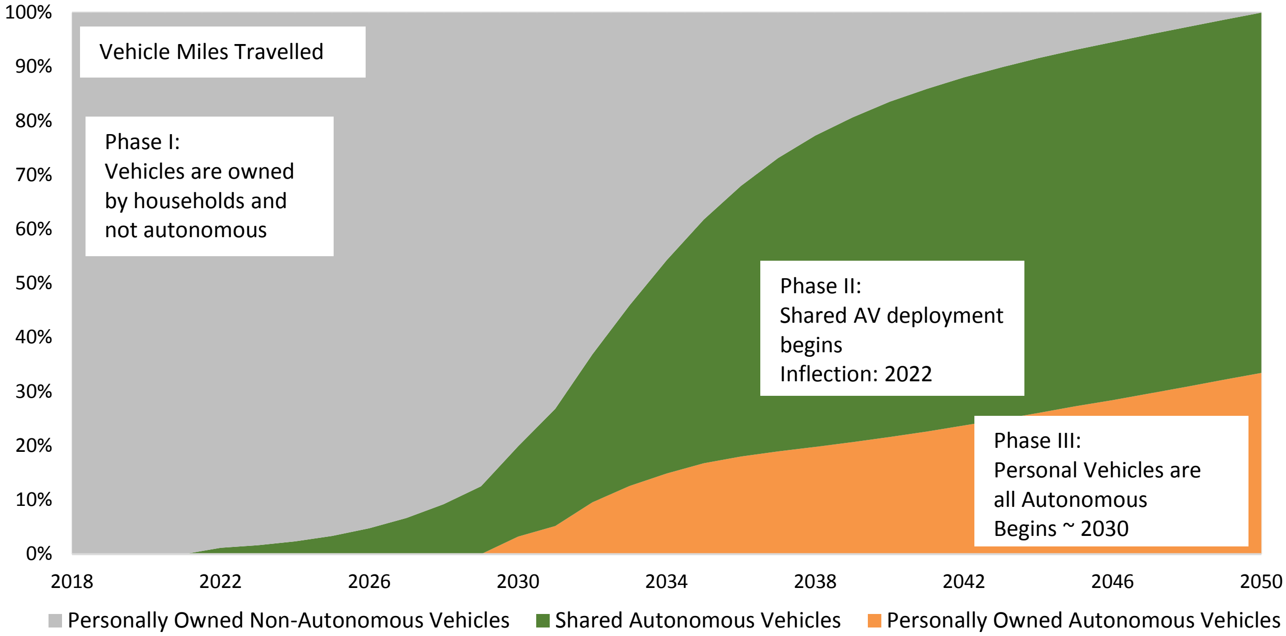
The light-duty sector (car) scenarios are pictured in Figure II-3. These two scenarios differ primarily in how AV ownership evolves, not the timescale on which technology develops. In both the “shared” (fleet) ownership and the “household” (personal) ownership light-duty scenarios, most AVs are initially shared, with initial deployment around 2020 and an inflection point into rapid adoption around 2030. The scenarios diverge at that point.

FIGURE II-3: Cars (Light-Duty Vehicles) Adoption Scenarios



Source: Securing America’s Future Energy

"FLEET": AGGRESSIVE SCENARIO OF TECHNOLOGY ADOPTION IN PASSENGER VEHICLES



Source: Securing America's Future Energy

Early stage deployment may be in restricted areas, although not only, or even primarily on limited access routes. For example, Waymo is planning to deploy in a defined area within Chandler, Arizona, but will likely be able to travel between any point A and point B within that defined area. As significant deployment occurs, we assume that most routes will be capable of supporting automation. But 100 percent deployment will require that the technology is fully developed and diffused.

- Cars-Personal: describes an AV adoption timeline for passenger (light-duty) vehicles with household ownership. Households own most cars and light trucks, as is now the case. Fleet ownership plateaus at about 10 percent of the market and households buy AVs for their household usage at the rate of current vehicle sales today.
- Cars-Fleet: describes an AV adoption timeline for passenger (light-duty) vehicles with fleet ownership. A set of transportation service providers own and operate most cars and light trucks. Compared to household ownership, fleets imply more centralized maintenance, fewer vehicles per person and more rapid adoption of electric vehicles. Household ownership of AVs grows to an appreciable fraction of the market, but fleet ownership comprises a strong majority (about 80 percent).

The heavy-duty sector (truck) scenarios are pictured in Figure II-4. These two scenarios incorporate the influence of the age of rolling stock and are primarily differentiated by the timeline for technology adoption. Thus, the difference between the two timelines reflects factors such as speed of technology development, policy support, or societal acceptance. To broadly illustrate technology development, we divide technological development into three stages.

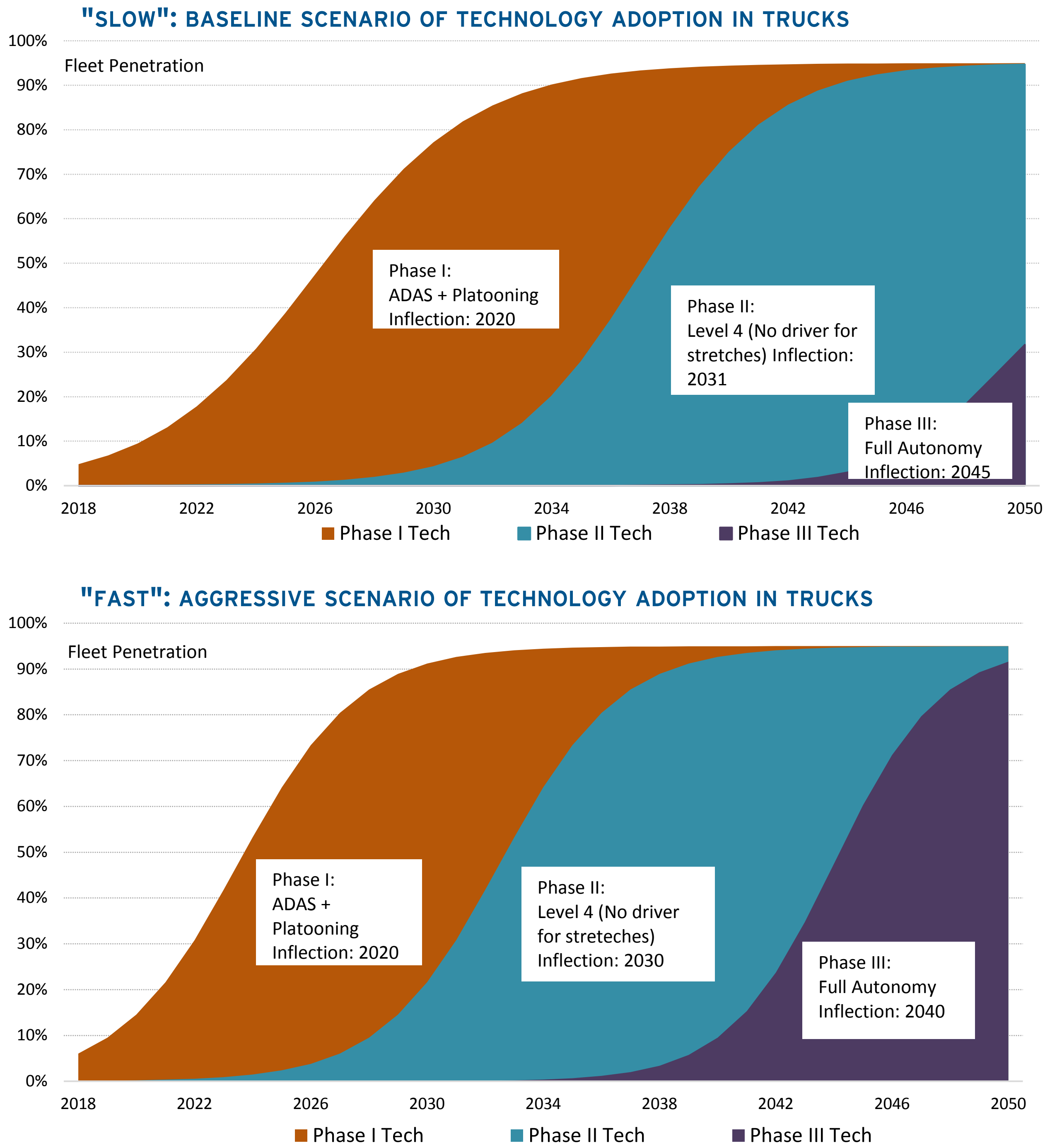
- Phase I is a composite of Advanced Driver-Assistance Systems (ADAS—equivalent to Level1/2 automation), platooning (trucks move in a convoy all controlled by the lead truck), and early applications of Level 3 automation (where vehicle control transfers back and forth between automated system and human driver). These technologies may make a trucker's drive safer and more comfortable, but it does not change the reality that a driver's attention must be accessible at all times, not so different from today.
- Phase II represents a stage in which the driver can be removed from the truck for some subset of trips or parts of trips on some restricted set of routes (advanced Level 3 or early Level 4 automation).
- Phase III represents the stage when the driver is not required for most trips on most, if not nearly all, routes (advanced Level 4 or early Level 5 automation).[34]

The two scenarios represent two different timelines for progressing through these phases.

- **Trucking-Slow:** describes a baseline AV adoption timeline where trucking takes about 30 years adapting to driver-assisted AV before it proceeds to fully autonomous trucks that do not need drivers. It sees Phase I technology becoming mainstream in the 2020s, Phase II in the 2030s, and Phase III technology becoming available in the 2040s.
- **Trucking-Fast**: describes an aggressive AV adoption timeline where trucking AV technologies gain adoption on a more accelerated timeline, perhaps as much as a decade in advance of the "Slow" scenario. In particular, full adoption of Phase III technology is predicted to be nearly complete by 2050.

[34] The levels of automation referred to here and throughout our report are drawn from the framework established by the international Society of Automotive Engineers (SAE), Stanford Center for Internet and Society, http://cyberlaw.stanford.edu/blog/2013/12/sae-levels-driving-automation (reproduced as Table IV-2).

FIGURE II-4: Trucking (Heavy-Duty Vehicles) Adoption Scenarios



Source: Securing America's Future Energy

These four scenarios drive the displacement timelines in our simulations. For example, in the year when adoption of a phase is half complete, we simulate that half of the layoffs associated with full adoption of the phase will have occurred. This approach is somewhat crude in that we do not apply differential phasing for the various occupations. That is, we abstract from the fact that some occupational job losses may occur early in adoption (perhaps auto repair mechanics), while others may be concentrated later on (perhaps some of the drivers). We start our simulations in 2017 and end in 2050.

D. Occupations at risk

We base our simulations on workforce status paths drawn from the experiences of displaced workers, data on the occupations likely affected, turnover projections, and estimates of earnings losses from displacement.

i. Which jobs may be eliminated by AVs?

We follow previous studies in identifying occupations likely to be affected by AV, building on occupational classifications identified as "driving related" by the Commerce ESA study.[35] We break all occupations into four impact groups. Table II-1 describes the categories and provides examples of the occupations in these groups, which are:

1. **Primary drivers**: Jobs whose primary responsibility is driving on roads, such as drivers of trucks, taxi cabs, and buses
2. **Other on-the road drivers:** Jobs associated with personal driving in which the primary responsibility is not driving, such as traffic and highway police officers, parking lot attendants, and driving instructors
3. **Duties changed:** Jobs that require skills now (such as driving) that will change with the advent of AV, including incidental drivers such as home health aides, building contractors, visiting nurses, real estate agents and other sales people, regional supervisors, automobile and vehicle insurance workers, and taxi dispatchers
4. **Unaffected:** Jobs not listed above, such as teachers

Our analysis (like the Commerce ESA study) relies on the Standard Occupational Classification (SOC) system.[36] This system is used across the federal statistical system and is updated regularly. Yet, no classification system will be perfect for all uses in a dynamic economy. An in-depth discussion of the number of truck driver jobs that may be eliminated by AV within the next dozen years and its relation to SOC codes can be found in Gittleman and Monaco.[37]

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[35] David Beede, Regina Powers, and Cassandra Ingram. Office of the Chief Economist, Economics and Statistics Administration, U.S. Department of Commerce. (August 11, 2017). "The Employment Impact of Autonomous Vehicles" *ESA Issue Brief* # 05-17. http://www.esa.doc.gov/sites/default/files/Employment%20Impact%20Autonomous%20Vehicles_0.pdf

[36] For descriptions of the affected occupations see https://www.bls.gov/oes/current/oes_stru.htm.

[37] Murray Gittleman and Kristen Monaco. "Truck Driving Jobs: Are They Headed for Rapid Elimination?" Bureau of Labor Statistics unpublished paper, October 2017.

TABLE II-1: AV Impact Analysis Occupational Classifications

Classification category	Definition	How identified	Examples of occupations
1. Primary drivers	• Light duty drivers: Workers in occupations whose primary responsibility is driving cars, vans, and small trucks on the road • Heavy duty drivers: Workers in occupations whose primary responsibility is to drive heavy duty vehicles on the road	Following Commerce ESA 2017	Drivers of trucks, buses, taxis, and ambulances
2. Other on-the-job driving occupations	• Workers in occupations where driving is often required, but whose primary responsibility is not driving and whose role may be eliminated by AV	Following Commerce ESA 2017	Security guards, police, patrol officers, auto mechanics, parking lot attendants
3. Duties changed — Incidental drivers	• Workers in occupations whose primary responsibility is not driving but currently must drive in order to reach clients or job sites.	Following Commerce ESA 2017	Home health aides, real estate agents, visiting nurses, salespeople, building inspectors
4. Unaffected occupations	• Workers whose occupational responsibilities will be largely unaffected by AV	All occupations not in categories 1-3 above.	

Source: David Beede, Regina Powers, and Cassandra Ingram. "The Employment Impact of Autonomous Vehicles." Office of the Chief Economist, Economics and Statistics Administration, U.S. Department of Commerce. *ESA Issue Brief* #05-17. August 11, 2017
http://www.esa.doc.gov/sites/default/files/Employment%20Impact%20Autonomous%20Vehicles_0.pdf

ii. How many jobs are at risk?

For the simulations we focus on the first two groups of occupations. As shown in Table II-2, these two sets of occupations account for more than 6 million U.S. jobs—over 4 percent of U.S. nonfarm payroll jobs.

TABLE II-2: Job Loss Calibrations for AV Simulations

Occupation	Employment Level in thousands, 2016	Share of jobs eliminated under full implementation of scenario				Number of jobs eliminated under full implementation of scenario			
		Trucking-Fast	Trucking-Slow	Cars–Fleet	Cars–Personal	Trucking-Fast	Trucking-Slow	Cars–Fleet	Cars–Personal
Primary Driver Occupations									
Heavy and Tractor-Trailer Truck Drivers[38]	1,532	0.65	0.6	0	0	996	919		
Light Truck or Delivery Services Drivers[39]	781	0.55	0.45	0	0	430	351		
Bus Drivers, School or Special Client	212	0.5	0.5	0	0	106	106		
Driver/Sales Workers	383	0	0	0.2	0.2			77	77
Taxi Drivers and Chauffeurs	300	0	0	0.7	0.2			210	60
Bus Drivers, Transit and Intercity[40]	75	0.75	0.7	0	0	56	53		
Ambulance Drivers and Attendants, Except Emergency Medical Technicians	10	0.05	0.05	0.05	0.05	1	1	1	1
Primary Driver Total (percent of total jobs)	3,293					**1,588 (48%)**	**1,430 (43%)**	**287 (9%)**	**137 (4%)**
Other On-The-Job Driver Occupations									
Security Guards	646	0.024	0.024	0.024	0.024	16	16	16	16
Police and Sheriff's Patrol Officers	673	0.05	0.04	0.05	0.05	34	27	34	34

38 Assumes wider penetration under fast scenario.

39 Assumes wider penetration under fast scenario.

40 Assumes wider penetration under fast scenario.

Automotive Service Technicians and Mechanics	711	0.1	0.1	0.5	0.5	71	71	356	356
Postal Service Mail Carriers	271	0	0	0.2	0.2			54	54
Parking Lot Attendants	48	0	0	0.5	0.5			24	24
Automotive Body and Related Repairers	116	0.05	0.05	0.5	0.5	6	6	58	58
Refuse and Recyclable Material Collectors	64	0.5	0.5	0.0	0.0	32	32		
Automotive and Watercraft Service Attendants[41]	57	0	0	0.6	0.4			34	23
First-Line Supervisors of Police and Detectives	103	0.05	0.05	0.05	0.05	5	5	5	5
Couriers and Messengers	143	0	0	0.02	0.02			28	28
Automotive Glass Installers and Repairers	15	0	0	0.25	0.25			4	4
Insurance Appraisers, Auto Damage	14	0.3	0.2	0.25	0.25	4	3	4	4
Electronic Equipment Installers and Repairers, Motor Vehicles	7	0	0	0.5	0.5			4	4
Travel Guides	1	0	0	0.5	0.5			1	1
Total, Other On-The-Job Driver Occupations (percent of total jobs)	**2,869**					**167 (6%)**	**159 (6%)**	**620 (22%)**	**608 (21%)**
Grand Total (percent of total jobs)	**6,162**					**1,756 (28%)**	**1,589 (26%)**	**907 (15%)**	**745 (12%)**

Notes: 1. For Phase II of Truck scenarios we use 0.1*full implementation job losses. 2. For combined AV scenarios (such as the "Trucking-Fast" Scenario combined with the Cars-Fleet scenario) the shares displaced are added together. Sources: Occupational employment: Bureau of Labor Statistics Occupational Employment Survey 2015. Share of jobs eliminated based on consultation with industry experts.

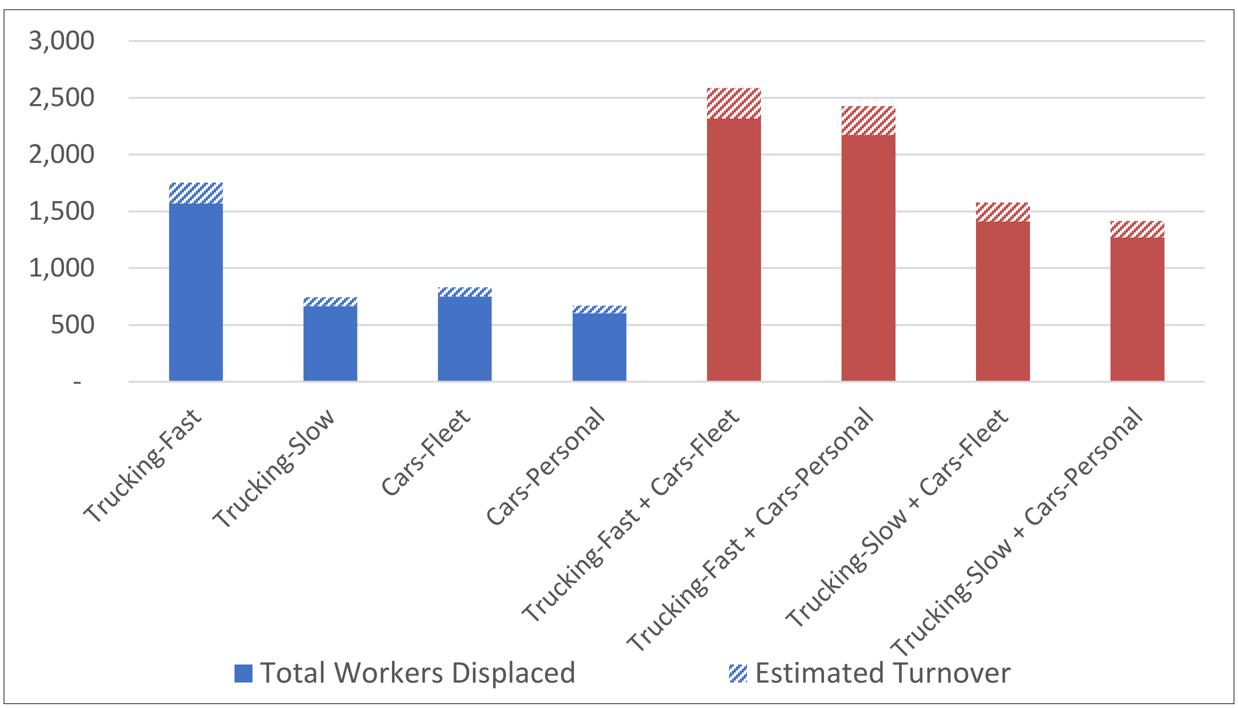
[41] Assumes more electric vehicles in fleets.

Of course, AV will not eliminate the need for every position in these jobs. Columns 3-6 of Table II-2 show our estimates of the share of positions in each occupation that will be eliminated under each AV scenario. Although admittedly speculative, these shares reflect our understanding of what industry experts at SAFE expect will happen. Over time, such estimates will certainly require refinement. When we multiply these shares by the employment levels in each occupation, we get the number of potential layoffs by occupation associated with the four scenarios.

The trucking AV transition affects occupations with greater employment, mostly primary truck drivers, and a large share (26-28 percent) of the jobs in those occupations. AV technology in passenger vehicles has a more diffuse impact, affecting many jobs where the primary activity is not driving, with a smaller share (12-15 percent) of the positions in those occupations. Although we do not account for it in our simulations, these percentages may be large enough to cause considerable job insecurity even in those workers who are not ultimately laid off.

How many jobs are at risk, according to the adoption scenarios? Figure II-5 shows the total number of jobs eliminated from 2018 through 2051, calculated by multiplying the shares affected in Table II-2 by the number of workers in each occupation. All told, the Trucking-Fast scenario alone involves job reductions of almost 1.8 million workers, while Cars-Personal causes about 0.7 million reductions. Combining scenarios yields a range from 2.6 million reductions for Trucking-Fast plus Cars-Fleet to 1.4 million for Trucking-Slow plus Cars-Personal, out of an overall U.S. labor force of about 159 million workers in 2016. This represents an impact on 1.6 percent to 0.9 percent of the labor force. Clearly, the adoption path matters considerably. In addition, as we will see below, other factors will also make a difference.

FIGURE II-5: Total Number of Workers Displaced by AV Adoption Scenario, 2018 - 2051, in Thousands



Source: Authors' calculations.

III. Job Loss and Displacement Effects

Informed by the framework in Section II, we now simulate key labor market impacts of the adoption of AV over the next few decades. First, we discuss turnover and then we focus on results, specifically how AV-adoption layoffs might raise unemployment, lower labor force participation, and reduce workers' earnings.

Importantly, we offer these simulations not as definitive forecasts, but as gauges of the potential size and nature of the disruption to the labor market posed by the adoption of AV as if they were taking place today. In particular, we do not adjust counts of workers affected in future decades by business cycle effects or demographic trends, including population growth. This approach allows us and the reader to interpret simulation outcomes in the context that we understand best, today's world. In so doing, this perspective abstracts from all manner of economic and demographic evolution that would be taken into account in a forecasting exercise. When adoption of AVs actually takes place, its costs and benefits will undoubtedly be affected by conditions prevailing at the time as well as employers' and policy choices.

A. Job loss and occupational turnover

The number of workers displaced from an occupation is not the same as the number of jobs eliminated. That is, we cannot assume that employers will lay off workers one-for-one with each job that is eliminated. To the extent that employers opt to retain and reassign workers to similar or better positions or workers leave the occupation for other reasons, the number of layoffs could be smaller. This point calls attention to a key aspect of our simulations: we must somehow make the conceptual leap from the anticipated employment reduction in various occupations to projecting how many workers will be displaced. That is, we want to use changes in employment "stocks" to construct displacement "flows." To make this leap in a reasonable way, we must consider that workers do leave occupations regularly and that employers have means other than layoffs to reduce employment in declining occupations.

Occupational turnover occurs when workers leave an occupation. For example, a worker may retire, become disabled, take a job in another occupation, go back to school, be promoted, take on family responsibilities, be fired for cause, or pass away. An occupation's annual turnover reflects the rate at which jobs in the occupation would decline if no exiting workers were replaced. Factors that influence occupational turnover include the average age of the workforce, injury rates, whether it is an entry-level job, and if experience in that job applies to other occupations.

To cut its workforce by 10 drivers after adopting AVs, an employer could lay off 10 drivers. If it could anticipate that some would leave soon for other reasons, it might lay off only eight or nine. It might also look to fill vacancies that it has in other jobs by offering reassignment and training to its excess drivers. For example, the employer might train some workers in sales, programming, traffic coordination, maintenance, or roadway repair jobs. Or, it might redesign its driving jobs into hybrid occupations with changed duties: less driving and more coordination, sales, or maintenance.

Should we account for turnover, and if so, in what way? Drivers are reputed to have particularly high rates of job churn, so it may be that the fluid nature of these occupations will naturally reduce the disruption caused by AV adoption.

From one perspective, there is no need to explicitly account for turnover because vacancies reflect the normal degree of churn in the particular occupational environment. High turnover occupations occur when workers move frequently out of the occupation or the labor market.[42] From this point of view, not filling a vacancy is like removing a seat during a game of musical chairs. Although no one sits in the chair at the moment, removing it forces someone out of the game. When many open positions in an occupation are eliminated, people between jobs in that occupation are caught out as are those who sought training with the expectation that there would be jobs in that field. From this perspective, the estimated disruption is not reduced by the normal amount of churning in the labor market.

An alternative, more conservative view emphasizes the voluntary nature of some turnover and assumes that most potential entrants are not heavily invested in taking a job in a declining occupation. In that case, to the extent that an employer can rely on vacancies rather than layoffs to make needed reductions, some disruption is avoided.[43]

To make this adjustment we need estimates of occupational turnover. Fortunately, as part of its Employment Projections program, the BLS produces 10-year projections of turnover-related vacancy rates by occupation. The latest turnover statistics are BLS Occupational Openings and Separations projected for 2016-2026.[44] These are estimates of turnover caused by workers exiting the labor force, due to retirement or other reasons, and separations caused by workers transferring to different occupations. They take into account occupational factors including past patterns, age, and education. By construction, the estimates do not count workers who change jobs but remain in the same occupation, nor do they include expected net job growth.

To provide a reasonable simulation of displacement that incorporates turnover, we reduce the anticipated job reductions by their annual occupational turnover rates. That is, since Heavy Truck and Tractor Trailer Drivers have an annual turnover rate of 10.5 percent, then eliminating 10,000 jobs in a particular year would result in 8,950 truckers laid off (that is, [1-0.105]*10,000). By doing this we implicitly assume that 10.5 percent of the job reductions affect spots held by workers who were leaving the occupation anyway, so they are not displaced.

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[42] Steve Viscelli. *The Big Rig: Trucking and the Decline of the American Dream*. University of California Press. 2016. https://www.ucpress.edu/book.php?isbn=9780520278127.

[43] The assumption that potential entrants are not heavily invested in entry to these occupations is least tenable when those workers have few alternative options, for example because they live in an economically depressed area or a one-industry town.

[44] BLS projects occupational turnover using two different models, one for labor force exits and another for occupational transfers. Both models use a regression analysis of historical data to identify the characteristics of a worker, such as age and educational attainment, which make them likely to separate from their occupation. These patterns from historical data are then applied to the current distribution of employment for each occupation to project future separations. These are described in https://www.bls.gov/emp/ep_separations.htm

We present occupational turnover rates for the AV-affected occupations in Table III-1, along with the ranges for the total number of jobs eliminated across all four combined scenarios. More explanation is provided in Appendix B.

TABLE III-1: Occupational Turnover Projections for AV-Affected Occupations, 2016-2026

Occupation	Jobs eliminated in AV scenarios, range in thousands	Annual occupational turnover as a percent of employment
Primary Driver Occupations		
Heavy and Tractor-Trailer Truck Drivers	919-996	10.5%
Light Truck or Delivery Services Drivers	351-430	10.5%
Bus Drivers, School or Special Client	106	11.9%
Driver/Sales Workers	77	10.5%
Taxi Drivers and Chauffeurs	60-210	10.0%
Bus Drivers, Transit and Intercity	53-56	11.9%
Ambulance Drivers and Attendants, Except Emergency Medical Technicians	1	14.2%
Other On-The-Job Driver Occupations		
Security Guards	16	13.0%
Police and Sheriff's Patrol Officers	27-34	6.3%
Automotive Service Technicians and Mechanics	71-356	9.2%
Postal Service Mail Carriers	0-54	6.7%
Parking Lot Attendants	0-24	14.7%
Automotive Body and Related Repairers	6-58	9.4%
Refuse and Recyclable Material Collectors	0-32	11.8%
Automotive and Watercraft Service Attendants	0-34	16.3%
First-Line Supervisors of Police and Detectives	5	5.9%
Couriers and Messengers	0-28	9.0%
Automotive Glass Installers and Repairers	0-4	9.5%
Insurance Appraisers, Auto Damage	3-4	8.1%
Electronic Equipment Installers and Repairers, Motor Vehicles	0-4	9.6%
Travel Guides	0-1	17.1%
All US Occupations		**10.9%**

Sources: Occupational employment: Census Bureau, American Community Survey 2016. Occupational turnover: BLS Occupational Projections 2016-2026. Jobs eliminated: See Table II-2.

Turnover projections for the affected occupations vary from a minimum of 6.7 percent for First-Line Supervisors of Police and Detectives to a maximum of 17.1 percent for Travel Guides. Among the primary driver occupations, the rates are mostly similar to the U.S. average of 10.9 percent, ranging from 10.0 percent for Taxi Drivers and Chauffeurs to 14.2 percent for Ambulance Drivers and Attendants, Except Emergency Medical Technicians.

The projections for truck drivers will surely surprise readers who understand these occupations' turnover to be extremely high. For example, the American Trucking Associations (ATA) reports 95 percent turnover for truck drivers in the third quarter of 2017.[45] Some part of the discrepancy is likely due to differences between sectors of the trucking industry. Turnover tends to be much higher in the less-than-truckload (LT) sector, which often has poor compensation and working conditions. By contrast, turnover is much lower in the full truckload (FT) sector, where compensation and working conditions are better. Many employers of truck drivers in the FT sector are not primarily trucking companies, so they may not be included in the ATA survey. See Section V.D. for more discussion of the differences in trucking sectors.

Another key part of the discrepancy stems from omitting between-employer job changes from occupational turnover estimates. This is appropriate for our goal of gauging the number of workers displaced overall. Although high job-hopping may lower the number of pink slips that employers need to issue, it does not reduce the number of workers that must find new livelihoods when jobs in their occupation are eliminated.

Our overall approach takes account of the frictions in the labor market noted in our framework. Workers cannot move seamlessly to take vacancies at any other employer anywhere else in the country. If the labor market had no frictions, the correct adjustment for turnover would be much higher. We could, for example, estimate all the vacancies in the industry and calculate displacements as occurring only if the number of job reductions exceeds the number of vacancies in the entire occupation. This polar approach is certainly too strong. Workers who lose jobs with particular employers must then search for new work. To not count them as displaced just because there is some opening in their occupation somewhere else in the country is clearly incorrect.

Thus, we adjust for turnover only on the number of jobs eliminated. This reduces the measured displacement arising from a job elimination by the occupation-specific probability that the worker would have left the occupation during that year anyway.

While this approach adjusts for a normal number of occupational reassignments, it does not factor in the potential for more reassignments and retraining by employers in order to avoid AV-related layoffs. To develop a reasonable estimate of the potential labor market disruption of AV adoption, we intentionally do not assume that employers will take more intensive efforts to reassign workers to other positions than they have in the past, for two reasons. First, much of the attraction of AV is in the potential for reduced labor costs. This suggests that many employers will want to reduce the size of their workforce. Second, reassigning and retraining workers is an important mitigation step that employers could take, with or without some assistance. Yet it would run counter to the

[45] American Trucking Associations. "Large Truckload Driver Turnover Rate Rose in Third Quarter." Press Release. December 7, 2017. http://www.trucking.org/article/Large-Truckload-Driver-Turnover-Rate-Rose-in-Third-Quarter

spirit of this exercise to essentially assume away some major part of the problem from the beginning. We believe that employers could play an important role of this sort, but we cannot assume they will.

Note two other features of our approach to turnover. First, the turnover estimate that we use is static, projected for the decade of 2016-2026. Consistent with the rest of our approach, we do not take into account expected demographic and other changes beyond this close horizon. Second, since the adjustments do not vary as a share of job destruction, we do not incorporate how slower job destruction could help workers and employers adjust. That is, we abstract from employers' and workers' greater ease of adjustment to slow-moving changes. When job destruction happens at a slower pace, information has more time to be shared and absorbed.[46] In addition, workers and employers have more options for adjustment, including longer training programs and more experimentation. This is a limitation of our approach.

B. How will displacement affect workers?

As the framework in Section II shows, an estimate of the number of workers displaced does not get to the heart of how disruptive a transition will be for the labor market. For that we must simulate what happens to workers after they are laid off. To recognize the current gaps that slow transitions in the U.S., we use actual experiences (wage changes and labor market status paths) of displaced workers to simulate the impact of AVs.

From recent BLS Displaced Worker Surveys (DWS) we construct the likely path followed by a cohort of displaced workers using an approach described in detail in Appendix B.[47] We express the path in terms of shifting shares of the cohort of displaced workers in the three possible labor force states (employed, unemployed, or out of the labor force) during the years after displacement. Figure III-1 illustrates the path we derive from our analysis of the whole DWS sample. Just before displacement (we call this "Year -1"), all the workers are employed (shown in green), while none are unemployed (in red) or out of the labor force (in yellow). At the moment they are laid off, none are employed: some leave the labor force and the rest are unemployed. So, for the year containing the layoff (Year 0) as a whole, they are all employed part of the time, then unemployed, and then pursue some combination of looking for work, starting another job, and leaving the workforce. As a group, they vastly increase their unemployment and out-of-labor-force shares. Their layoffs add to the number of unemployed in the economy because they moved as a group out of jobs to unemployment. By Year 2 after the layoff, many more have a new job. Yet their unemployment rate is still markedly above the rate for the economy as a whole. In each year that follows, their unemployment rate converges closer to a new normal state.

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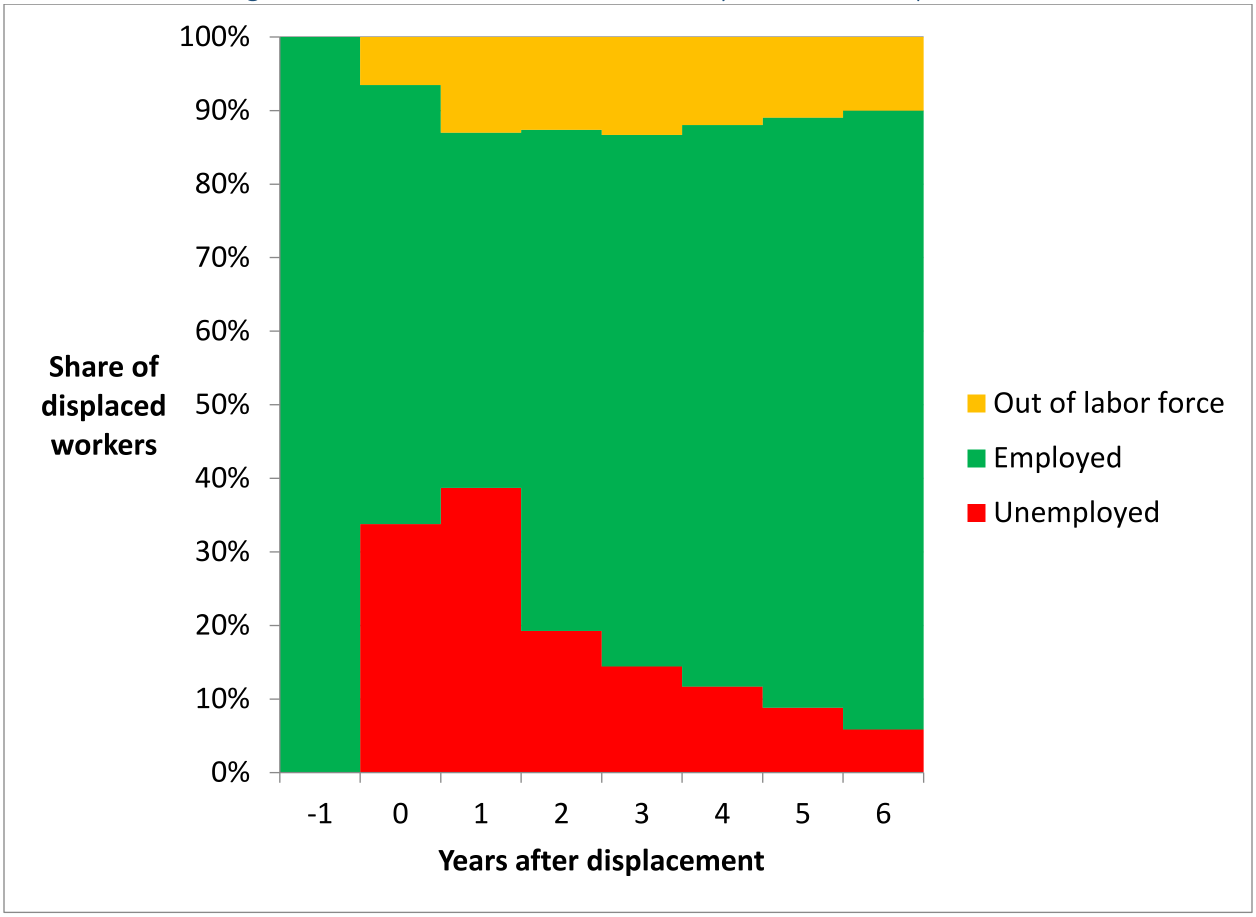
[46] In particular, when there are fewer jobs in an occupation, young people tend to avoid going into that occupation. When a field changes slowly, there is adequate time for young workers to learn about the poor prospects for that occupation and to plan accordingly.

[47] According to the BLS: "Displaced workers are defined as persons 20 years of age and older who lost or left jobs because their plant or company closed or moved, there was insufficient work for them to do, or their position or shift was abolished." https://www.bls.gov/news.release/disp.nr0.htm

FIGURE III-1: Average Labor Market Status of Workers by Year After Displacement



Source: Authors' calculations.

Although the DWS asks about only three years of experience post displacement, we extend the time covered by making assumptions about eventual convergence of the displaced workers to workforce averages, as detailed in Appendix B. The path constructed is consistent with prior studies which find that displaced workers experience above average unemployment for a long time and are disproportionately likely to be out of the labor force after displacement.[48]

With this information (post-displacement paths, numbers of workers in occupations affected, and the timing of transition phases) we simulate how many unemployed workers and labor force exits will be added to the labor market due to the adoption of AV over the coming decades, for each of the four scenarios.

In each year, we measure how much this cohort adds to the pool of unemployed. That is, we subtract how many would have been unemployed without the displacement, which we call the baseline amount of unemployment. In Years 0 and 1, we count all the unemployed displaced

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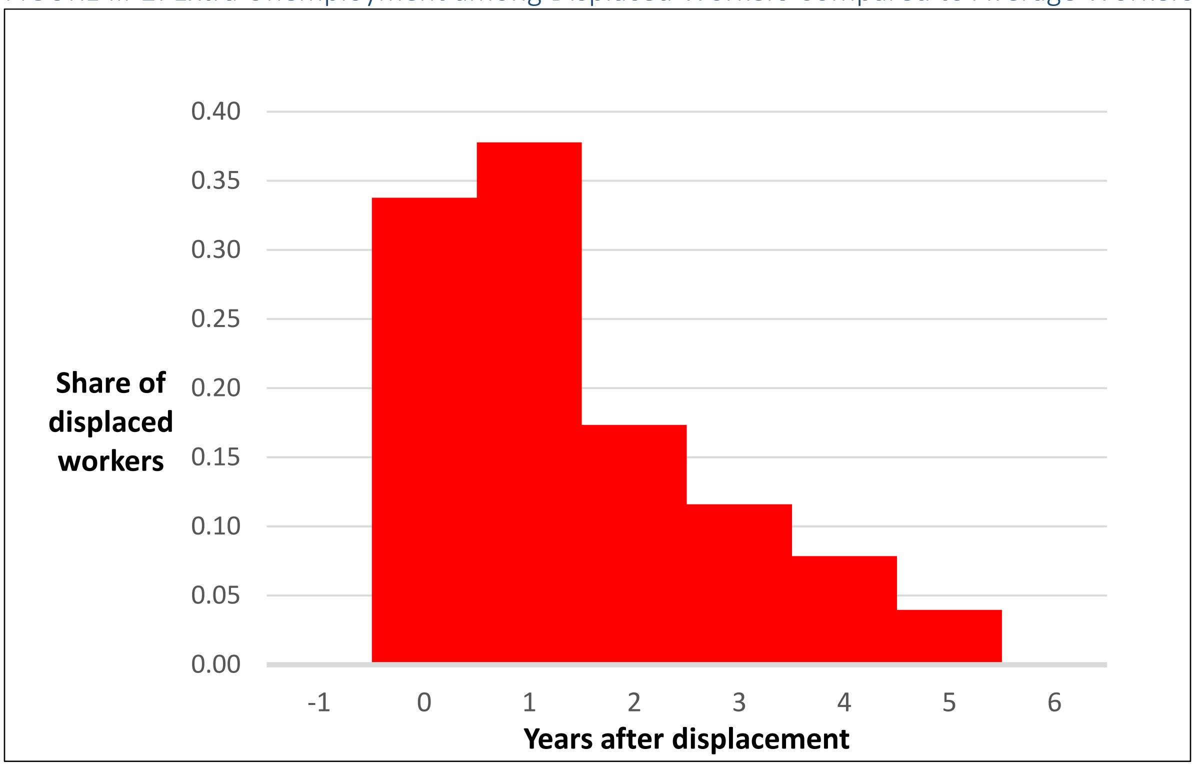
[48] See Steven Davis and Till von Wachter. "Recessions and the Costs of Job Loss." *Brookings Papers on Economic Activity*, 2011 no. 2. https://www.brookings.edu/bpea-articles/recessions-and-the-costs-of-job-loss/ and the references within.

workers as AV-induced additions to unemployed because they underwent this sudden change. But eventually, we cannot expect the cohort's unemployment rate to go much below the prevailing unemployment rate. So, the baseline for comparison is an unusual sort of baseline; it must converge over time to the average rate for workers in the rest of the economy. At the beginning their unemployment baseline is zero because they were all employed. By Year 6, though, their baseline compares them to the average rate of unemployment. We adopt a linear path for the baseline between these two endpoints.

Figure III-2 shows the pattern for unemployment post layoff. This is the contribution that one displacement makes (on average) to the number of employed during the years after the layoff. For example, in Year 1, the peak year, a displacement of 100 workers raises the number of unemployed by about 38 people.[49] We sum these additions to unemployment for each year for each worker affected by our scenarios to simulate the impact of AV displacement on unemployment.

FIGURE III-2: Extra Unemployment among Displaced Workers Compared to Average Workers



Source: Authors' calculations.

Note that we do not explicitly model job growth in this approach. Rather, we infer growth from the way that the economy has reabsorbed displaced workers in the past as tracked in the DWS. If no barriers to re-employment were present, the red areas in Figures III-1 and III-2 would be very

[49] The remainder in Year 1 are employed (48), out of the labor force (13), or would have been unemployed anyway (1)—which is what the baseline captures. See Table B-1 for these numbers.

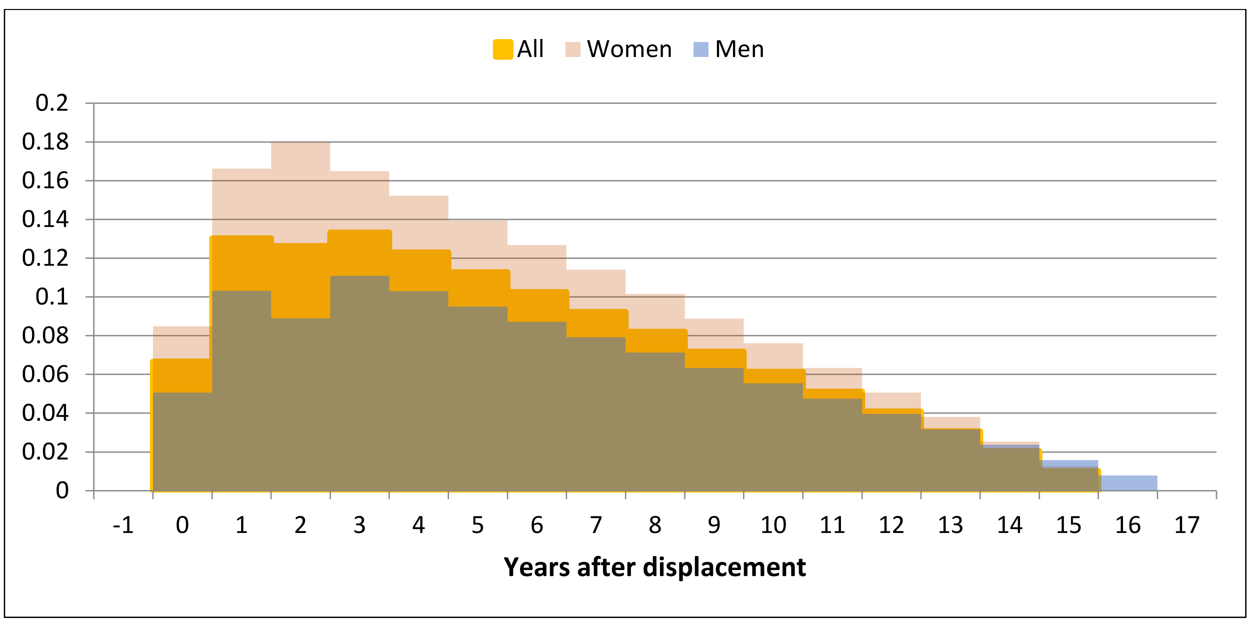
small, reflecting little increase in unemployment after layoffs. During a recession or in a very stagnant economy, the areas would be very much larger.

For labor force participation, the exercise is similar, but the horizon is much longer because the behavioral reaction is different. As can be seen in Figure III-1, many more displaced workers seek new work than opt to exit the labor force. Yet, the share of workers that exit does not decline rapidly subsequently, in contrast to unemployment. Indeed, except for the youngest workers in the DWS, in no case does labor force participation recoup its decline. For younger workers, this is likely due to temporary exits to get more education or training. Neither does participation fall noticeably over time (as you might expect for discouraged job seekers), except for the oldest workers. Taken together, this suggests that the overall propensity to spend time out of the labor force takes a long-lived bump up after displacement.

This does not mean that the particular people who leave the labor force at the time of layoff stay out permanently. There can be a lot of cycling in and out within a steady rate. But it certainly means that on average, displacement weakens workers' attachment to working.

Figure III-3 shows how this weaker attachment plays out. Like Figure III-2 for unemployment, this one shows that the share of displaced workers that exit the labor force is above what one would expect if they had not been displaced. The figure says that in each of Years 1, 2, and 3 after 100 workers are displaced, the workforce will have 13 fewer participants. The impact then declines over time as the cohort ages. The effect ends at sixteen years because that is the expected years of work life remaining for the average displaced worker in the DWS. The figure also shows that the participation effect is much stronger for women. This might be expected as they generally earn lower wages and may be more likely to take on family responsibilities. For more detail on the construction of these estimates, see Appendix B.

FIGURE III-3: Share of Displaced Workers Out of the Labor Force as a Result of Displacement



Source: Authors' calculations.

C. Displacement, unemployment, labor force participation and lost earnings simulations

In this section we simulate the impact of AV-related layoffs under the four adoption scenarios. Importantly, these simulations should not be used as definitive forecasts, but as gauges of the potential size and nature of the disruption to the labor market posed by the AV transitions. In order to place the effects in the easily-understood context of today's labor market, these simulations abstract from many expected and unexpected changes in demographic and economic conditions over coming decades. When AV transition actually takes place, its costs and benefits will undoubtedly be affected by conditions prevailing at the time (in particular the rate of growth of the overall economy), as well as employers' and policy choices.

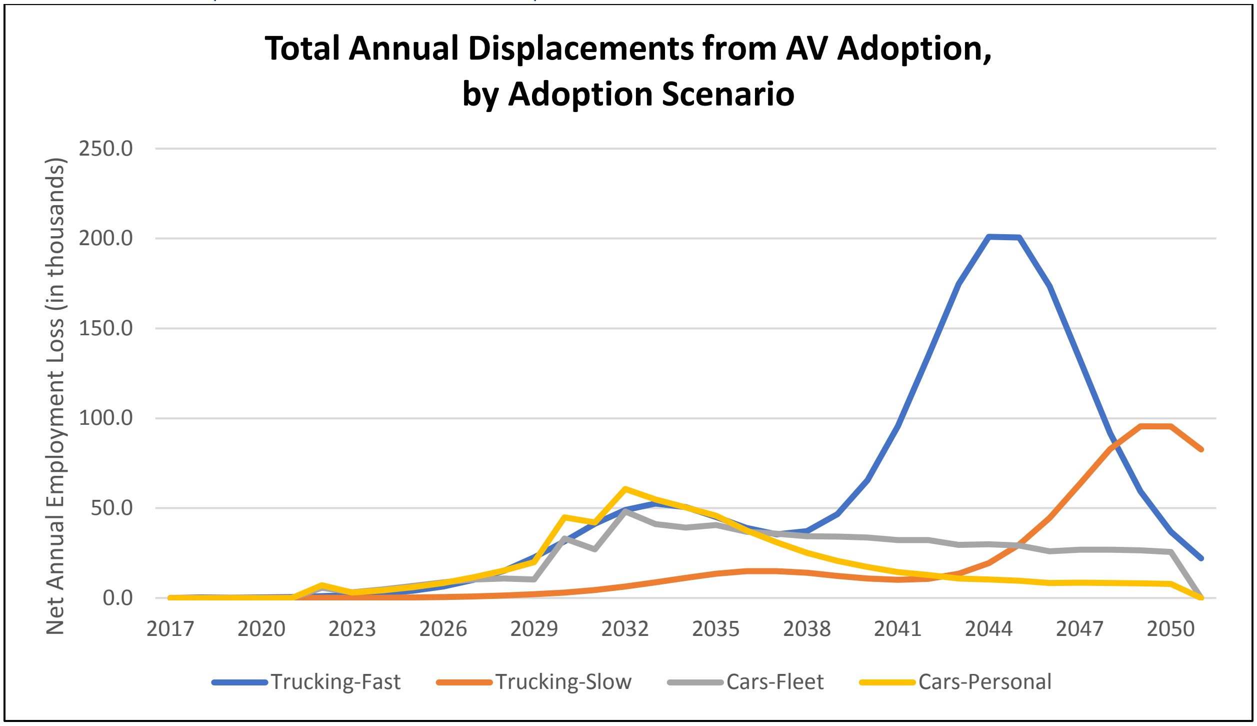
i. Effects of AVs on displacement

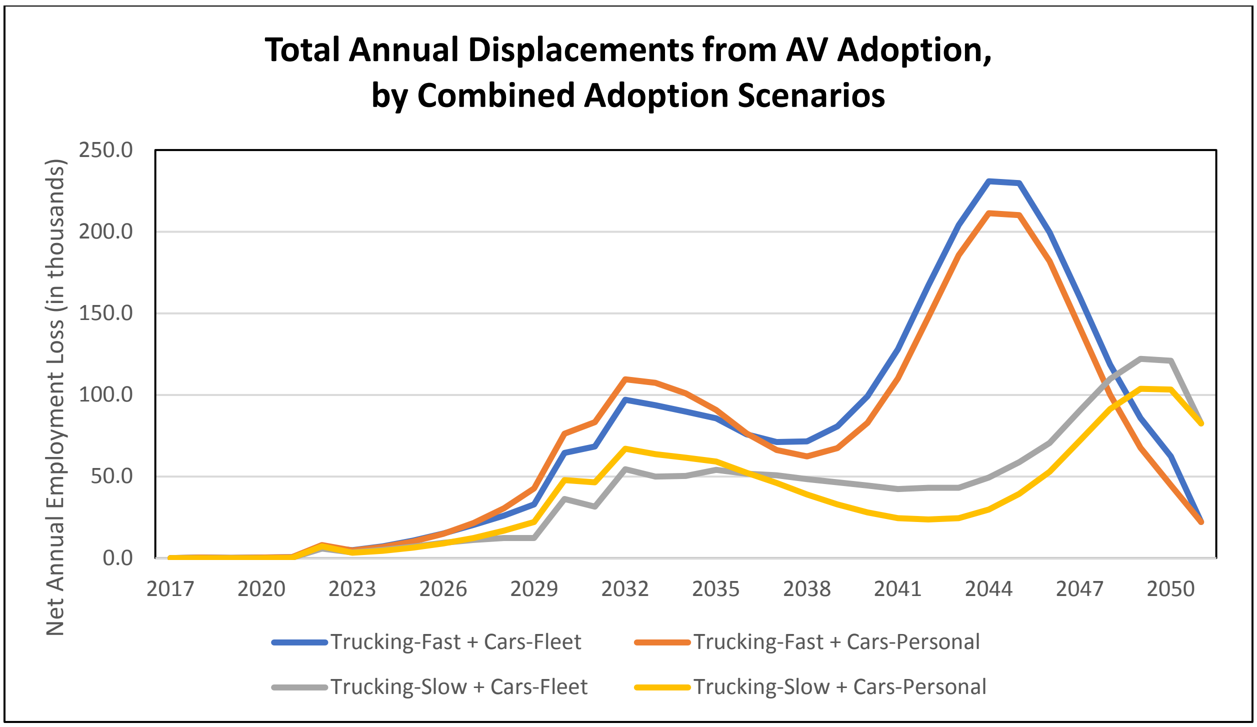
The top panel of Figure III-4 shows the implied pattern of job displacement for each of the scenarios separately. Job losses from AVs ramp up slowly and do not reach over 50,000 per year for any scenario until 2031 at the earliest. Most striking is the difference between fast and slow adoption of AVs by trucking, even though the total number of jobs lost under the two trucking scenarios is not so different. Aggressive adoption could cause annual displacements of about 200,000 workers around 2045. By contrast, under the slow trucking scenario, peak annual layoffs are half as high and occur in 2049 and 2050.

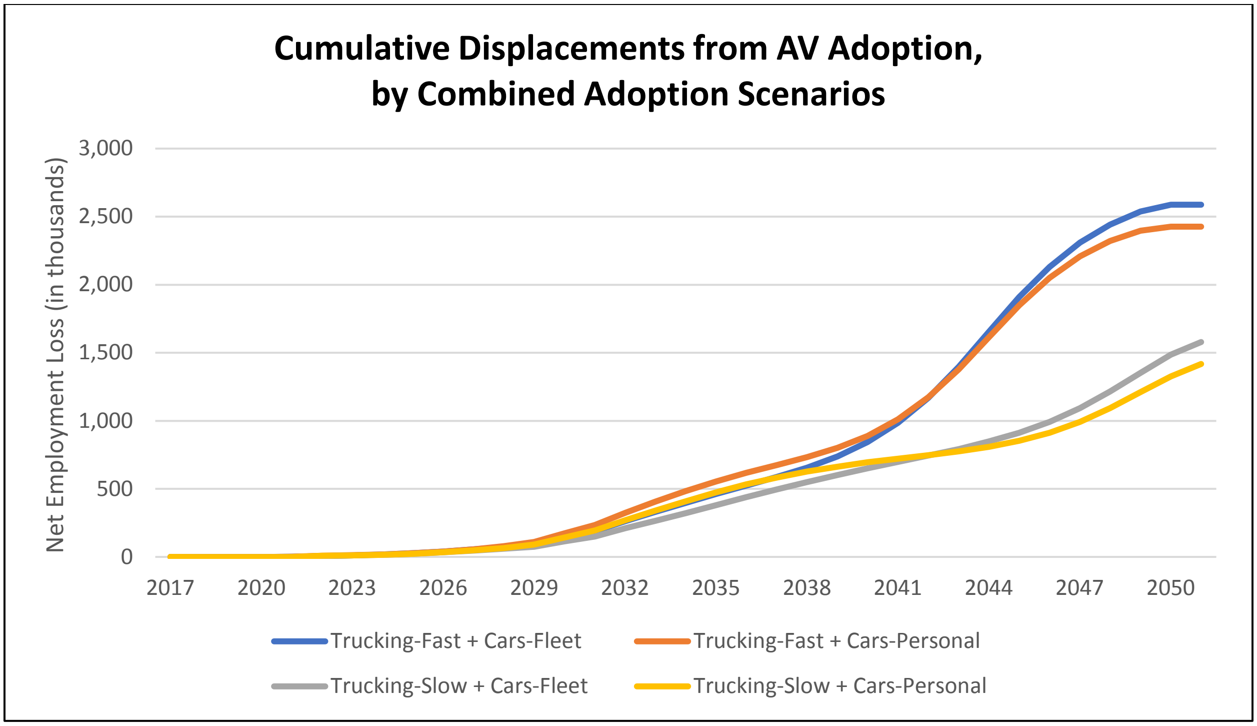
Adopting AV for cars causes earlier and fewer job losses than we see in trucking. The two car scenarios start out similarly, but fleet ownership causes more displacement than personal ownership from 2039 onward. The reason is that fewer cars are needed and fleets are more likely to adopt electric vehicles which will reduce employment of Automotive and Watercraft Service Attendants, who do oil change and brake job maintenance, etc.

Of course, AV is likely to be adopted by both cars and trucks, so the second panel of Figure III-4 shows the four possible combined scenarios. These make it clear that the biggest source of variation in outcomes is fast versus slow adoption of AV for trucks. The Trucking-Fast scenario causes the most concentrated job losses of the four considered. To reiterate, from a labor market perspective, the most challenging combination would be combining aggressive truck adoption with a fleet approach to car AVs.

FIGURE III-4: Displacements from AV Adoption







Source: Authors' calculations.

ii. Effect of AV displacements on unemployment

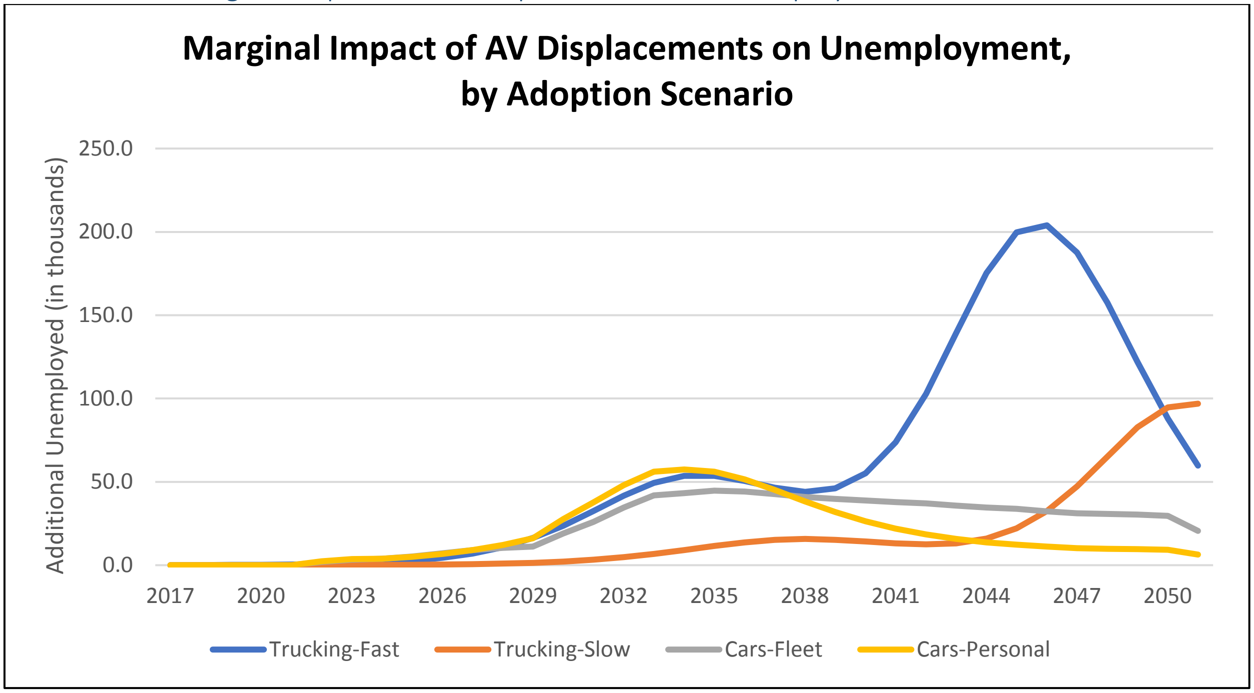
Figure III-5 translates these job losses into unemployment effects. Compared to the layoff pattern in the previous figure, unemployment effects are clearly more persistent. At its peak, the rise in unemployment under the Trucking-Fast scenario is about four times higher than the peak impact of any of the other transition scenarios. The peaks are little different in height from the layoff peaks, but the elevations last longer. The easiest way to see this is to compare the trucker unemployment in 2050 to layoffs that year. Lingering unemployment from previous years means that although layoffs decline to 22,000 in 2050, there are over 60,000 truckers unemployed.

Combining the Truck-Fast transition with either passenger car AV transition swells the ranks of the unemployed by over 200,000 workers across the U.S. at the peak of impact, around 2045.

Is this effect large enough to raise the unemployment rate? Yes, but modestly. Figure III-6 translates the number of unemployed into the impact on the unemployment rate. For simplicity, we display only the high and low estimates, which correspond to the Trucking-Fast/Cars-Fleet and Trucking-Slow/Cars-Personal scenario combinations respectively. The shaded area on the figure shows the range between high and low estimates in each year. Relative to a baseline of full employment, the advent of AVs is projected to increase the unemployment rate to a small degree in the 2030s and more strongly in the late 2040s, with a peak, temporary addition to annual unemployment rates of 0.06–0.13 percentage points at peak impact.

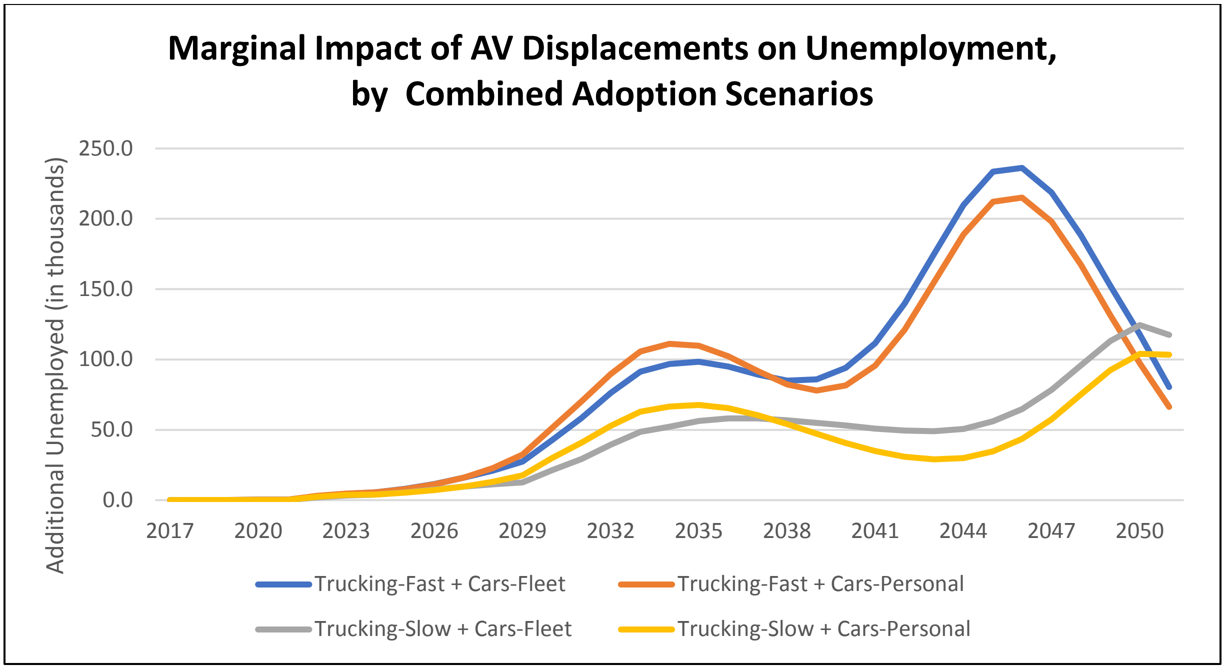
It may be useful to compare our estimates of dislocation from AVs to that caused by the decline of manufacturing.[50] U.S. manufacturing has lost 6.7 million jobs since its peak in 1978, or about 1.7 million jobs per decade. We estimate AVs will disrupt 1.3 to 2.3 million jobs over 30 years, which is as much as 800,000 jobs per decade—about **half** the size of the manufacturing job loss. The AV impact will be further weakened by the larger size of the U.S. labor force in the future, and the disruption will be less geographically concentrated than in manufacturing. However, given the large impact of manufacturing job loss on U.S. workers, the economy, and political system, a potential new disruption about half that size in another industry certainly merits serious attention.

FIGURE III-5: Marginal Impacts of AV Displacements on Unemployment



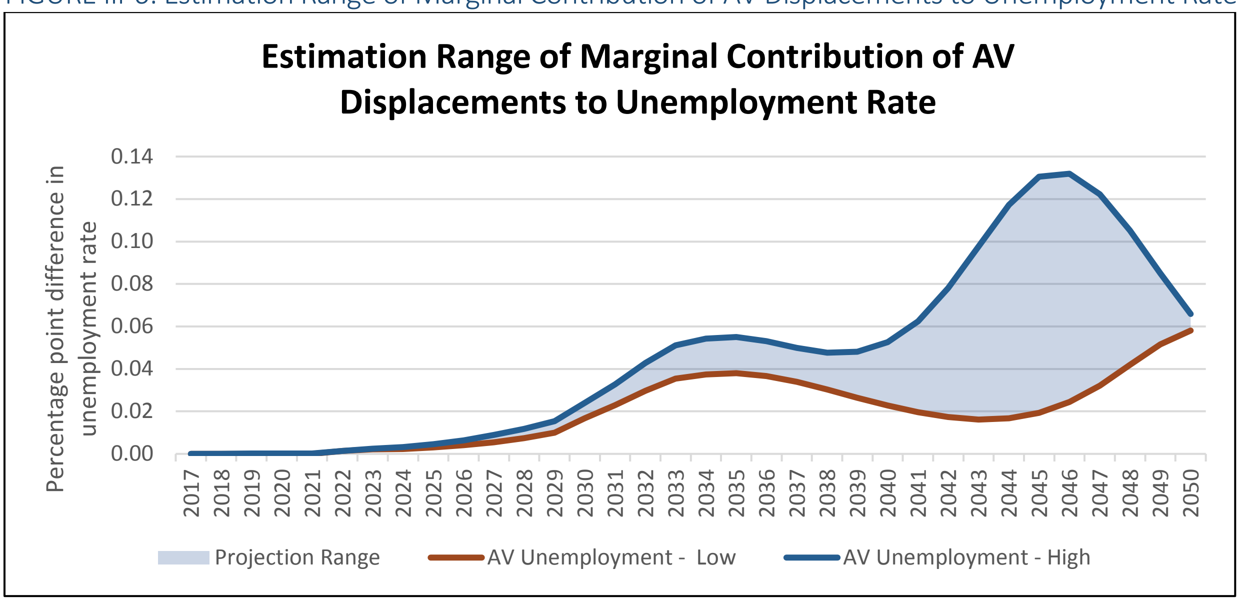
Source: Authors' calculations.

[50] Thanks to Michael Mandel for suggesting this comparison.



Source: Authors' calculations.

FIGURE III-6: Estimation Range of Marginal Contribution of AV Displacements to Unemployment Rate



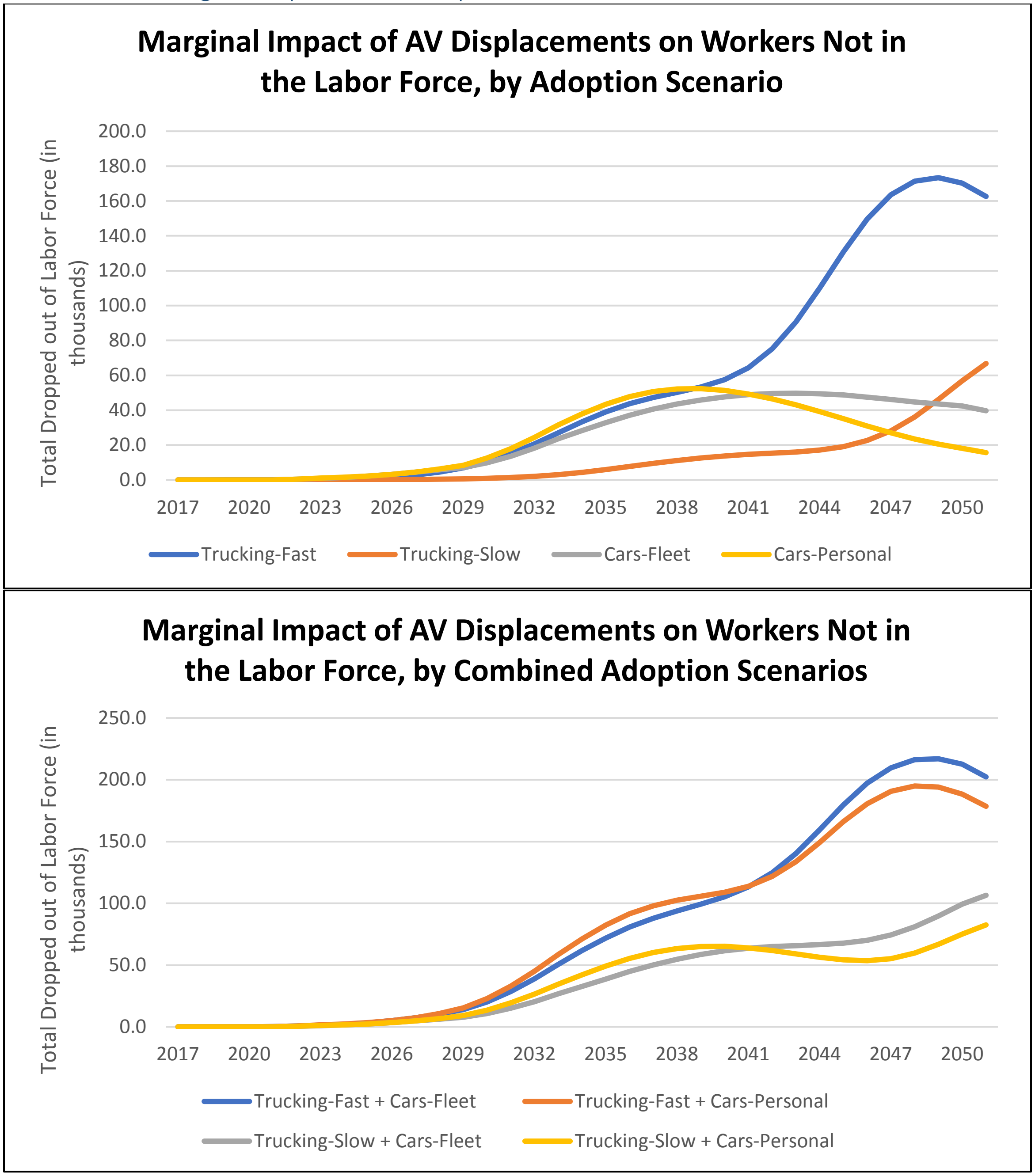
Source: Authors' calculations.

Note: "Low" refers to the combination of Trucking-Slow and Cars-Personal scenarios. "High" refers to the combination of the Trucking-Fast and Cars-Fleet scenarios.

iii. Effect of AV displacements on labor force participation

Our simulations also suggest that the adoption of AVs will increase the number of workers who leave the labor force, as shown in Figure III-7. The persistence of participation effects is shown in the smoothness of these lines and their general upward trend. The Trucking-Fast plus Cars-Fleet scenarios could shrink U.S. labor force participation by over 160,000, which is close to lowering the U.S. labor force participation rate by 0.1 percentage points. Thus, the number of workers not in the labor force after AV-induced displacement is on a par with the rise in unemployment and lasts longer.

FIGURE III-7: Marginal Impacts of AV Displacements on Workers Not in the Labor Force

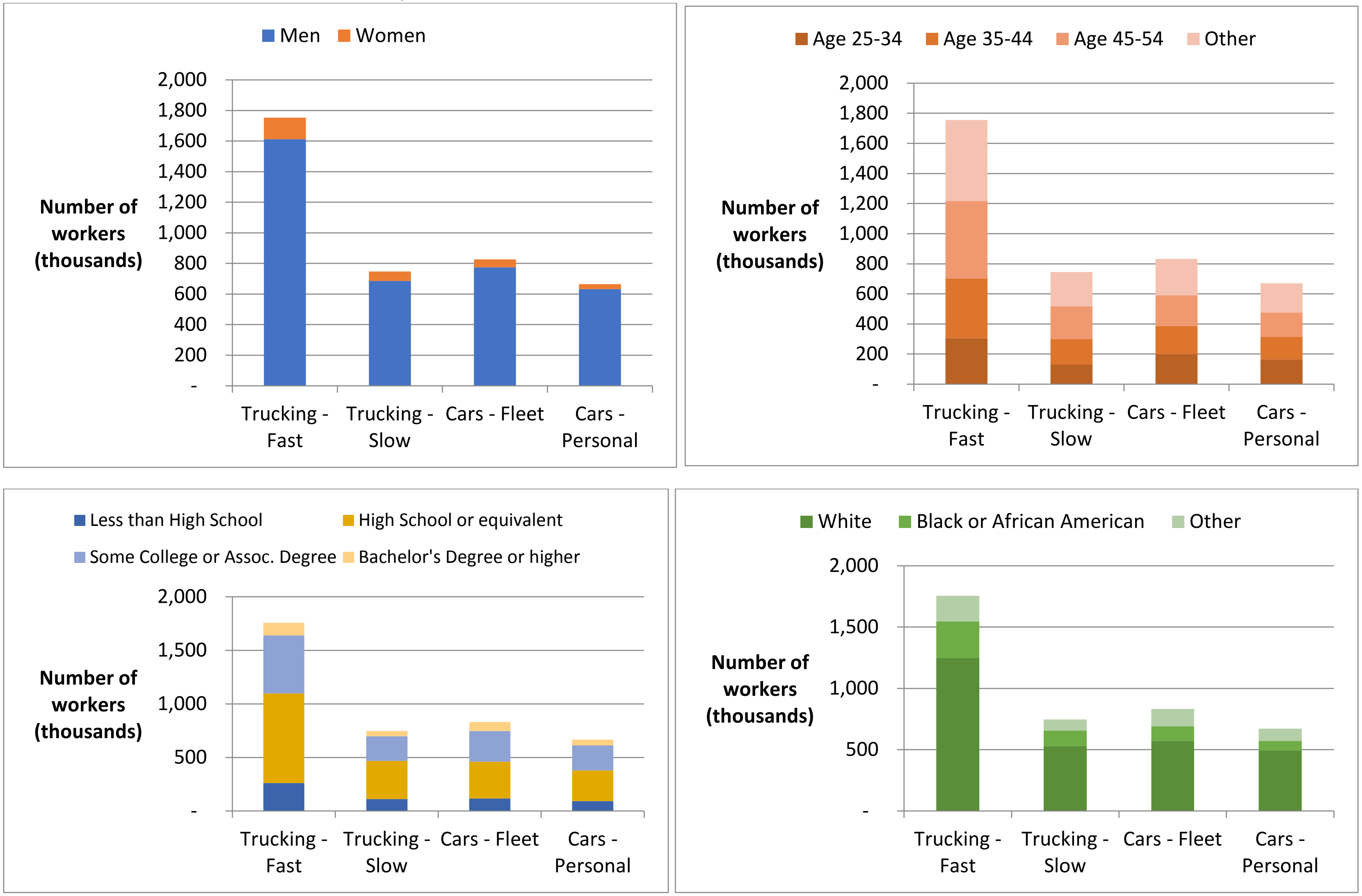


Source: Authors' calculations.

iv. Demographic and regional effects from AV adoption

Some demographic groups will be more strongly affected than others. Figure III-8 breaks down the job losses for each scenario by sex, age, education, and race. Not surprisingly, workers at risk of lay-off by AV will be mostly men. Over half of them are over 45. (The Other age group consists mostly of people over 54.) Very few have a college degree, although many have some college. Most are white. These are the people whom the adoption of AV will push toward more unemployment and lower labor force participation.

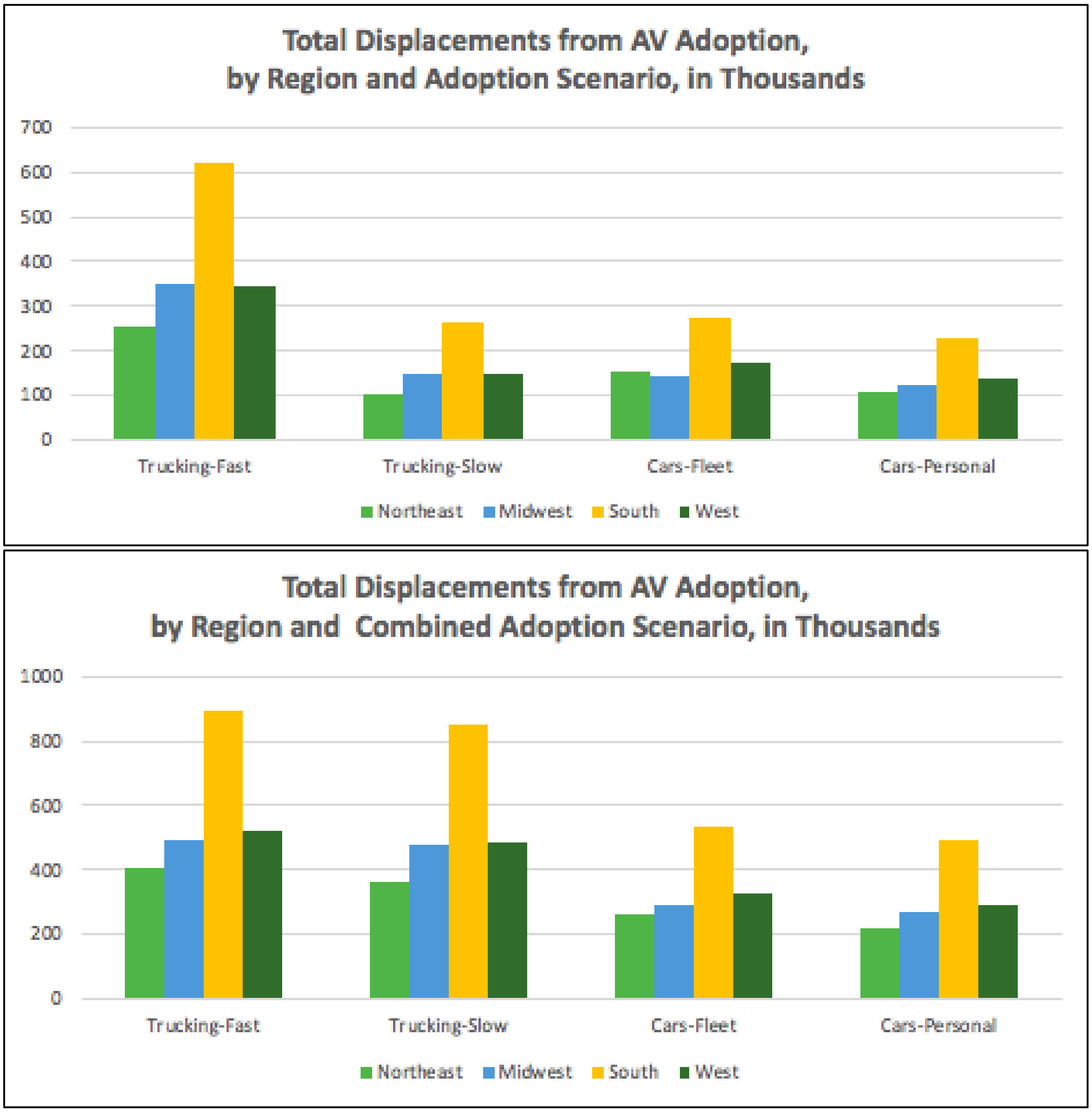
FIGURE III-8: Characteristics of AV-Displaced Workers



Source: Authors’ calculations.

Figure III-9 breaks down total worker displacement by region. In all four scenarios, the South sustains the most displacements. The Midwest and West have similar number of displaced workers, while the Northeast has the lowest number. Adoption of AVs in trucking has a more regionally disparate impact than AV adoption in cars, likely because the south in particular is a net supplier of long-haul trucking services to the rest of the country. By contrast, professional drivers of cars are more locally based.

FIGURE III-9: Total Displacements from AV Adoption by Region



Source: Authors' calculations.

In addition, we can look at the extent to which particular states specialize in providing workers in the occupations most affected by AVs. This approach helps point to geographic areas that might suffer most lost jobs and to workers who might sustain the largest losses. The standard measure of geographic employment concentration is called a location quotient. Applied to occupations in states, it is defined as an occupation's share of jobs in a state divided by that occupation's share of jobs in the U.S. as a whole. A value of one means that the share matches that of the nation. For example, Wyoming has a location quotient equal to 1.89 for Drivers/Sales Workers. This means that Wyoming has 1.89 times as many Drivers/Sales Workers as it would if it matched the overall U.S. share—or 89 percent "extra" Drivers/Sales Workers. Thus, it is likely to take a bigger hit from the elimination of those jobs than other states.

Table III-2 lists all states with 50 percent or more "extra" primary driving jobs—that is cases of state occupation location quotients of 1.50 and higher. (Table B-4 presents a full list of the location quotients.)

TABLE III-2: Analysis of State Occupation Location Quotients (LQs) for Primary Driving Occupations

	Heavy and Tractor-Trailer Truck Drivers	Light Truck or Delivery Services Drivers	Bus Drivers, School or Special Client	Driver/ Sales Workers	Taxi Drivers and Chauffeurs	Bus Drivers, Transit and Intercity	Ambulance Drivers and Attendants, Except Emergency Medical Technicians
Standard deviation of state LQs	0.475	0.158	0.336	0.268	0.901	0.500	1.313
Total US employment, in thousands**	1,532	781	212	383	300	75	10
Jobs eliminated in AV scenarios, range in 000s**	919-996	351-430	106	77	60-210	53-56	1
States with Location Quotients of 1.5 or greater	ND-2.36		WV-2.11	WY-1.89	NV-6.88	HI-3.00	ND-7.37
	AR-2.30		CT-1.68		MA-2.13	NY-1.90	ME-3.73
	NE-2.29		MN-1.52		CT-1.71	MD-1.88	SC-3.57
	IA-2.02		NY-1.51		VT-1.67	NV-1.67	PA-3.23
	WY-1.85		PA-1.50		HI-1.57		WV-2.83
	MS-1.66						AL-2.04
	TN-1.65						NM-1.75
	SD-1.53						NY-1.72
							GA-1.71
							NJ-1.59

*Occupation LQs measure whether a state specializes in providing a certain type of labor. They are defined as the ratio of an occupation's share of jobs in a state to the occupation's share of jobs in the U.S. as a whole. LQs greater than one signify that the state has a higher concentration of jobs in that occupation than the U.S. as whole. LQs less than one indicate that the state has a lower share than in the U.S. An LQ of two indicates that the state has double the share of jobs in that occupation as the country as a whole. The standard deviation of LQs for an occupation is lower if that occupation has a consistent share of jobs in most states. See Table B-4 for full state detail.
**See Table II-2 for sources.
Source: Authors calculations from Bureau of Labor Statistics Occupational Employment Survey 2016. https://www.bls.gov/oes/tables.htm

Of particular interest are Heavy and Tractor-Trailer Truck Drivers because this occupation is likely to lose the most jobs, as indicated in Table III-2. Eight states show strong concentration in these jobs, from North Dakota in the lead at 2.36 to South Dakota with 1.53. Not surprisingly, inland states with low population density are the most likely to take the brunt of layoffs in this occupation: North Dakota, Arkansas, Nebraska, Iowa, Wyoming, Mississippi, Tennessee, and South Dakota.

In stark contrast, the occupation poised for the next highest losses, Light Truck or Delivery Services Drivers, has no state location quotients of 1.5 or higher. Since this occupation is much more locally based, all areas tend to have similar shares of workers in it.

This contrast shows that occupations vary in their degree of regional concentration. All else equal, job eliminations in more regionally concentrated occupations are likely to pose more challenges for workers since more workers with similar skills in their labor markets will be out of work at the same time and the whole local economy is more likely to suffer. To measure how regionally concentrated occupations are, we can take the standard deviation of location quotients across all states—shown in the top row of Table III-2. All else equal, a lower standard deviation indicates that job losses in an occupation will have less disparate regional impacts. Indeed, Light Truck or Delivery Services Drivers' standard deviation of 0.158 is the lowest in this group, followed by Driver/Sales Workers.

Interestingly, Ambulance Drivers show the highest evidence of concentration, which may reflect different ways that this work is organized in states, partly for regulatory reasons. Since AV-related job losses in this occupation are expected to be small, this anomaly is not likely to distort our analysis very much.

Taxi Drivers and Chauffeurs are the second most regionally concentrated, particularly in Nevada, which has almost seven times the normal share in this occupation. In all, five states may be particularly vulnerable, particularly if fleets are adopted, with at least 50 percent "extra" workers in this occupation. Those five states are Nevada, Massachusetts, Vermont, and Hawaii.

While the location quotients for Heavy Truck drivers are not extreme, the size of the job losses in this occupation suggests that the eight states named above (North Dakota, Arkansas, Nebraska, Iowa, Wyoming, Mississippi, Tennessee, and South Dakota), which have the highest concentration of Heavy Trucking jobs, are likely to be the most vulnerable to AV-related displacement. Nevertheless, the transition to AV has the potential to cause problems in some other states and occupations also.

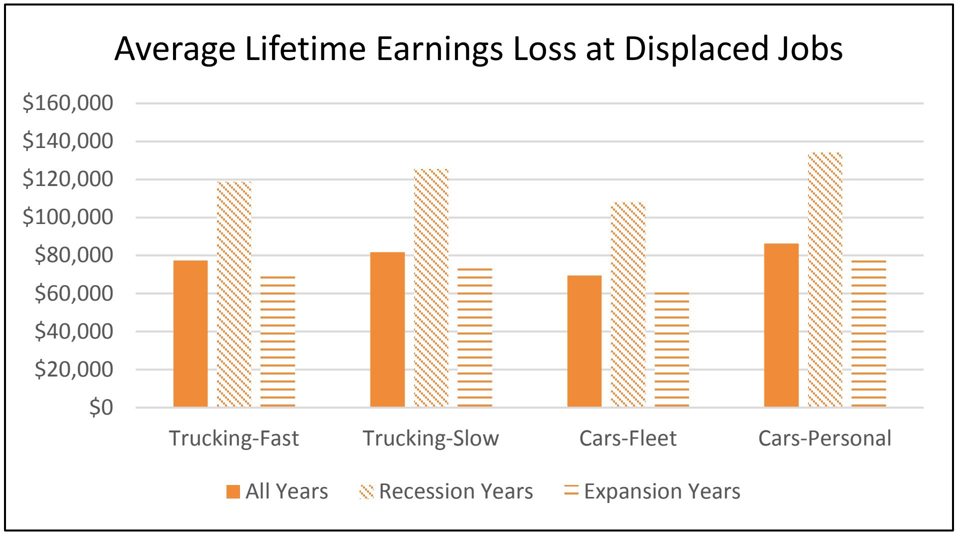
v. Earnings losses from AV displacement

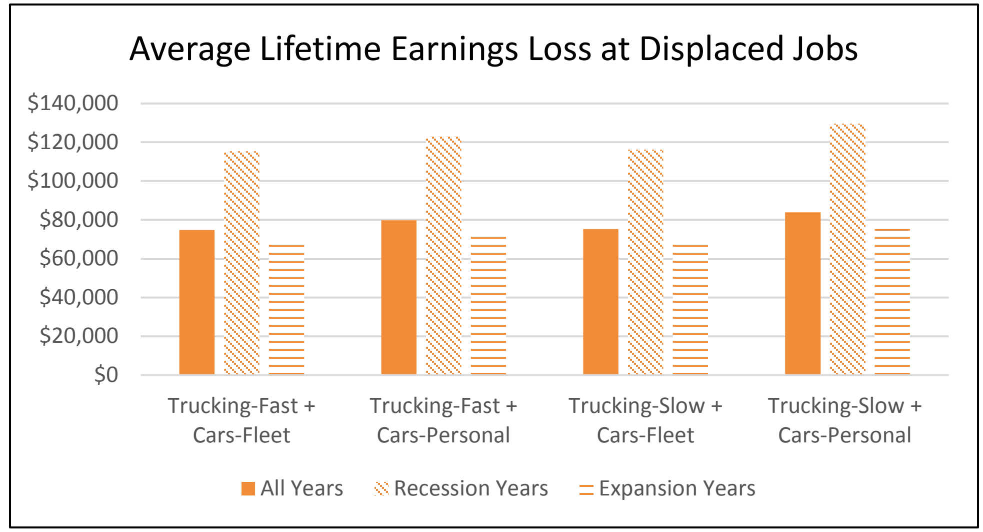
To simulate the earnings losses associated with displacement, we turn to estimates provided by Davis and von Wachter.[51] They calculate average lifetime wealth losses as a multiple of previous

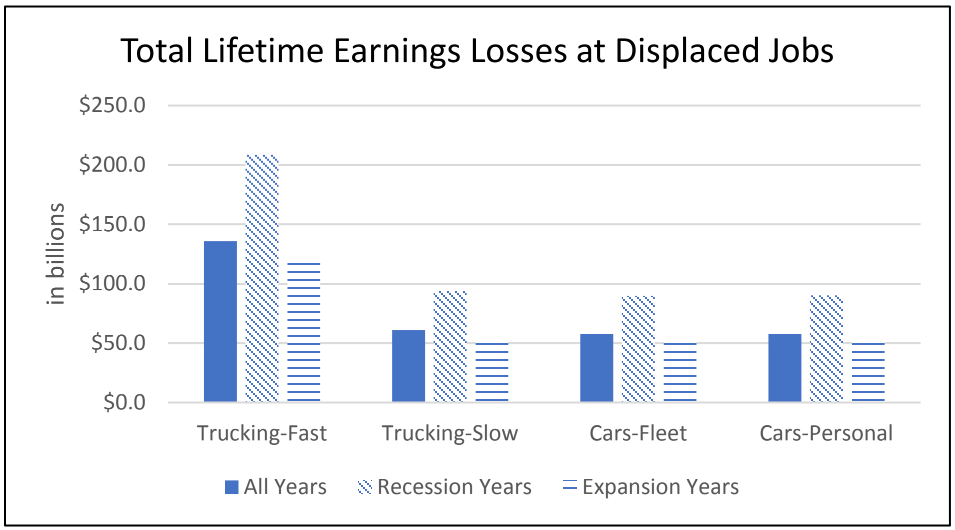
[51] Steven Davis and Till von Wachter. "Recessions and the Costs of Job Loss." *Brookings Papers on Economic Activity*, 2011 no. 2. https://www.brookings.edu/bpea-articles/recessions-and-the-costs-of-job-loss/.

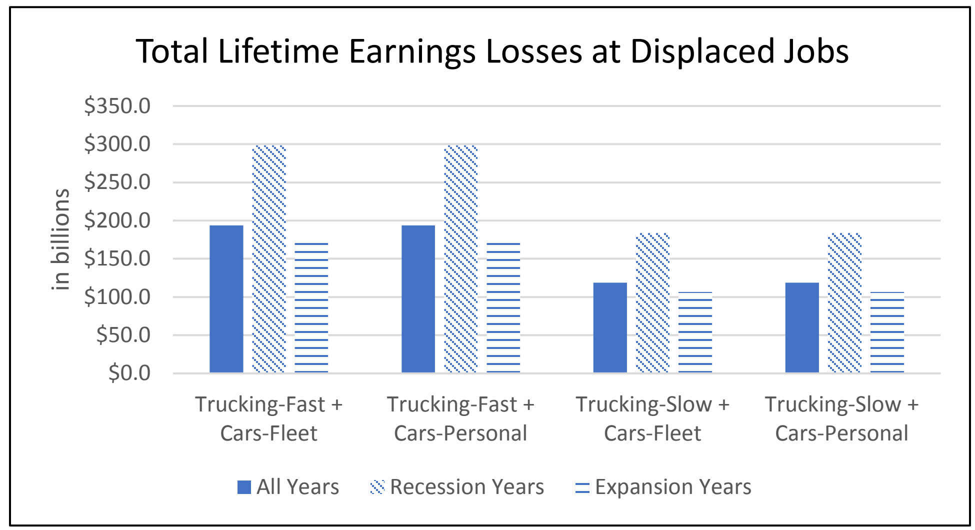
earnings. As described in Appendix B, we use American Community Survey earnings averages for the AV affected occupations to simulate losses, as shown in Figure III-10.

FIGURE III-10: Average and Total Lifetime Earnings Loss at Displaced Jobs, by Scenarios and Combined Scenarios









Source: Authors' calculations.

The two upper panels show that AV-adoption layoffs would cost workers an average of over $80,000 apiece in lifetime wealth, with higher amounts in trucking and less for cars, largely as a consequence of their current occupational salaries. Note that these estimates are subject to a number of key caveats that could have strong effects—such as whether the workers laid off have more or less tenure than average, work full-time or not, or are laid off during a recession. Workers displaced during a recession would sustain losses that average about $120,000. Whatever the actual circumstances, we see laid off workers would lose a substantial amount of wealth. These are earnings that families and communities would not recover even after re-employment.

Taking these losses together, we see combined losses of over $180 billion that would be sustained by U.S. workers as a consequence of AV adoption under the Trucking–Fast scenarios and over $100 billion for the Trucking–Slow scenarios. Again, workers' losses would be dramatically higher if they take place during recession years, potentially over $250 billion. It should be noted, however, that this total cost pales in comparison to the annual $800 billion to $1 trillion in benefits estimated by SAFE and Atkinson.[52] The comparison supports the idea that AV adoption is likely to be a net benefit to the country and that there are potential resources available to mitigate costs.

vi. Workers with changed duties

Finally, the duties of workers in many other occupations are likely to change with the adoption of AV. According to the BLS Occupational Requirements Survey, 30 percent of workers are required to do some driving on their jobs.[53] Figure III-11 shows what the percentage of workers that are required to drive cars or other vehicles in selected occupations. When that driving is no longer a requirement, many jobs will change substantially. And others that don't drive now may still see changes in duties.

For example, removing from many occupations the requirement to be able to drive will benefit workers whose disabilities now prevent them from driving. For others, time now spent driving may be available for productivity-enhancing activities such as writing, completing paperwork, or making sales calls. In addition, jobs related to roadway accidents or personal ownership of cars will be strongly affected. Another large category are current drivers who will continue in their occupation with much more assistance from technology derived from the development of autonomous vehicles, as is the case with airline pilots and auto assembly line workers.

The ESA noted jobs that were most likely to have their duties change.[54] In total, these jobs employed 7.7 million people in 2016. Figure III-12 shows the characteristics of the workers in

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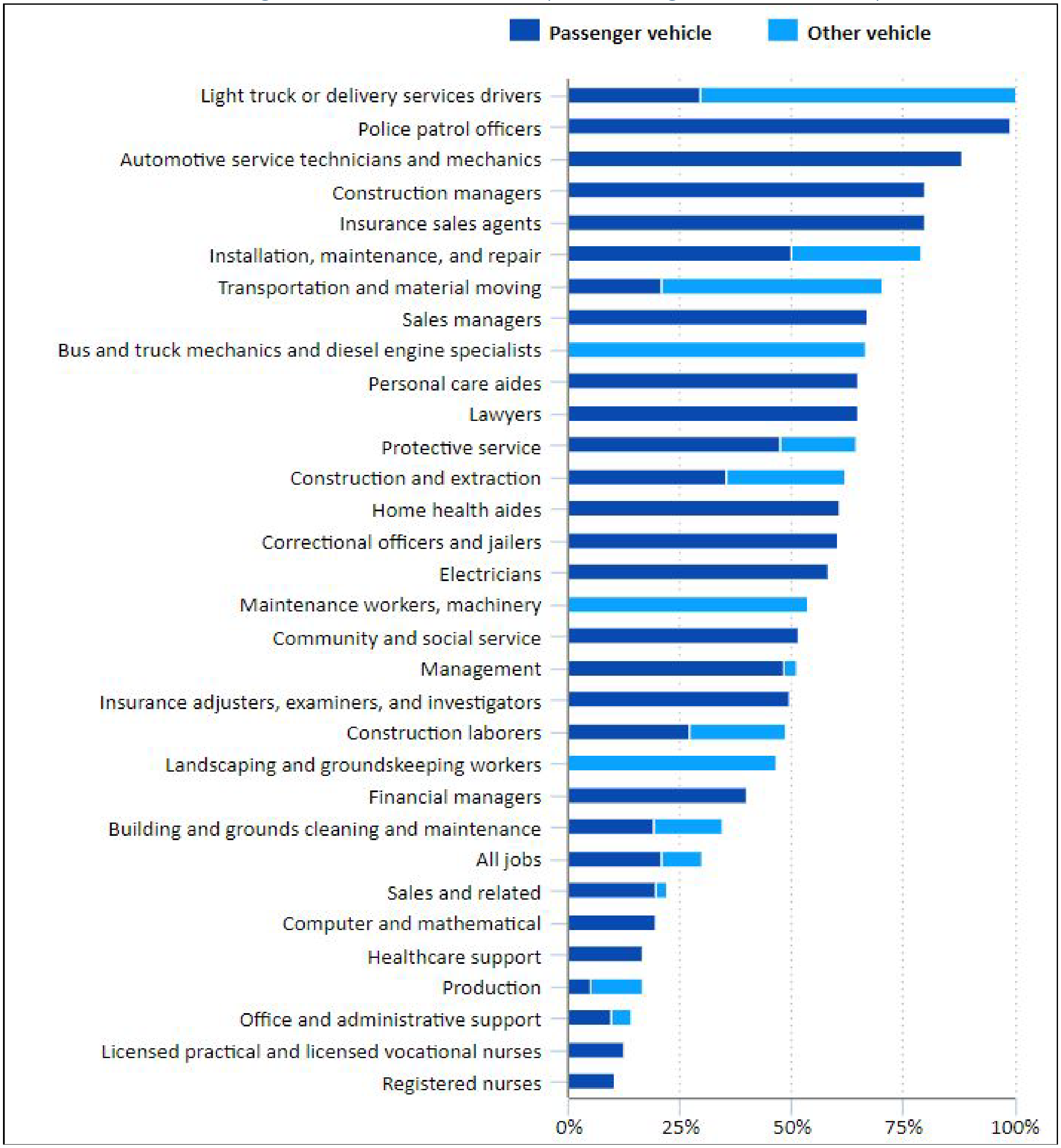
[52] See Securing America's Future Energy, "The Impact of Autonomous Vehicles on Consumers, the Economy and the U.S. Labor Force, " (June 13, 2018) and Robert Atkinson, "The Coming Transportation Revolution," *Milken Institute Review*. 4th Quarter 2014. https://itif.org/publications/2014/10/17/coming-transportation-revolution.

[53] Bureau of Labor Statistics. "30 Percent of Civilian Jobs Require Some Driving." *The Economics Daily*, June 27, 2017. https://www.bls.gov/opub/ted/2017/30-percent-of-civilian-jobs-require-some driving-in-2016.htm

[54] David Beede, Regina Powers, and Cassandra Ingram. Office of the Chief Economist, Economics and Statistics Administration, U.S. Department of Commerce. August 11, 2017. "The Employment Impact of Autonomous Vehicles" *ESA Issue Brief* # 05-17. http://www.esa.doc.gov/sites/default/files/Employment%20Impact%20Autonomous%20Vehicles_0.pdf

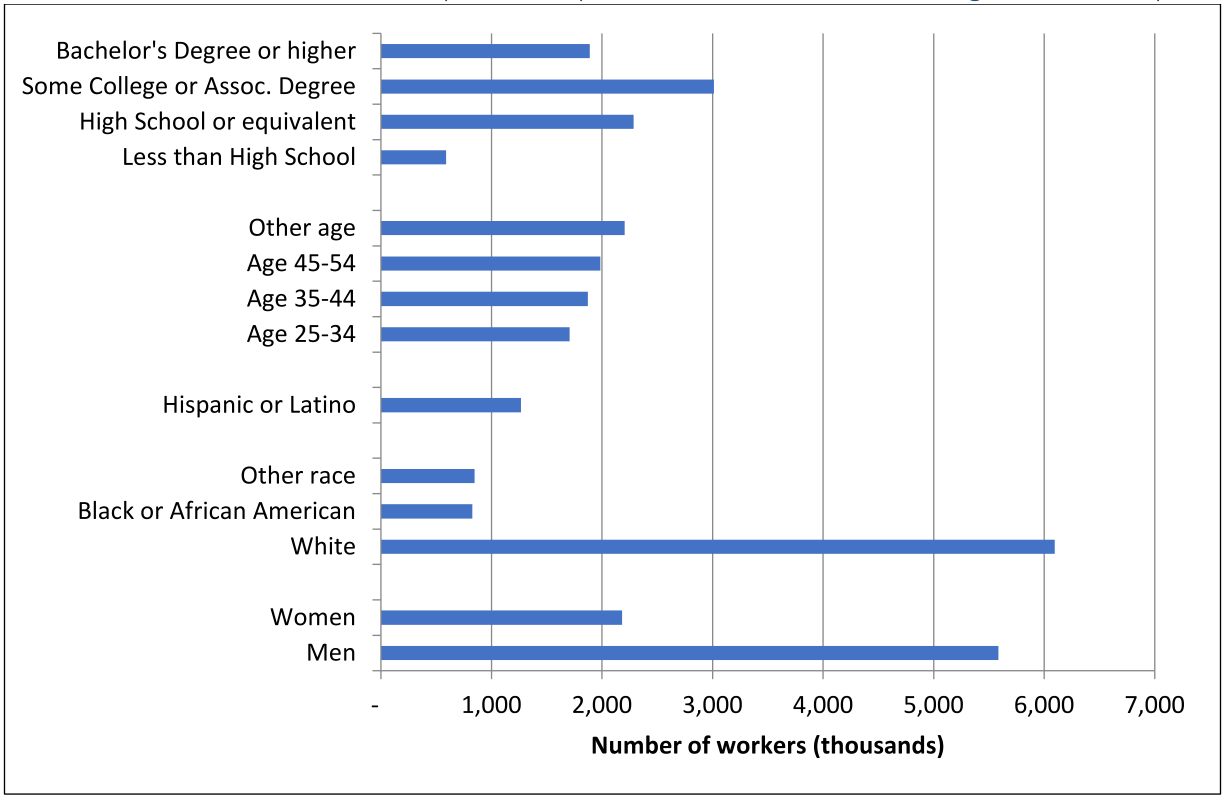
these jobs. The largest occupation in this group is Personal Care Aides, many of whom now drive to work with a variety of dispersed clients and also take them on errands. Compared to the displaced workers, the workers with changed duties are more female, more educated, and younger.

FIGURE III-11: Percentage of Civilian Jobs that Require Driving, in Selected Occupations, 2016



Source: Bureau of Labor Statistics https://www.bls.gov/opub/ted/2017/30-percent-of-civilian-jobs-require-some-driving-in-2016.htm

FIGURE III-12: Characteristics of People in Occupations Whose Duties Will Change with AV Adoption



Source: Census Bureau, American Community Survey 2016 and authors' calculations.

IV. Job Creation, Impact on Well-Being, and Pace of Change

In line with past experience and our framework (from Section III), our simulations assume that enough new jobs will arise to restore the economy to full employment. However, this assumed job creation does not argue for a passive approach to job losses from AV adoption. Not all jobs are equal and the path to a new job may be short and smooth or long and uncertain. The historical examples reviewed in Section II show that technology alone will not determine which new jobs are created and how painlessly displaced workers are slotted into them.

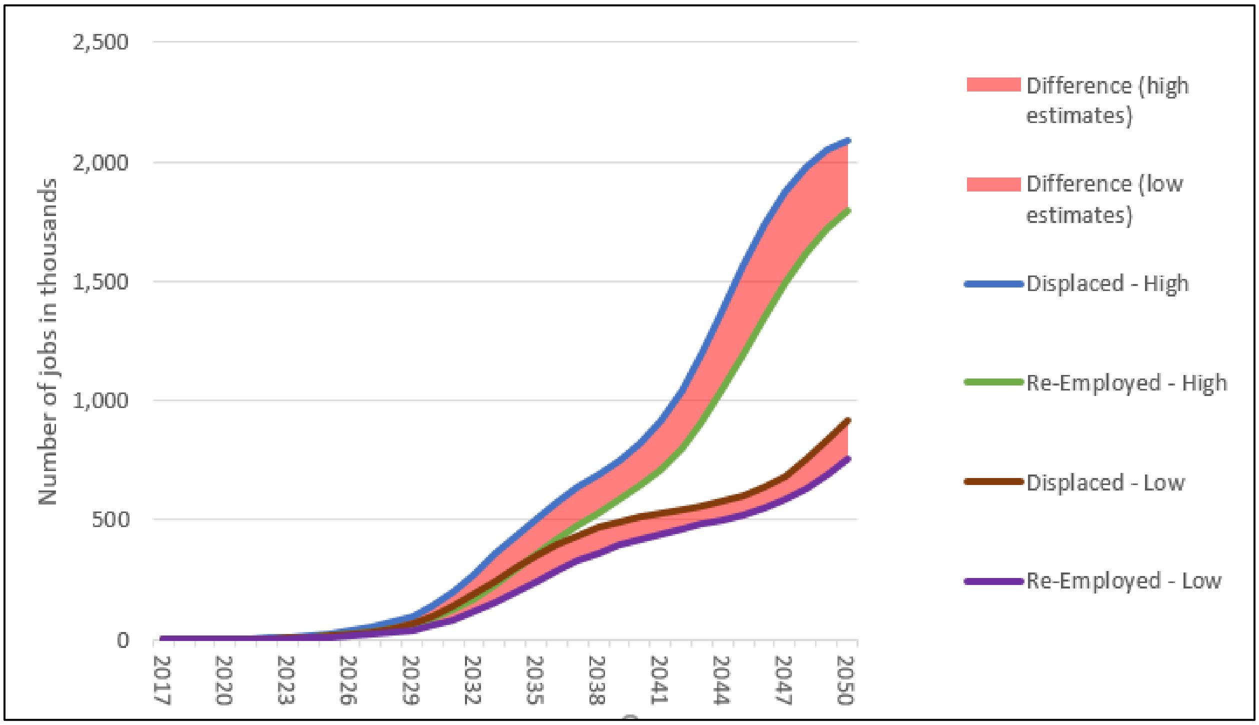
Here we discuss what we can know about the job creation that will replace the jobs eliminated by AV adoption. We begin by focusing on the job creation implied by our analysis framework and consider a baseline case as well as two contrasting job creation variants. We also review some broader implications for wellbeing from AV adoption. Then we discuss a number of major uncertainties and how they could affect our simulations. Finally, we discuss the case of truck drivers in depth to illustrate how different the futures could be and the uncertainties involved.

A. Job creation

The outcomes described in our simulations assume no other major changes or disruptions to the U.S. labor market. That is, our simulations project that the experience of workers displaced by AV adoption will be similar to the recent path for a typical laid-off worker in the U.S. We assume that even with no major policy changes that employers will still create enough new jobs reasonably quickly to employ the workers that need to be reabsorbed. In that sense, despite the losses noted above, we describe a relatively rosy outcome.

How many new jobs will be created? Figure IV-1 illustrates the process of replacing the jobs changed by AV deployment under the high and low displacement scenario combinations. The upper line in each pair is the projected cumulative number of workers who will be displaced due to AV adoption and adjusted for retirements. Even as the AV-related displacement occurs, previously displaced workers will continue to take jobs; this quantity is represented by the lower line in each pair. This shows the additional labor market churn caused by the transition to AVs.

FIGURE IV-1: Job Displacement and Re-Employment



Source: Authors' calculations.

Note: "Low" refers to the combination of Trucking-Slow and Cars-Personal scenarios. "High" refers to the combination of the Trucking-Fast and Cars-Fleet scenarios.

If displaced workers all landed new jobs immediately, then the number of jobs created would be the same as the number of jobs eliminated in each year. However, we have seen that after they are displaced, some workers will be unemployed for a time or exit the workforce. Their paths to re-employment are slowed by the four frictions (geography, skills, worker voice, and investment), as discussed in the framework (Figure II-2). Thus, job creation lags job destruction, which opens a temporary gap between job destruction and job creation and lowers employment for a time. The job gaps for the high and low deployment scenario combinations are represented by the two shaded areas in Figure IV-1.

Our simulations suggest that displacement rates will be fairly modest until about 2040. After that, the gap between displacement and re-employment widens as more workers are displaced annually, so that a larger number of workers experience a time lag before they land new positions. The gap will peak at 380,000 in 2047 for the high scenario combination and 170,000 in 2051 for the low scenario combination.[55] After those years, the gap begins to dwindle as AV-related worker displacement tapers off and an increasing number of workers find new jobs. Sometime after 2051, all jobs eliminated by AV deployment will be replaced with new jobs that will be filled with workers.

The number of new jobs created implied by the high and low simulations (shown in the high and low job re-employment lines of Figure IV-1) is substantial—a range between 0.7 to 1.7 million new jobs created by 2051. Of course, many workers displaced by AV will not take newly created jobs; they will be hired into pre-existing jobs. Other workers, often young people just entering the workforce, will take the new jobs. Regardless of who fills which job, our simulations (as informed by past experience and economic theory) suggest substantial job creation in the wake of AV adoption. There are at least two contrasting alternatives to the churn paths laid out above: employers may not create good new jobs so quickly or consumers could expand their use of transportation enough so that few workers will be displaced. How would those job creation variants differ from the baseline outcome?

First, why might employers lag in job creation? Our framework (Figure II-2) lists four reasons why job creation may be delayed and income losses may mount:

1) **Geography**: New jobs may arise in different places from where existing jobs are lost. For example, many long-haul truck drivers live in rural areas. Job growth in rural areas has been slower than for the rest of the U.S. If many of the displaced workers are not mobile and live in areas where job growth is slow, adjustment would be more prolonged.
2) **Skills**: New jobs may require different skills from the old jobs. Very different requirements (for example, between new occupations in hospitals and driving), challenges for mid- or late-career workers in acquiring new skills, and high costs for training could slow their adjustment.
3) **Worker voice**: Institutions and regulations that surface workers' voices to facilitate the sharing of productivity gains and preserve the value of employees' human capital may be lacking. When displaced workers have no voice in allocating productivity gains or in reorganizing work, insufficient resources may be directed toward retraining or other assistance they need to smooth their adjustment. Workers can have a voice through unionization, employer practices, and the political system. Without this voice, wages are more likely to remain depressed as the laid-off workers crowd into and compete for the few jobs available for workers like them. In addition, the new jobs created will be less likely to be "good jobs," that offer high wages, stability, a chance for advancement, etc.
4) **Investment**: Incentives or access to capital for investments to create new jobs may be too low. An economy in recession, a lack of local investment capital, information gaps, or

[55] Note: The scenarios do not extend past 2051, so it is possible that the gap would grow after that date.

overly restrictive policies or regulations could all hinder employers from expanding employment.

The larger these gaps are and the more they compound each other for particular workers, the longer their unemployment spells will be while they search or prepare for their next job. And if many workers lose their jobs, unemployment will rise substantially for a long time, and displaced workers' new jobs will likely pay far less than they received before. Search times might double, and time out of the labor force would be far higher. Indeed, as noted above, Davis and von Wachter[56] found that income losses to workers displaced during recessions were two to three times higher than losses to those who lost their jobs during economic expansions. These higher losses could occur in locally depressed economies even when the rest of the nation was expanding. So, under this variant, all the negative outcomes are substantially higher.

Second, in contrast with the first scenario of slow job creation, lower transportation prices could spur dramatically higher spending on transportation. If so, after AV adoption, more people may move further away from each other and their workplaces. The ability to travel further from home, at lower cost and without a commute that requires a driver's attention, could open new job possibilities to some workers. Under these conditions, many fewer transportation workers would lose jobs, but urban sprawl, congestion, energy use, and environmental costs could rise rapidly, reducing the overall social benefits from AVs. We examine this issue further below when we discuss some wellbeing impacts of AV adoption.

The three sorts of jobs created by AVs are those outlined in our framework: additional transportation jobs, AV-supplying jobs, and jobs from expanding non-transportation consumption. As these two alternative outcomes suggest, the number of jobs in each category and their speed of creation matters a lot for achieving the rosy outcome.

i. New transportation jobs

To the extent that AVs reduce the cost of transportation, people will demand more transportation. Even if AVs achieve high levels of autonomy (levels 4 or 5), humans will still be necessary for the operation of the transportation system. For example, people will be involved in dispatching fleets of vehicles, repairing them on the road (it probably will be a long time before it is practical to have a robot change a tire next to a busy highway), etc. There are also some tasks that are currently bundled with driving, such as delivery of a package to the customer's door, helping a frail, disabled or very young customer and her luggage to get into/out of a vehicle, and other types of customer service. As the cost of transportation falls, the quantity demanded of these non-driving tasks (those now bundled with driving jobs) will likely increase, thus partially (though not fully) offsetting the reduced demand for driving tasks.[57]

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[56] Steven Davis and Till von Wachter. "Recessions and the Costs of Job Loss." *Brookings Papers on Economic Activity*, 2011 no. 2. https://www.brookings.edu/bpea-articles/recessions-and-the-costs-of-job-loss/

[57] Danielle Paquette. "Pizza Hut boldly says driverless delivery will actually create more jobs," *Washington Post*. January 11, 2018. https://www.washingtonpost.com/news/wonk/wp/2018/01/11/pizza-hut-boldly-says-driverless-delivery-will-actually-create-more-jobs/?utm_term=.0bbc63cd377d ; David Beede, Regina Powers, and Cassandra Ingram. "The Employment Impact of Autonomous Vehicles." Department of Commerce, Economics and

For example, discussing a small experiment designed to gauge new demand for transportation in an AV-enabled world, Harb et al. say:[58]

> We found an 83 percent overall increase in VMT [Vehicle Miles Travelled]. The number of long trips and trips after 6 p.m. increased by 91 percent and 88 percent respectively. Retirees were the cohort with the largest increase in these two trip types (175 percent and 246 percent respectively). 21 percent of the increase in VMT was a result of “zero-occupancy” vehicles, where subjects sent their chauffeur [simulating an autonomous vehicle] on errands.

More generally, previous studies suggest that people’s use of transportation is quite responsive to price. One review of the literature summarizes the findings as follows:[59]

> Although there is a large literature on elasticities of VKT or fuel demand with respect to fuel prices, estimates for light duty VKT elasticities with respect to generalized travel costs per kilometer are few. FHWA (2005) suggests a long-run elasticity of 1.0 to 2.0, while Graham and Glaister (2002) recommends 2.3. For heavy vehicles, freight demand elasticities with respect to total costs range from 0.5 to 1.75 (Cambridge Systematics, 2009; Graham and Glaister, 2004; Winebrake et al., 2012), with a choice of 0.97 to 1.0 as a central value by HDR/ICF (2008) and Cambridge Systematics (2009).

ii. New AV-related jobs

Here we attempt to anticipate what jobs will be created directly from the expanded adoption of AVs, both cars and trucks, and by both individuals and businesses (fleets). We start with manufacturing-related employment, for which we have a more solid basis for projection, and then move to services where our thoughts are more speculative given the well-known difficulty in predicting the indirect job creation tied to new technologies.

Statistics Administration, Office of the Chief Economist. *ESA Issue Brief* #05-17. August 11, 2017. http://www.esa.doc.gov/sites/default/files/Employment%20Impact%20Autonomous%20Vehicles_0.pdf

Advocates for the disabled have proposed several modifications to AVs that will ease access to AVs for those with different types of disabilities: Tim Frisbie. “Will Autonomous Vehicles Be Accessible to People with Disabilities?” Shared-Use Mobility Center. October 31, 2017. http://sharedusemobilitycenter.org/news/will-autonomous-vehicles-be-accessible-to-people-with-disabilities/

[58] Mustapha Harb, Yu Xiao, Giovanni Circella, Patricia L. Mokhtarian, and Joan L. Walker. “Projecting Travelers into a World of Self-Driving Vehicles: Estimating Travel Behavior Implications Via a Naturalistic Experiment.” Working paper. November 15, 2017. Presented at the Transportation Research Board 97th Annual Meeting (January, 2018). http://www.joanwalker.com/uploads/3/6/9/5/3695513/harb_et_al_chauffeur_-_nov_2017_working_paper.pdf. Note, however, that these transportation services were offered free of charge, which would tend to over-estimate the ultimate increase in VMT from AVs.

[59] Zia Waduda, Don MacKenzie, and Paul Leiby. “Help or hindrance? The travel, energy and carbon impacts of highly automated vehicles.” Transportation Research Part A: Policy and Practice, 86, 1-18 (April 2016). https://www.sciencedirect.com/science/article/pii/S0965856415002694

AV-Related Manufacturing

AVs will need to be manufactured and so far, every indication is that automakers (current and possibly new entrants, following the model of Tesla) will do that job. The tech companies (including Waymo, Uber/Lyft, and Apple) are backing away from saying they will do manufacturing themselves, and the contract manufacturing capacity for the automotive sector has been shrinking rather than expanding in recent years. Automakers are also working hard to make sure they retain their system integrator role for future vehicles, anticipating the full range of technological advances.

Most of the technologies that permit AVs to function autonomously are layered onto existing vehicle technologies. Cameras, sensors, regular radar, and lidar (laser-powered radar) are the hardware components most likely to be added to existing vehicle designs. To support the vastly greater information processing demands of AVs, many advanced chips and microprocessors, incorporated into integrated control units (ICU), will be added, along with storage capacity and backup ICUs for redundancy protection needed to deal with the extreme operating conditions in automobiles and trucks.

Another area of expansion will be the information and communications technologies (ICT), both hardware and software, needed for within-the-vehicle hard-wired networks plus outside-the-vehicle protocols related to Wi-Fi that will support vehicle telematics[60] (and provide business services) and very likely both vehicle-to-vehicle (V2V) and vehicle-to-cloud or vehicle-to-infrastructure (V2C/V2I) communication. While some standards for near-range wireless communication already exist, including the DSRC (Dedicated Short Range Communication) standard already backed by the National Highway Traffic Safety Administration (NHTSA), most observers believe that the full implementation of wireless communication needed for the combination of AV and "connected car" services (what some call "CAV") will await the implementation of the 5G standard in telecommunications.[61] Once properly outfitted, vehicles will become both transmitters and receivers of signals in an expansive 5G network; Wi-Fi performance on the road may be at its best in a traffic jam!

What about the fundamental structural design and materials for an AV? How might those differ from today's vehicles? Here it is important to discuss current regulatory developments at the federal level that promise to exempt a certain number of AV test vehicles—per manufacturer, per year – from the FMVSS (Federal Motor Vehicle Safety Standards). FMVSS are developed and enforced by NHTSA, based on the National Traffic and Motor Vehicle Safety Act of 1966, and are divided into three categories: crash avoidance, crashworthiness, and post-crash survivability. Automotive original equipment manufacturers (OEMs—the large automakers) are responsible for validating that vehicles meet FMVSS; U.S. law (going back to *McPherson vs. Buick* in 1916) also holds OEMs responsible for legal liability and for undertaking recalls, even where a safety problem

[60] Communication of large amounts of computer data to either help drive the vehicle or to satisfy passenger business needs.

[61] Cellphones currently use either the 3G or 4G standard.

can be linked to a component made by a specific supplier, because of their system integration role.

If the current bill to regulate AVs passes both houses of Congress (it is currently stalled at the Senate), AVs used for testing purposes in all states will not have to meet FMVSS as long as their manufacturers self-certify them as “safe.” However, this is unlikely to bring changes in the basic materials or structural design of these test vehicles. Steel (with some aluminum) construction with many crumple zones to protect occupants, along with safety technologies like air bags, are likely to be the default characteristics of any vehicle operating during the long transition to system-wide (i.e. 100 percent) implementation of AVs. Once system-wide implementation is achieved, it is possible that AVs (assuming that their safety record in avoiding accidents, deaths, and injuries is as impressive as its proponents claim) could be made of lighter-weight materials that wouldn’t need to be designed to protect occupants as in current vehicles. However, that is very far off; in our scenarios, that would be reached well after 2060, if at all. Our expectation is that as long as there is any mix of AVs and conventional vehicles still operating, societal expectations will continue to support safety standards at the level of current FMVSS.

This is important because if future AVs were built with radically different structural designs involving much less steel and occupant protection, manufacturing requirements would be much simpler—and the associated manufacturing employment would also be much less. If for the foreseeable future, AVs both need to meet current FMVSS and are adding lots of new technologies, the overall manufacturing task will become greater/more complex rather than less, which will preserve manufacturing employment at OEMs and suppliers at current levels (assuming a balancing of greater work content with productivity improvements).

Where the new technological components are manufactured will obviously affect U.S. employment levels; automotive supply chains are already extraordinarily international and are characterized by contradictory locational dynamics, with labor-intensive components flowing to low-labor cost locations but with heavy, high value-added, and/or key customized components tending to be manufactured relatively close to final assembly plants in order to keep inventories lean/low and feedback loops quick for quality assurance.

A separate factor often considered in evaluating future manufacturing requirements is the prevalence of electric vehicles (EVs) in the future. EVs generally are simpler and have a more modular product architecture than conventional cars, and electric motors and other drive train components are simpler to build than internal combustion engines (ICE). Thus if EV sales increase greatly, labor requirements in automotive assembly plants may drop; since EVs have fewer moving parts than ICEVs (estimates start at 25 percent fewer and go up from there, depending on the level of granularity in counting components), less assembly labor is needed.

In terms of technological interdependence, there is no necessary requirement for AVs to be EVs—or vice-versa. Thus, there is no reason to assume that fast diffusion of AVs will reduce manufacturing complexity or labor hours if those AVs have ICEs—or hybrid gasoline-electric drivetrains, which are also time-consuming to manufacture. However, AVs and EVs could be bundled together for many reasons, including regulatory mandates, consumer preference, and the fact that both AVs and EVs need much more electrical system capacity than exists at present.

In the short term, cities allowing AV testing might require that the test vehicles be EVs as well in order to achieve environmental policy goals. For now, based on current EV diffusion patterns (i.e. impressive growth but from a very low baseline and hence with very low impact on overall sales), we do not anticipate much reduction in manufacturing employment requirements because we do not expect a tight coupling between EV and AV designs. That is, we expect the number of vehicles with EV/AV coupled designs to remain relatively low for a long while.

In summary, we anticipate that the manufacturing requirements associated with designing and building an AV will be equal or higher than for current vehicles through the entire period of transition when AVs and traditional vehicles are on the road; only full system implementation (100 percent AVs) would allow a dramatic shift in FMVSS and hence in vehicle structural designs and manufacturing requirements. If the new ICT technologies needed for AVs, from lidar to advanced chips and ICUs, are not manufactured in the U.S., the employment gain related to greater use of these new technologies would not help to offset U.S. job losses from AVs—even if retraining were available to help displaced workers move into these manufacturing jobs.

One possible development that could keep these ICT-related jobs in the U.S. (and other developed economies) is the likelihood that AVs will require sophisticated hardware/software integration and associated customization requirements. For example, the 2011 Tohoku earthquake in Japan called the world's attention to the fact that a single factory of semiconductor firm Renesas made 60 percent of a particular customized electronic chip/ICU needed by virtually every vehicle built in the U.S., Europe, Japan, and Korea. This dependence arose because Renesas had a rare/scarce ability to design both the chips (hardware) and the associated applications (software) along with customization to each OEM's requirements. For AVs, lidar is a crucial technology that is often described as inevitably following a path to being a commodity, readily available in a standardized design at a low cost. This is certainly what one would predict based on the most common trajectory of ICT digital products. But perhaps competitive advantage in lidar (and hence in the overall AV system) will emerge for the firms most able to pull together the best-performing combination of operating system, 3-D mapping data, and hardware/software configuration for lidar, cameras, sensors. Waymo—the AV subsidiary of Google's Alphabet—appears to hold a leading position in integration and customization skills that are not yet in evidence at other firms, e.g. Uber.[62] In general, high skill jobs in digital technologies are likely to grow with AVs—along with demand for prospective employees with engineering degrees in artificial intelligence, vision systems, and advanced data analytics. These are likely to be highly sought-after jobs for young people embarking on careers involving these new technologies rather than jobs for which older workers from manufacturing could be retrained.

[62] This comparative assessment is speculative but can be inferred in the aftermath of the recent fatality in which an Uber vehicle operating in autonomous mode (albeit with a test driver behind the wheel) killed a pedestrian with a bicycle near Phoenix. The signs of a less-than-adequate hardware configuration (one rather than six lidar units) and lower test driver coverage (one rather than two) at Uber stand in contrast to the confident assertion of Waymo's CEO that the Phoenix accident would not have occurred with their AV system (i.e. integrated hardware/software/mapping).

AV-Related Services

As noted above, forecasting job creation in services related to AVs is much more difficult than for manufacturing. We know very little now about what will be needed (or required by regulation) to operate AVs, particularly in fleet applications such as ride-sharing. Furthermore, there is a huge range of possible services that could appeal to the occupant of an AV who has a long commute and no need to pay attention to driving or parking, yet little basis for forecasting which will be most technologically feasible, most appealing to consumers, and most profitable for service providers. What we offer here is thus, of necessity, quite speculative.

One persistent prediction about AVs is that the first applications are likely to be in fleets rather than individual ownership. Indeed, fleet management capabilities are likely to be both necessary and highly valued by both the automotive OEMs building AVs and the tech companies providing AV operating systems. AVs will be an expensive durable asset for which return on investment will depend on smart management for high utilization (although it will be easy to surpass the current level of usage of privately-owned automobiles, which sit unused 95 percent of the time). Also necessary will be smart capital investment choices about timing, financing, and volume purchases, smart maintenance choices to minimize AV depreciation and maintain a high operating ratio, and smart replacement and end-of-life management of the asset. Neither automakers nor tech companies have much expertise in these areas; more likely candidates are rental car companies (Hertz, Avis, etc.); truck leasing companies (Ryder, Penske, etc.); car-sharing companies (Zipcar, already owned by Avis; car2go); and vendors who retrofit and guarantee pre-owned vehicles (CarMax, CarVision, TrueCar). Waymo has already contracted with Avis and CarMax to maintain their fleet of Chrysler Pacifica minivans in their AV tests around the U.S. These companies would enjoy a substantial surge in demand for their services with growth in AV fleets and their employment requirements would grow accordingly for jobs in asset acquisition and financing; utilization management; maintenance and replacement; and user support services.

Another prediction is that Level 4 AVs (no driver, no controls by which a human could operate the vehicle) will, in many situations, need support from a traffic specialist or operator in a remote location. The air travel analog is air traffic control centers. Remote drone operation, for military or commercial purposes, is a newer example. Another analog are today's traffic engineers and technicians, who study and design traffic flow patterns. Consider the case when employers can replace drivers (who focus on a single vehicle's operation) with remote operators (who can hypothetically monitor many vehicles at once). At that point, the labor cost savings are potentially huge, as are the implied job losses, all depending on the ratio of remote operators to vehicles. Three "known unknowns" are whether policymakers or companies will set remote operation or traffic management guidelines, what criteria they will use for setting guidelines, and whether the ratio of operator to vehicles will be low (e.g., 1/50) or high (1/8).

Let's consider a scenario about trucking that raises the question of where remote operator activities might be situated. In one possibility, driverless trucks with Vehicle-to-Cloud communication will connect with a remote operation center that covers multiple states and oversees all trucks' cross-country travel on interstate highways. Such a center would presumably have a relatively high operator-to-vehicle ratio, of, say, 1 to 30.

But imagine instead a platooning situation in which a convoy of 4-6 trucks is traveling together in tight configuration to gain aerodynamic benefits. At present, platooning can occur but only with a driver present in each truck. The technology is likely to advance so that some trucks in a convoy could operate with no driver. But perhaps the remote operator role would be played by the truck driver in the lead vehicle of the convoy who would monitor all convoy vehicles plus environmental conditions while possibly performing other tasks such as communicating with delivery destinations or working out schedule complexities. In this case, the ratio of operator to vehicle would likely be closer to 1 to 5.

The employment and skill consequences of these two scenarios could be quite different. The analog to an air traffic control center would involve a relatively small number of very high skill jobs not readily available to a truck driver whose job was displaced by AVs. In contrast, the lead driver in a platoon who monitors all other vehicles in the convoy would have a more multi-faceted role involving a range of skills, and current truck drivers facing elimination of their driving responsibilities could probably be trained for this role relatively easily and cheaply.

Divergent scenarios can also be imagined for many other service offerings. Remote call centers that wait for AV occupants to call for help of some kind would have very different jobs, in both skill levels and employment levels, than centers that offer customized “concierge”-type services with proactive offers made to AV occupants based on data previously collected about their preferences and needs. Convenience-related services, in which AVs would bring occupants to destinations to accomplish errands, e.g. picking up groceries on the way home from work, are likely to generate extra jobs at the grocery stores, just as Instacart now provides for people ordering groceries for home delivery. In this situation, the AV provides the delivery functionality by bringing the consumer to the store and the grocery store staffer would need to prepare the order and bring it out to the AV at a precisely-coordinated time and place.

Some of the most futuristic visions for AV occupants involve a variety of health-related services. The seat for an AV occupant (particularly in a privately-owned AV) could contain a range of sensors to check a variety of health indicators, e.g. blood pressure, blood sugar levels, external air quality vis-à-vis pollutants and allergens, and to provide health-related guidance about what/where to eat lunch, exercise possibilities, etc. Communicating these data in real time to the individual’s doctor or medical support team could be hugely helpful in preventative approaches to health care that are highly customized and more representative of daily health conditions than any number of doctor’s office visits could accomplish.

A final category of AV services would be discretionary choices by occupants of how to spend the time freed up by not having to drive. These could include a variety of services supporting work activities (videoconferencing, data analysis, any computing or communications applications currently used in offices); personal growth activities (on-line courses; language instruction; travel information); entertainment/relaxation (watching movies, TV, meditation, enjoying an in-seat massage or aromatherapy session), and of course sleep. (If sex-related applications are often the first to dominate new technology applications, e.g. Internet porn, we can only imagine what could be possible in AVs in which seats are flexible and shades can be drawn.) It is nearly impossible to predict the pattern of adoption of such services. Furthermore, the skill/employment impact will be heavily dependent on whether those services simply substitute for consumption now occurring at non-driving times or represent some additional consumption.

iii. New jobs producing other goods and services

The remainder of the new jobs arise as consumers gain useful time while travelling, save money from lower transportation costs, and can earn more through access to safer, convenient travel. With these benefits, AVs will allow consumers to buy more non-transportation goods and services. For example, a family that earned more or spent less on their cars or taxi service might eat out more often, see doctors more often, buy more clothes, or renovate their home. The best guess is that those consumers would mostly expand consumption in the same directions as they are already trending. So, to understand what these jobs might look like, we turn to ten-year occupational Employment Projections produced biannually by the BLS and assume that the distribution of additional new jobs from this source will look much like those the economy is set to generate anyway.[63] BLS summarizes the projected new jobs as follows:

> About 9 out of 10 new jobs are projected to be added in the service-providing sector from 2016 to 2026…Employment in the health care and social assistance sector is projected to add…about one-third of all new jobs...
>
> Healthcare support occupations and healthcare practitioners and technical occupations are projected to be among the fastest growing occupational groups during the 2016–26 projections decade. These two occupational groups—which account for 13 of the 30 fastest growing occupations from 2016 to 2026—are projected to contribute about one-fifth of all new jobs by 2026. Factors such as the aging baby-boom population, longer life expectancies, and growing rates of chronic conditions will drive continued demand for healthcare services. Several other occupational groups are projected to experience faster than average employment growth, including personal care and service occupations, community and social service occupations, and computer and mathematical occupations.
>
> …Of the 30 fastest growing detailed occupations, 18 typically require some level of postsecondary education for entry.

iv. How new jobs would compare to eliminated jobs

Ongoing concerns about widening inequality and job polarization raise concerns about whether the new jobs will further contribute to widening gaps. The fear is that automation like AV can take over the more challenging work of low-skilled workers and fuel demand for highly skilled labor. This would leave low-skilled workers crowded into jobs that pay little and have few opportunities for advancement. For example, former truck drivers could find themselves left only with jobs loading and unloading trucks or serving fast food.

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[63] Bureau of Labor Statistics. "Employment Projections: 2016-26 Summary". https://www.bls.gov/news.release/ecopro.nr0.htm.

This need not be the case. Mandel[64] found that the recent growth of ecommerce has led to a net upgrading of jobs for high school graduates. The jobs in shrinking occupations (such as retail sales clerks) pay less and have worse working conditions than the fast-growing, automation-assisted ecommerce jobs in fulfillment centers.

In the case of AVs, the previous discussions show a wide variety of jobs that will likely arise to absorb AV-displaced workers. How will these new jobs stack up compared to those eliminated by AVs? As examples, Table IV-1 compares 2017 annual wages and highest state location quotients for the three occupations that we expect to lose the most jobs from AV adoption with examples of those where jobs are likely to be created. The comparisons show that the new jobs may occur at many levels of education and pay. They are not currently concentrated in states so different from those that employ the current drivers. Yet, former drivers would need retraining and more education in order to assume the better-paid positions, such as repair mechanics and traffic technicians, nurses, and ICT jobs. Without that retraining, their options are likely to be limited to the lowest-paid of the new jobs, such as personal care aides or food service and preparation.

[64] Michael Mandel. "How Ecommerce Creates Jobs and Reduces Income Inequality." Progressive Policy Institute. September 2017. http://www.progressivepolicy.org/wp-content/uploads/2017/09/PPI_ECommerceInequality-final.pdf

TABLE IV-1: Examples of Occupations Where Jobs Will be Created, Compared to Occupations with Largest AV-Displacement

	Median annual wage, 2017	Typical entry-level education	States with highest occupational concentration (location quotient)				
AV-reduced occupations (top three occupations)							
Heavy and Tractor-Trailer Truck Drivers	$42,480	Postsecondary nondegree award	Nebraska (2.23)	Arkansas (2.22)	North Dakota (2.15)	Iowa (2.02)	Wyoming (1.8)
Light Truck or Delivery Services Drivers	$31,450	High school diploma or equivalent	Montana (1.31)	Maryland (1.3)	Louisiana (1.28)	Rhode Island (1.25)	Illinois (1.25)
Bus Drivers, School or Special Client	$31,060	High school diploma or equivalent	West Virginia (1.71)	Connecticut (1.68)	Pennsylvania (1.54)	Minnesota (1.51)	New York (1.51)
New transportation jobs (beyond mitigating losses above)*							
Aides for older, young or disabled riders (Personal Care Aides who help with transportation**)**	$23,100	High school diploma or equivalent	California (2.18)	New Mexico (2.16)	Minnesota (1.78)	Maine (1.68)	Wisconsin (1.52)
Expediters/Roadway Automotive Repair Mechanics (Automotive Service Technicians and Mechanics for roadway service)	$39,550	Postsecondary nondegree award	Maine (1.48)	Montana (1.42)	West Virginia (1.32)	New Hampshire (1.30)	Missouri (1.27)
Package Deliverers (Light Truck or Delivery Services Drivers for the last mile)	$31,450	High school diploma or equivalent	Montana (1.31)	Maryland (1.3)	Louisiana (1.28)	Rhode Island (1.25)	Illinois (1.25)

New AV-related jobs*							
Traffic Engineers (Civil Engineers specializing in roadway traffic)	$84,770	Bachelor's degree	California (1.23)	Texas (1.08)	Florida (0.92)	New York (0.83)	Pennsylvania (0.99)
Traffic Technicians	$45,670	Associate's degree**	Tennessee (4.22)	New York (3.82)	Wyoming (2.68)	New Mexico (2.30)	Georgia (1.98)
Computer Programmers	$82,240	Bachelor's degree	Alabama (2.22)	Washington (1.9)	Connecticut (1.83)	New Jersey (1.57)	Utah (1.54)
Network and Computer Systems Administrators	$81,100	Bachelor's degree	Maryland (2.2)	Virginia (1.96)	Vermont (1.85)	Colorado (1.58)	Rhode Island (1.57)
All sectors job creation (top three occupations)							
Personal Care Aides	$23,100	High school diploma or equivalent	California (2.18)	New Mexico (2.16)	Minnesota (1.78)	Maine (1.68)	Wisconsin (1.52)
Combined Food Preparation and Serving Workers, Including Fast Food	$22,730	No formal educational credential	Louisiana (3.27)	Alaska (2.5)	Hawaii (2.2)	Maine (2.17)	Nevada (1.36)
Registered Nurses	$70,000	Bachelor's degree	South Dakota (1.47)	West Virginia (1.45)	Delaware (1.29)	Missouri (1.27)	Mississippi (1.26)

*Wages and location quotients listed for these emerging occupations are those for the occupation listed as similar to the emerging occupation. Actual wages and geographic distribution may deviate from those for the current occupation.
**Refers to the broader category of Civil Engineering Technicians.
Sources: BLS Wages and LQs, https://www.bls.gov/oes/current/oes_stru.htm, Typical Entry-Level Education: https://www.bls.gov/ooh/, All sectors job creation (top three occupations): https://www.bls.gov/emp/ep_table_104.htm

B. Well-being implications

i. Crashes and accidents

One major intended benefit of AV adoption is improved safety: lower injuries and fatalities from roadway accidents. In 2016, 37,461 lives were lost in the U.S. due to crashes and accidents.[65] For the labor market, the potential advantages include longer work lives, less absenteeism, fewer disabled workers, less traffic congestion, and lower workers compensation insurance premiums.

There is great potential for improvement. In 2016, 1,839 people lost their lives while on-the-job due to motorized land vehicles, as either pedestrians or occupants.[66] These accounted for 35 percent of all occupational fatalities that year—and 5 percent of all crash and accident fatalities. Employers reported an additional 44,350 incidents involving motorized land vehicles that were severe enough to result in days away from work, with more than half (23,320) keeping workers out for 11 work days or more.[67] Some now have permanent disabilities.

While these counts are the best available for on-the-job accidents, they do not include all the labor-market affecting incidents that AV may be able to prevent. First, the injuries data are known to be incomplete for a number of reasons, including systematic under-reporting of work-related injuries and illnesses by employers.[68] In addition, by design, injuries are included only if they result in days away from work, which omits the large and rising number of incidents that are serious enough to cause restricted duties or job transfers.[69] Furthermore, workers are also killed, disabled, or otherwise have their productivity hindered by the many incidents that occur off the job.

To take all these considerations into account, we turn to the National Highway Traffic Safety Administration, which periodically produces comprehensive estimates of the economic costs of all roadway accidents. Their latest report states: [70]

> In 2010 the total economic cost of motor vehicle crashes in the United States was $242 billion. This represents the present value of lifetime economic costs for 32,999

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[65] National Highway Transportation Safety Administration. "2016 Quick Facts." https://www.nhtsa.gov/press-releases/usdot-releases-2016-fatal-traffic-crash-data

[66] Bureau of Labor Statistics. "National Census of Fatal Occupational Injuries in 2016," *Economic News Release*, December 19, 2017. **https://www.bls.gov/news.release/cfoi.t02.htm**

[67] Bureau of Labor Statistics. "Employer-Reported Workplace Injury and Illnesses, 2016*," Economic News Release*, November 9, 2017. https://www.bls.gov/news.release/osh.nr0.htm

[68] Bureau of Labor Statistics. "Research on the Completeness of the Injury and Illness Counts from the Survey of Occupational Injuries and Illnesses," July 20, 2017. https://www.bls.gov/iif/undercount.htm

[69] Bureau of Labor Statistics. "Occupational Injuries and Illnesses: a pilot study of job-transfer or work-restriction cases, 2011–2013," Report 1056. https://www.bls.gov/opub/reports/job-transfer-or-work-restriction/archive/a-pilot-study-of-job-transfer-or-work-restriction-cases-2011-2013.pdf

[70] Lawrence Blincoe, Ted R. Miller, Eduard Zaloshnja, and Bruce A. Lawrence. "*The economic and societal impact of motor vehicle crashes," 2010*. *(Revised)* (Report No. DOT HS 812 013). Washington, DC: National Highway Traffic Safety Administration. May 2015. https://crashstats.nhtsa.gov/Api/Public/ViewPublication/812013

> fatalities, 3.9 million non-fatal injuries, and 24 million damaged vehicles. These figures include both police-reported and unreported crashes.
>
> When quality-of-life valuations are considered, the total value of societal harm from motor vehicle crashes in 2010 was $836 billion.
>
> …The cost components include productivity losses, property damage, medical costs, rehabilitation costs, congestion costs, legal and court costs, emergency services such as medical, police, and fire services, insurance administration costs, and the costs to employers. Values for more intangible consequences such as physical pain or lost quality-of-life are also examined in estimates of comprehensive costs, which include both economic cost components and quality-of-life valuations.

Three essential factors in this estimate have risen from 2010 to 2016: prices, vehicle miles travelled, and crashes per vehicle miles traveled. Prices rose by about 11 percent. The increase in miles traveled combined with higher crashes raised the number of injuries and fatalities by about 14 percent.[71] Combining these two effects yields a rough estimate of the comprehensive costs of motor vehicle crashes in 2016 of $1.05 trillion.

AV adoption is expected to shrink these costs dramatically by preventing most of the 94 percent of roadway accidents that are now caused by drivers.[72] How much overall accidents will decline is unclear for three reasons.

1. For the foreseeable future, humans will continue to do some driving. Even in 2051, both of our trucking scenarios allow for 5 percent non-AV enabled trucks. In Trucking-Slow, most AV trucks (57 percent) still have drivers responsible for some driving (that is Level 3). Even in Trucking-Fast, 2 percent of AV trucks will not reach Level 4, so they will have drivers. So, in our scenarios, at least 7 to 57 percent of trucks will still have people driving some part (but not all) of the time in 2051. The two car scenarios assume 100 percent penetration of AV enabled vehicles by 2051, but experts agree that full (Level 4) autonomy will be adopted later in cars than in trucks.

[71] National Highway Transportation Safety Administration. "Quick Facts 2016" and "Quick Facts 2011". https://crashstats.nhtsa.dot.gov/#/PublicationList/38 Since they were not yet available, we estimate the number of injuries for 2016 by extrapolating the number of injuries per 10 million vehicle miles travelled (VMT) in 2016 to 81 and multiplying that by the 2016 VMT. From 2010 to 2016, the number of fatalities rose by 13.5 percent and the number of injuries rose by 14.8 percent. We combine those to estimate that total costs rose by 14 percent due to increased crashes.

[72] Santokh Singh. "Critical reasons for crashes investigated in the National Motor Vehicle Crash Causation Survey." Traffic Safety Facts Crash•Stats. Report No. DOT HS 812 115. Washington, DC: National Highway Traffic Safety Administration. (February 2015). https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/812451

2. No technology is perfect, so widespread reliance on AV is likely to increase vehicle-caused accidents, which currently account for only 2 percent of crashes.[73] This will partly offset the reduction in driver-error crashes, but as yet there are no estimates how large this offset will be.[74] With ample testing and safeguards, the AV-caused accident rate should be low in the long run. Yet, some failures will occur, particularly early in adoption. For example, the potential for system failures in congested areas likely raises the chance of large-scale multi-vehicle accidents, however rare. It is unclear what level of safety improvement will be required before widespread adoption and what can be achieved by 2051.

3. Travelling more would also offset some of the reduction in accidents. To the extent that lower transportation costs raises vehicular miles travelled, the number of accidents will not fall in proportion with the decline in the accident rate.

So, by how much will annual costs of motor vehicle crashes be reduced by 2051? Probably substantially, but less than 94 percent. To be conservative, if crashes were reduced by 50 percent, AV adoption would save about 18,000 lives (900 on-the-job), 2.3 million injuries, and $500 million in costs per year. This would clearly benefit employers and their employees substantially. The benefits will be back-weighted, starting small and rising with adoption, accruing in each year. Many benefits will accrue to workers in terms of longer work lives, fewer disabilities, less pain and suffering, and less traffic congestion. Employers will also benefit from less absenteeism, lower Workers Compensation costs, fewer disability accommodations and reassignments, and more.

ii. Environment

The labor market will also be affected by AV's impact on the environment, including emissions, energy use, and urban density. If AV adoption produces lower emissions, reduced energy usage, and less urban sprawl, then it can make workers healthier, face lower costs and raise their productivity, with potential benefits for their earnings and overall wellbeing.

At present, though, whether AV adoption has net environmental benefits remains unclear. AVs are likely to reduce significantly the environmental impact of each mile driven (see below). However, the decline in the costs of transportation (in both dollars and attention) is likely to lead to a significant increase in miles driven. Reduced transportation costs may well have additional negative follow-on effects, by encouraging urban sprawl, larger houses, more distant vacation homes, etc. There is a key role for policy to ensure that users of all types of transport take into account the true costs (including congestion and environmental costs) of transportation.

Below, we examine these impacts in more detail.

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[73] Santokh Singh. Critical reasons for crashes investigated in the National Motor Vehicle Crash Causation Survey. Traffic Safety Facts Crash•Stats. Report No. DOT HS 812 115. Washington, DC: National Highway Traffic Safety Administration. (February 2015). https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/812451

[74] Jeffrey Mervis. "Not So Fast," *Science* vol. 358, issue 6369, p. 1371-1374 (December 15, 2017). http://science.sciencemag.org/content/358/6369/1370 Also, Matthew Hutson. "A Matter of Trust," *Science* vol. 358, issue 6369, p. 1375-1377 (December 15, 2017). http://science.sciencemag.org/content/358/6369/1375

Reduced Emissions

AVs can be programmed to drive more efficiently than humans, avoiding jackrabbit starts and costly detours. To the extent that safety improves, many costly adaptions to the foibles of human drivers can be eliminated.[75] Cars can follow each other more closely, increasing their carrying capacity of roadways and achieving aerodynamic benefits. Reduced need for human driving equipment (e.g., steering wheels) and crash protection in a full AV deployment scenario would reduce vehicle weight significantly, having a large impact on fuel economy.[76] Various features of AVs could lead to substantial benefits, as Brown et al. estimated:[77]

- Platooning: 3 percent to 25 percent reduction in energy consumption
- Eco-driving: Up to 25 percent reduction in energy consumption
- Enhanced vehicle performance: 5 percent to 23 percent reduction in fuel consumption
- Improved crash avoidance: Up to 25 percent reduction in fuel consumption

However, limited actual experience with AVs leaves these estimates subject to much uncertainty. In another study, the most optimistic scenario projected a 40 percent decrease in total road transport energy, and the most pessimistic scenario estimated a 105 percent increase in overall road transport energy use.[78]

Increases in Miles Traveled

We noted above that AVs are likely to reduce transportation costs, thus increasing the demand for transportation. That is, while AVs reduce emissions per mile travelled, they are likely to increase the number of miles travelled.[79]

> Miles travelled per person might also rise, since self-driving technology frees passengers to use travel time for work or sleep. And just as new highways prompt a rise in transport-intensive business, driverless vehicles could generate lots of new

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[75] Center for Automotive Research. "Environmental Effects of Connected and Autonomous Vehicles," forthcoming cargoup.org

[76] "For every 10% weight reduction, fuel economy increases by 6% for cars, and 8% for light trucks." http://web.mit.edu/sloan-auto-lab/research/beforeh2/files/IEEE-ISSST-cheah.pdf Cheah, Lynette, John Heywood, and Randolph Kirchain. "The energy impact of US passenger vehicle fuel economy standards." *Sustainable Systems and Technology (ISSST), 2010 IEEE International Symposium on*. IEEE, 2010.

[77] Center for Automotive Research. "Environmental Effects of Connected and Autonomous Vehicles," forthcoming cargoup.org. Austin Brown, Jeffrey Gonder, and Brittany Repac, "An Analysis of Possible Energy Impacts of Automated Vehicles," pp. 137-153 in *Road Vehicle Automation*. Gereon Meyer and Sven Beiker, editors. Springer International Publishing. 2014. https://link.springer.com/chapter/10.1007%2F978-3-319-05990-7_13

[78] Shelie A. Miller and Brent Heard. "The Environmental Impacts of Autonomous Vehicles Depends on Adoption Patterns." Center for Sustainable Systems, CSS16-43. 2016. http://css.umich.edu/publication/environmental-impacts-autonomous-vehicles-depends-adoption-patterns

[79] *The Economist*. "Why driverless cars may mean jams tomorrow." January 20, 2018. https://www.economist.com/news/finance-and-economics/21735019-they-will-spare-world-neither-traffic-congestion-nor-infrastructure-expense-why

> road-using activity. Where now a worker might pop into the coffee shop before going to work, for example, a latte might soon be delivered in a driverless vehicle.

As we note below, a study by Harb et al. finds this increase in vehicle miles travelled might be very large (more than 80 percent, in their estimate).[80] This "rebound effect" of increased demand for transportation is good news for employment but may well be bad news for the environment if policy does not incorporate the spillover costs of transportation (something mostly not included currently). *The Economist* suggests that might be possible:

> People seem not to object to paying by the mile when they are being driven—by taxis and services like Uber and Lyft—and the driverless programs now being tested by Waymo and GM follow this model. If a driverless world is one in which people generally buy rides rather than cars, then not only might fewer unnecessary journeys be made, but also political resistance to road-pricing could ease, and congestion with it.

On the other hand, reduced congestion and AVs' possibly greater ability to avoid accidents might increase the potential for greater highway speeds;[81] if so, there might be pressure to increase speed limits, which would lower fuel economy.

Changes in land use

Some argue that AV adoption will raise urban density because AVs can be packed together more tightly and shared vehicles need less urban space for parking. On the other hand, density might fall quite a lot, since travel time would personally tax the user much less since they could eat, read, sleep, etc. while they travelled and, perhaps, travel at much higher speeds. So people might choose to build large houses that consume more energy (and produce more greenhouse gases) in distant ex-urban areas if these costs are not properly internalized via a carbon tax or other means.

We have seen this scenario play out before: the development of the interstate highway system facilitated tremendous growth in economic activity occurring over larger distances but also led to a great deal of flight from cities, with deeply negative implications for the environment, income distribution, race relations, etc.[82] Thus, while AV has clear potential benefits for workers through its impact on the environment, it is far from certain how this will play out.

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[80] Mustapha Harb, Yu Xiao, Giovanni Circella, Patricia L. Mokhtarian, and Joan L. Walker. "Projecting Travelers into a World of Self-Driving Vehicles: Estimating Travel Behavior Implications Via a Naturalistic Experiment." Working paper. November 15, 2017. Presented at the Transportation Research Board 97th Annual Meeting (January, 2018). http://www.joanwalker.com/uploads/3/6/9/5/3695513/harb_et_al_chauffeur_-_nov_2017_working_paper.pdf

[81] Austin Brown, Jeffrey Gonder, and Brittany Repac. "An Analysis of Possible Energy Impacts of Automated Vehicles," pp. 137-153 in *Road Vehicle Automation*. Gereon Meyer and Sven Beiker, editors. Springer International Publishing. 2014. https://link.springer.com/chapter/10.1007%2F978-3-319-05990-7_13

[82] See for example, Myron Orfield. *Metropolitics: A Regional Agenda for Community and Stability.* Brookings. 1997. https://www.brookings.edu/book/metropolitics/

iii. Productivity

Two key factors for workers' overall wellbeing are their individual productivity and that of the nation as a whole. Compensation and national wealth depend on both. AV has large potential benefits for both. Calculating the impact of AVs on productivity, and hence on GDP, faces many sources of uncertainty so the points made here are tentative of necessity.

Many potential benefits from AV derive from relieving people of the burden of driving while they travel. According to the AAA American Driving Survey, Americans spend about 293 hours per year driving.[83] The report says:

> On average, drivers reported making 2.2 driving trips per day, spending 50.6 minutes on the road and driving 31.5 miles. Projecting these results to all drivers nationwide, U.S. drivers made an estimated total of 186 billion driving trips, spent 70 billion hours driving and drove 2.62 trillion miles in 2016.

This is about 5 percent of Americans' waking time (assuming 7 hours of sleep). Assuming that the large amount of time now spent driving is not productive (especially in increasing GDP), AVs offer the possibility that some of this time would be converted to productive uses as people become riders.

AVs will soon, if not immediately, have Wi-Fi connections to the Internet. In order to support a system of AVs, Wi-Fi infrastructure will be extended and strengthened so that AV occupancy will be a reliable source of a fast Wi-Fi connection. Moreover, this is likely to be a free Wi-Fi connection. While it is conceivable that AV fleets could charge occupants for Wi-Fi, as airlines now do, this is unlikely since the actual incremental cost of providing access is near zero and free Wi-Fi is becoming increasingly common, e.g. in hotels, convention centers, and any place where people have discretionary time for communicating, shopping, etc. To the extent that access to AVs, either private or in fleets, is widespread – with public policy that is attentive to avoiding discrimination in such access on either income or locational grounds—AVs may provide an opportunity for reducing the so-called "digital divide," much like a public library. (Conversely if access to AVs is affected by racial or economic class discrimination, this will perpetuate stratified access to the Internet.)

Just as Internet use at work for personal purposes has cut into productivity, there is no guarantee that more ubiquitous Internet access during commuting—a time period now regarded as "personal time"—will be used for GDP-enhancing productivity-boosting tasks. However, by giving individuals more flexibility in when and where they accomplish both work and personal tasks requiring an Internet connection, productivity as well as personal welfare is likely to be enhanced. Consistent with the popular idea of AVs as a potential "office on wheels," the interior of a typical privately-owned AV could be equipped relatively easily with the technological tools needed for work tasks, including video and audio functionality for conferencing, easy-to-read screens and

[83] B. C. Tefft. "American Driving Survey: 2015- 2016." (Research Brief). AAA Foundation for Traffic Safety. January 2018. https://aaafoundation.org/wp-content/uploads/2018/02/18-0019_AAAFTS-ADS-Research-Brief.pdf

keyboards, etc. This scenario would be far more productivity-friendly than, for example, working on one's mobile phone while on the bus or subway.

Ride-sharing provided by AV fleets offers other opportunities for either productivity or welfare-advancing changes. The economics of ride-sharing presume much lower cost for all occupants in return for a somewhat longer ride controlled by the routing algorithms of the ride-share provider. During that longer time period, one is joined by an unpredictable mix of other riders. (It is interesting to speculate on whether individuals with predictable routes and schedules would end up being assigned to the same ride-share AV day after day. Might some ride-share providers offer customers the opportunity to express such "AV-mate" preferences for a small price premium?) Any given set of riders might be homogeneous on certain dimensions, i.e., income and lifestyle preferences based on all living in the same micro-neighborhood, yet heterogeneous on other dimensions, i.e., people using ride-share for last-miles commuting to the same work location, having arrived at the ride-share departure point by varied transportation options, could hold a wide array of different jobs in terms of organizational position, skill set, salary/wages. If ride-sharing norms evolve to encourage verbal communication, AVs might provide opportunity for interaction among citizens that now rarely happens. (Even when buses and subways offer such opportunities, they are mass modes of transportation, often with crowding and background noise that discourages interpersonal interaction.) Conversely, if AVs are great places to get Wi-Fi access, they could simply be places where individuals are in close physical proximity but otherwise separate due to immersion in their digital devices, as now happens in many coffee shops with free Wi-Fi. Interpersonal interaction can, of course, have either networking or knowledge-transfer benefits that could ultimately contribute to productivity enhancement or could be consumed as personal experience, for better or worse.

The main benefits of AV-based fleet services over current car- or ride-sharing arrangements are likely to be low cost, ubiquity, flexibility in scheduling, and flexibility in routing. In contrast, car-pooling arrangements among employees at the same workplace who work the same schedule have proven difficult to sustain given inflexibility and/or costliness (in terms of inconvenience or time spent waiting) on one or all of these dimensions.

These benefits are likely to be magnified as they help non-transportation sectors become more productive also. Traditional productivity analysis considers the impact of productivity gains in different sectors of the economy. For example, we know from Domar and Hulten that the first-order aggregate effect of productivity gains in a sector equal the ratio of that sector's gross output to value added (i.e., its Domar weight).[84] Among major sectors (NAICS 2-digit, from the BEA industry accounts), transportation and warehousing have the third-largest gross output/value added ratio (1.9 in 2016; manufacturing is the highest at 2.6, and agriculture and forestry, etc. is second at 2.4). That means AV productivity gains will really "punch above their weight" in terms of aggregate impact. Of course, the employment implications of these knock-on productivity effects will depend on factor substitution and demand elasticities.

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[84] Evsey D. Domar. "On the Measurement of Technological Change." *Economic Journal* 71 (1961): 709-29. And Charles R. Hulten. "Growth accounting with intermediate inputs." *Review of Economic Studies*, 45:3 (1978), 511-518. https://academic.oup.com/restud/article-abstract/45/3/511/1573872?redirectedFrom=PDF

The many channels described above, combined, suggest a broad potential for raising productivity and wellbeing of workers. And, when it makes transportation more productive, it has large ripple effects across other sectors of the economy. Thus, the potential of AVs to make the proverbial "pie" larger suggests that there are resources that can be tapped to ease transitions for displaced workers and their communities.

C. The pace of change: accelerators and brakes

In order to produce the simulations, we make some strong assumptions that are subject to large degrees of uncertainty. These could speed or slow the pace of AV adoption or of subsequent job creation and impact safety, environment, and productivity outcomes. These include:

- Speed of adoption: As can be seen from the comparison of the two trucking scenarios, a rapid shift to AV, as compared to a slow pace, may cause more total disruption with fewer effective policy remedies. We believe it is important to keep separate the longer-term trends affecting mobility of people and goods from the shorter-term fits and starts that will accompany a period of transition. A long-term trend that favorably portends the many benefits we see from AVs is not necessarily threatened by factors that throw up short-term barriers or delays in implementation. Indeed, as we argue, a slower pace of change allows for better planned (and funded) mitigation strategies and more adjustment through attrition. Hence, a slower pace means less dislocation vis-à-vis jobs, earnings, labor force participation, and skills.
- Types of technology adopted: If Level 4 automation (no steering wheel or other controls for a human driver) prevails, the impact on driving jobs will be higher than if Level 2 or 3 automation (in which a human remains responsible for some driving tasks) dominate. Some firms, led by Waymo (now owned by Google's Alphabet), have announced that they see Level 3 autonomy as an infeasible engineering solution; Waymo abandoned Level 3 testing after seeing videos of its engineers falling asleep while monitoring a vehicle set to full autonomy.[85] Waymo saw the difficulty in safely handing control of the vehicle back and forth between algorithms and the human driver: individuals who grow habituated to autonomous controls will need a lot of time to shift their attention to a suddenly-urgent driving situation, apprehend what is going on, and make the right driving choices. Level 3 automation does require a human driver and would therefore have less impact on employment in driving jobs. Level 4 automation is more technically difficult to achieve across all driving situations and thus might be implemented more slowly.
- Modes of personal mobility adopted: Widespread individual ownership of AVs will have different consequences than fleets of AVs offering ride-hailing services to individuals who no longer own vehicles. This difference is partially anticipated in the two different scenarios for passenger vehicles ("Cars-Personal" vs. "Cars-Fleet"). Which of these modes

[85] James Ayre. "Google/Waymo Stopped Testing Level 3 Self-Driving Tech After Testers Literally Fell Asleep While Using It, Switched To Full Autonomy." *CleanTechnica*. November 1, 2017. https://cleantechnica.com/2017/11/01/googlewaymo-stopped-testing-level-3-self-driving-tech-testers-literally-fell-asleep-using-switched-full-autonomy/

will dominate will depend on many things, including 1) urban vs. rural/suburban location (since fleets will make economic sense first in cities); 2) the cost of purchasing and maintaining an individually-owned AV relative to conventional vehicle prices and ownership costs; 3) the ubiquity and convenience of ride-hailing options versus an underutilized-but-always available vehicle provided by personal ownership;[86] and 4) the cost (in money and time) of ride-hailing services based on either one customer per ride (more expensive and could boost congestion, increase, fuel use and pollution, and lengthen rides) or multiple customers pooled per ride (cheaper but possibly avoided by those who place a high premium on their time given the potential delay of multiple drop-offs).

- Price sensitivity of demand for package delivery and distribution mode adopted: Uber researchers predict a very strong increase in demand for package delivery in response to declining transportation costs. They also predict slow adoption of AVs for local trucking. So, they offer a simulation that delivers an increase in the number of truck drivers after AV adoption, with most truck drivers working strictly locally. The quality of those jobs would also depend crucially on whether the workers are paid as contractors (per mile, which returns a low hourly rate without benefits) or as employees (per hour with benefits).
- Public sentiment for a "human in the loop" as a "moral crumple zone"[87]: The availability of a technological capability does not, in and of itself, mean that it will be implemented. The autopilot example for commercial aviation reveals the power of a societal expectation of having a pilot present for responsibility and liability, regardless of the extent to which automation could replace the pilot's direct tasks of flying the aircraft. We could find that a similar sentiment will affect the progress of autonomous technology in large trucking applications. Platooning in commercial trucking, in which hardware/software integration and cloud-based monitoring allows a group of trucks to travel with minimal spacing among them, has major aerodynamic benefits with fuel savings sufficient to justify the capital investment needed to outfit trucks. While platooning could potentially replace drivers altogether, it could also coexist with Level 3 automation to support a continued driver role, albeit with the driver able to do a variety of other job-related tasks related to logistics, future planning, and reporting on current activities. Both the public and regulators will likely decide on the "moral crumple zone" policy of mandating that driver role even if it could hypothetically be eliminated.
- Phase of the business cycle: Laid off workers are jobless for longer and suffer more wage loss during recessions than during booms with the difference in earnings losses

[86] Personal vehicles are also quite often specialized to meet the needs or desires of the owner. For example a personal vehicle might be purchased that is capable of carrying large amounts of work tools, building materials, debris, or other items; of hauling a large boat, jet ski, snowmobile, camper, horse trailer, etc.; of tackling rough, mountainous, or snowy roads; or even of bushwhacking off-road.

[87] Madeleine Clare Elish. "Moral Crumple Zones: Cautionary Tales in Human-Robot Interaction." We Robot Working Paper, 2016. Data and Society Research Institute. http://robots.law.miami.edu/2016/wp-content/uploads/2015/07/Elish_cautionary-tales_prelim_draft.pdf

documented by Davis and von Wachter[88] providing strong evidence. Recessions could also slow the adjustment to AV adoption. The economic history literature about the pace of technical change during recessions suggests it can be surprisingly high. Old capital often gets junked when firms go out of business. The surviving firms, when they expand, will typically buy the newest technology for an aggregate jump up in the overall level of technical capabilities. If the pace of these capital investments in AV is higher than the creation of other new jobs, which is likely if the new technologies are labor-saving, we could see an upward trend towards AV adoption during (and immediately after) a recession accompanied by a lingering dearth of job creation and skill retraining during that time.

- Environmental and other policies: Public policy will affect how AV is implemented and how the rest of the economy reacts. The levers at the disposal of policymakers, many of which we mention throughout this paper, include the level of gasoline taxes, congestion pricing, regulations imposed on AV operations, zoning restrictions, and safety and testing requirements for AV systems.

- Individuals' responses to new mobility options. The new transportation options made possible by AVs will affect behavior beyond the ones previously mentioned, such as package delivery and car versus fleet ownership. For example, a University of Michigan Transportation Research Institute study[89] predicts a drop in the number of vehicles owned per U.S. household from 2.1 (now) to 1.2 (a reduction of 43 percent) based on having an AV with 'return to home' capability, i.e., the AV takes a breadwinner to work and returns home to be available for other household members until a similarly 'driverless' day-end trip for the pick-up. However, if you combine this AV functionality with its impact on where people choose to live, the scenario could play out quite differently. Knowing that their commute can be automated, people could choose to live further away from their workplace in order to live in their "dream home" or "dream neighborhood." Imagine that the round trip in an AV to drop off the bread-winner would take 90 minutes to 3 hours; double that to pick the person up. (Note that this would also generate more congestion, miles traveled, fuel consumed, and pollution generated.) The amount of time that the AV would be back at home, available to others, would be relatively short and the AV might be unavailable at exactly the times (e.g. after school activities for kids) when it is needed on the home front. The family might decide that a second vehicle is still needed, preserving the two-car household mean. Similarly, Harb et al. found that people offered chauffeur services similar to what AVs could provide raised their vehicle miles travelled (VMT) by an

[88] Steven Davis and Till von Wachter. "Recessions and the Costs of Job Loss." *Brookings Papers on Economic Activity*, 2011 no. 2. https://www.brookings.edu/bpea-articles/recessions-and-the-costs-of-job-loss/

[89] Brandon Schoettle and Michael Sivak. "Potential Impact of Self-Driving Vehicles on Household Vehicle Demand and Usage," University of Michigan Transportation Research Institute, Report No. UMTRI-2015-3, February 2015. https://deepblue.lib.umich.edu/bitstream/handle/2027.42/110789/103157.pdf

average of 83 percent, with night-time, elderly, riderless and long-distance travel particularly increasing.[90]

D. Truck drivers–a thin-slice, near-term, systemic perspective

Thus far in this report, we have relied on scenarios for AV adoption in both cars and trucks that only show significant impact from 2030 to 2051. Furthermore, we have attempted to look broadly at the impact of AV technologies on all occupations that involve driving tasks, examining job loss, job creation and skill change. This reflects the charter we took on. However, we also think there is much to be learned by considering the near-term changes in specific occupations that AV technologies could bring.

In this section, we focus narrowly on the occupation of Heavy and Tractor Trailer Truck Drivers and the prospects for job loss and job change over the next 12 years. This covers the time up to 2030, when our scenarios predict an acceleration of adoption. We call this a thin-slice, near-term systemic perspective for three reasons.

- It is thin-slice because we focus on the particular subset of drivers who deliver goods and must have a special commercial driving license, weeks of training, and potentially months of driving experience in order to be fully capable of doing the job. Other delivery drivers primarily operate vans or cars that do not require special training or licenses to drive.
- It is near-term in order to easily illuminate the dynamics of change and range of uncertainty about which technological options and business models will come to dominate by looking at the present and the near-term future.
- It is systemic so that we can combine lessons from past technological change, prospects for direct job loss, opportunities for job creation or job content change, and a survey of the choices available to the stakeholders (firms, policy makers, and workers) all into an integrated analysis.

We do not claim that the situation of truck drivers will generalize to all other driving-related jobs. Truck driving as an occupation has a complex history and has undergone considerable change in the past 40-50 years. Its current status and future path are likely to be quite different from those of taxi or bus drivers; salespeople or visiting nurses who drive to get to customers; or the exploding number of employees and contractors devoted to last-mile (or last-block) deliveries to customers' homes or workplaces. Instead of generalities, we hope to convey both the complexity and the nuance of the intertwined changes in technology, firm strategy, regulatory environment, and behavior of the users of mobility services now looming large in the U.S. and many other economies around the world.

[90] Mustapha Harb, Yu Xiao, Y., Giovanni Circella, Patricia L. Mokhtarian, and Joan L. Walker. "Projecting Travelers into a World of Self-Driving Vehicles: Estimating Travel Behavior Implications Via a Naturalistic Experiment." Working paper. November 15, 2017. Presented at the Transportation Research Board 97th Annual Meeting (January, 2018). http://www.joanwalker.com/uploads/3/6/9/5/3695513/harb_et_al_chauffeur_-_nov_2017_working_paper.pdf

i. Why truck drivers?

The impact of AV technology on truck driving jobs has seized public attention—or at least the imagination of journalists and commentators who often focus on this particular occupation. The job of truck driver already has an outsized image in American culture, representing a certain combination of autonomy, skill, work that is free of restrictions (physical and social) but also solitary and far from home, and an independent thinker admired for practical wisdom. For many years, it was also likely to be a highly-paid, secure, and often unionized job. The current attributes, though, are quite different, featuring marginal and variable pay, uncertain schedules, and with little union coverage. Nonetheless, the nostalgic image still helps to attract newcomers to the occupation—and even to the far more precarious route of becoming an independent owner-operator.[91]

Our goal is less to provide a definitive forecast (were that even possible) than to convey a sense of the range of possibilities. The symbolism is powerful. The cowboy-like, frontier-pushing truck drivers of yore are to be displaced by automation, leaving no one at the wheel (and perhaps no steering wheel at all). The sense of loss will be felt by far more than the drivers themselves—although they will feel the consequences most acutely. And these job losses could exacerbate concerns among the individuals and communities already disadvantaged by contemporary trends in trade, economic development, and technology, with important implications for both politics and policy.

ii. Lessons from past technological disruptions

First, we offer a reminder that the mere existence of a feasible technological capability, adequately demonstrated and economically attractive to key players, is no guarantee that it will be implemented or that its use will diffuse broadly throughout the economy. We have already seen demonstrations of autonomous truck technology and we will see many more in the next several years. A successful demonstration is potentially effective in catching attention in order to educate the public, attract investors, reassure regulators, and send signals to both capital and labor markets. It is also, almost certainly, carefully constructed not just for learning but also for success in influencing various constituencies. Only broader usage—either testing on a much wider scale, as we are starting to see for self-driving cars, or active implementation of a specific business application—will provide the experience base that will shape longer-range diffusion patterns.

Second, we reiterate that no deterministic outcomes are the inevitable outcome of implementing a particular technology. The fact that autonomous technology can successfully perform all the driving tasks of a truck driver does not necessarily mean that all truck driver jobs will be eliminated. Truck drivers do more than drive; their non-driving tasks might be infeasible or too expensive to automate. AV trucks may need monitoring in ways that will require humans with truck driving experience to do the monitoring. Society—via governmental laws and regulations—has decided to insist on the presence of two airline pilots in all commercial flights, regardless of how much autopilot technology might be able to perform their piloting tasks. Following a similar "moral crumple zone" logic, society might require the presence of a responsible human to oversee the

[91] Steve Viscelli. *The Big Rig: Trucking and the Decline of the American Dream*. University of California Press. 2016. https://www.ucpress.edu/book.php?isbn=9780520278127

operation of heavy-duty trucks which, like automobiles, are fast-moving objects operating in public space that can injure, kill, and destroy property. Business decisions on how to divide up different elements of the transportation services provided by trucks may create new segments of the industry and hence different types of truck driver jobs (i.e., different jobs in which there is a new mix of driving and non-driving tasks for which humans are better suited or more economical than automation). Regulations can also shape the space in which those business decisions are made. The future for autonomous trucks—like all technological futures—will be chosen rather than preordained.

iii. How much direct job loss?

Addressing this question requires a multi-part analysis of the following:

- How many truck drivers are there?
- What are the job requirements of truck drivers?
- How many truck driver tasks are likely to be affected by AV technology?
- Where does AV technology replace vs. simply change the job of truck drivers?

How many truck drivers are there?

In the Standard Occupational Classification (SOC), truck drivers are included in a category called "driver/sales workers and truck drivers." Of the three occupational subcodes within this category, only one matches the truck driving work that requires a commercial driver's license: Heavy and Tractor-Trailer Truck Drivers. While all driving jobs are potentially affected by AV technology, here we focus on this subcode (SOC 53-5032), for which U.S. payroll employment in 2016 was 1.5 million, according to the American Community Survey (ACS). The average annual salary for these truck drivers in 2016 in the ACS was $44,000. This count includes self-employed owner-operators, a group that has been growing in recent years.

What are the job requirements of truck drivers?

Occupational requirements are defined by the amount of education or training required to gain access to the job and then the cognitive and physical demands of the tasks involved in the job. There are no specific educational requirements for truck driving and most drivers span a range from no degree to a high school diploma. Specific vocational preparation for truck drivers, based on the Occupational Requirements Survey (ORS), varies but Gittleman and Monaco report that the largest proportion of drivers fall in the "1-4 years" category, which included training, certificate and licenses, and past experience. They summarize other data on truck driver task requirements as being "…at the lower end of educational and cognitive requirements but on the high end of strength requirements, compared to all workers."[92] These tasks included both structured and unstructured contacts with individuals beyond regular working relationships (e.g. when making deliveries) and a mix of decision-making requirements from selecting among set options to assessing uncertain situations.

[92] Murray Gittleman and Kristen Monaco. "Truck Driving Jobs: Are They Headed for Rapid Elimination?" Bureau of Labor Statistics unpublished paper, October 2017.

How many truck driver tasks are likely to be affected by AV technology?

After analyzing ORS task lists, Gittleman and Monaco identify the following non-driving tasks: freight-handling, customer service, safety compliance, paperwork, and operating non-truck equipment.[93] While the lower-skill end of this range of tasks is potentially easier to automate, the key point here is that truck drivers do much more than drive and the AV technology only automates the driving tasks. Viscelli reports one estimate from a single trucking firm (JB Hunt) that its drivers spend roughly 50 percent of their work time driving.[94] Whether automation of the other tasks done by truck drivers is technologically feasible and economically attractive is a separate matter entirely.

Where does AV technology replace vs. simply change the duties of truck drivers?

While the common first reaction to the idea of AV technology is to imagine full replacement of drivers, the reality is that there is a range of automation available for driving tasks. In the multi-level categorization established by the Society of Automotive Engineers (SAE)[95] (see Table IV-2), Levels 1-3 still require a human driver. Levels 1-2 automation provides automated assist to humans who retain full driving responsibility. Level 3 automation envisions a transfer of driving responsibility back and forth between humans and AV technologies. Note that Level 3 automation could reduce the time spent on driving tasks but could still require one human driver per truck. (See below for coverage of platooning technologies, which could alter this equation). Level 4 is “no driver” but within a set of designated operating conditions that could include “geofencing” (operating only in geographies that are physically separate from other driving situations).

In summary, increased use of Levels 1-2 automation will likely not affect truck driver employment at all, although it could make certain driving tasks easier, safer, or less physically demanding. Level 3 automation will still require human drivers, in some number, with all necessary driving skills for those occasions when control is passed back to them. Only Level 4 automation fits the scenario of full displacement of humans from truck driving jobs. The most common (and likely to be first implemented) Level 4 scenario involves primarily highway miles interspersed with local travel to pick-up and delivery stations (often warehouses or distribution centers close to highway exits).

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[93] Murray Gittleman and Kristen Monaco. “Truck Driving Jobs: Are They Headed for Rapid Elimination?” Bureau of Labor Statistics unpublished paper, October 2017.

[94] Steve Viscelli. *The Big Rig: Trucking and the Decline of the American Dream*. University of California Press. 2016. https://www.ucpress.edu/book.php?isbn=9780520278127

[95] SAE Levels of Driving Automation, from Stanford Center for Internet and Society. http://cyberlaw.stanford.edu/blog/2013/12/sae-levels-driving-automation

TABLE IV-2: Summary of Levels of Driving Automation for On-Road Vehicles

Summary of Levels of Driving Automation for On-Road Vehicles

This table summarizes SAE International's levels of *driving* automation for on-road vehicles. Information Report J3016 provides full definitions for these levels and for the italicized terms used therein. The levels are descriptive rather than normative and technical rather than legal. Elements indicate minimum rather than maximum capabilities for each level. "System" refers to the driver assistance system, combination of driver assistance systems, or *automated driving system*, as appropriate.

The table also shows how SAE's levels definitively correspond to those developed by the Germany Federal Highway Research Institute (BASt) and approximately correspond to those described by the US National Highway Traffic Safety Administration (NHTSA) in its "Preliminary Statement of Policy Concerning Automated Vehicles" of May 30, 2013.

Level	Name	Narrative definition	Execution of steering and acceleration/ deceleration	Monitoring of driving environment	Fallback performance of *dynamic driving task*	System capability (*driving modes*)	BASt level	NHTSA level
***Human driver* monitors the driving environment**								
0	**No Automation**	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a	Driver only	0
1	**Driver Assistance**	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes	Assisted	1
2	**Partial Automation**	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes	Partially automated	2
***Automated driving system* ("system") monitors the driving environment**								
3	**Conditional Automation**	the *driving mode*-specific performance by an *automated driving system* of all aspects of the *dynamic driving task* with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes	Highly automated	3
4	**High Automation**	the *driving mode*-specific performance by an *automated driving system* of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes	Fully automated	3/4
5	**Full Automation**	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**	-	

cyberlaw.stanford.edu/loda

iv. Indirect effects of AV trucking technologies on job creation and new job content

As above, addressing this question requires a multi-part analysis:

- What technologies (including AV technology) are being applied to truck driving?
- Which sectors that utilize truck drivers will adopt AV technology first and most fully?
- How will the pace of adoption affect the current truck driver population?

What technologies (including AV technology) are being applied to truck driving?

Viscelli offers a detailed survey of different technologies that incorporate some degree of automation affecting truck driving, which we summarize briefly here.[96]

Adaptive cruise-control platooning uses currently available technology (a combination of hardware and software plus cloud-based connection to an external service provider) to place trucks very close to each other during highway operations. This has primarily aerodynamic benefits that save fuel, which (along with labor) is the highest input cost factor for trucking. Both the lead and trailing trucks gain fuel-savings, with greater savings for the trailing truck. While two-truck platooning is already being implemented by companies such as Peloton, this approach could hypothetically be extended to larger convoys. The approach pioneered by Peloton allows platooning between trucks of different ownership, as long as they are equipped with the appropriate hardware/software package. Peloton oversees the platoon pairings, allows driver overrides when conditions require, and divides the total fuel savings between the truck owners. Early reports from drivers are that being in a platoon requires close attention (lane positioning, at present, is still the responsibility of each driver) but is overall less tiring than being fully responsible for driving. *In this regard, platooning is essentially sophisticated Level 1 automation.*

Driver in the sleeper (aka autopilot) is at least a *Level 3 (and possibly Level 4) automation concept* that envisions the driver and AV algorithms trading driving responsibility over time. Level 3, as defined, foresees a technological solution that allows the driver to engage in other tasks. Eventually, these tasks might extend to sleeping in the sleeper, so that the driver could meet the requirements of Hours of Service (HOS) regulations while on the road. In this situation, the human driver would still be available for all non-driving tasks, could maintain control in any difficult driving situation, and potentially would be the one to choose when to switch to autopilot mode. Capacity utilization of the truck increases in this scenario, causing some to see this option as particularly attractive to owner-operators. The reality of truck routes, many of which are shorter than 500 miles, indicates that this scenario is better suited to short driver breaks, i.e. possibly for naps but not for the longer periods of time needed for restful sleep. There is also a presumption that periods designated for sleep would have few to no incidents requiring driver intervention, since the challenge of waking a sleeping driver in time to comprehend the driving situation and take control in a reasonable amount of time is considerable. Indeed, Google/Waymo's assessment that such Level 3 situations were "engineering infeasible" to automate is the reason for its strategic decision to focus exclusively on Level 4 automation in its passenger AVs.

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[96] Steve Viscelli. "Technology and the Future of Work: The Trucking Sector." Forthcoming from Labor Center, UC Berkeley and Working Partnerships USA, U. of California Press.

Exit-to-exit autonomous is a *Level 4 automation approach* that relies on AV control in the semi-geofenced conditions of interstate highway driving and then re-engages a human for all driving after exiting. This would require locations at interstate exits for these exchanges to take place; whether these would be provided by individual trucking companies, industry associations, or government (federal, state, or city) is unclear. This scenario is appealing to various actors for multiple reasons. AV trucks could be optimized for highway operation while vehicles for local deliveries could be smaller and optimized to the environment (whether dense city streets or sparse rural areas) in which final stage miles occur. Delivery scheduling and its variability would be concentrated in the non-AV local stage, making exit-to-exit scheduling simpler and more predictable. Jobs for human drivers would be more local, with drivers able to live at home and work normal-length shifts. In all likelihood, truck driver jobs would be fewer if this approach were widely implemented. But the jobs that remained could be more attractive in terms of working hours and conditions (i.e. able to be home) while being possibly less attractive in terms of pay and task demands (i.e. larger supply of local delivery drivers reducing wages, many short-distance deliveries with schedule pressure more stressful).

Drone operation after exit-to-exit autonomous is an extension of this concept in which a human operator with driving skills would guide the truck remotely after exiting the highway, from an operations center, to the point of final delivery. Starsky Technologies is the best-known company advocating this approach. This would employ fewer actual drivers but would potentially offer new jobs to experienced drivers in the remote operating centers. It is worth noting that: first, the AV requirements for the final miles to delivery are much more demanding; second, delivery vehicles other than heavy-duty tractor-trailers are better suited to those locations; and third, over time, training of remote operators who don't have much actual driving experience (beyond training or use of simulators) would be a challenge.

Both of these exit-to-exit autonomous scenarios at Level 4 automation, even in full implementation, do not fully eliminate truck driving jobs but do reduce the number of jobs and shift the skill requirements in ways that might not make them attractive or attainable to the truck drivers who would be displaced.

Human-drone platooning envisions a convoy of platooning trucks in which many are fully autonomous but the lead truck has a human driver who is responsible for monitoring and overseeing the convoy's overall behavior. This is an intersection of driver-assist platooning, which has no employment impact, and exit-to-exit autonomous, which has the largest potential employment impact. This might well require a staging area for assembling the multi-truck convoy in the best configuration. It is also a concept better suited to a single company's fleet of trucks, which would gain from convoy optimization, but would be more difficult to manage if the composition of trucks in the convoy was constantly shifting, in numbers, ownership, and/or vehicle/load type. The lead driver jobs would undoubtedly have higher skill requirements and might offer an appealing career path for drivers who had developed considerable experience with level 2 platooning automation. At present, it is less clear whether this model is sufficiently appealing as a business model to attract much investment, as it either requires high scale within a single fleet or a difficult set of coordination tasks for a third-party service provider.

Which sectors using truck drivers will adopt AV technology first and most fully?

A full typology of different types of trucking and how technologically feasible and economically attractive AV technology will be for each type is beyond the scope of this brief survey. Viscelli summarizes his analysis of this issue as follows: "The strongest case for adoption is in the dry and refrigerated truckload segments… It is unlikely that other segments will be easily transformed to adopt…" where the latter includes local deliveries, intermodal trips, and flatbed trucking.[97] Viscelli highlights the possible exception of port-originated hauling where large firms with fleets of trucks set up for exit-to-exit autonomous operation could compete to deliver freight that now travels primarily by rail. For our purposes, the key point here is that even the optimistic technology-based scenarios above only apply to certain segments of trucking, albeit the ones that are both most visible and most fully embody the archetypical truck driving job.

How will the pace of adoption affect the current truck driver population?

Beyond the current automation-based worries about job elimination, the most urgent issue highlighted about truck drivers at present is the current severe labor shortage. A February 2018 article ventures the opinion that: [98]

> …for a variety of reasons, it is truck drivers that represent the most worrisome constraint on U.S. economic growth at the moment. The trucking industry is unique because it's the lifeblood of moving goods around the country, representing 70 percent of the nation's freight volume by weight. Without enough trucks and drivers on the road, some combination of things is going to happen: Shipments will be delayed, and producers will have to pay higher prices to get goods to market.

Unlike other sectors that routinely complain of labor shortages, like construction (which added 200,000 jobs in 2017), trucking employment, based on BLS statistics, is unchanged since mid-2015. Public earnings announcements from companies that depend heavily on truck deliveries (e.g. Hershey, Clorox, Sysco) and are reporting substantial reductions in adjusted gross margins have led to sharp reductions in their share prices. The American Trucking Associations, representing trucking companies, says that the industry needs over 50,000 more drivers to meet rising demand, citing a study by DAT Solutions that just one truck-with-driver is available for every 12 loads needing to be shipped in early 2018, the lowest since 2005. [99]

Among the factors affecting the labor shortage, according to industry observers: aging of drivers, whose average age is now 55; limited success in recruiting women drivers given the away-from-home demands of the job and difficulties encountered in such a male-dominated profession; negative perceptions of the demands of the job that now overshadow its past appeal; new

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[97] Steve Viscelli. *The Big Rig: Trucking and the Decline of the American Dream*. University of California Press. 2016. https://www.ucpress.edu/book.php?isbn=9780520278127

[98] Conor Sen. "The U.S. Is Running Out of Truckers." *Bloomberg News*. February 9, 2018. https://www.bloomberg.com/view/articles/2018-02-09/the-u-s-is-running-out-of-truckers

[99] Samantha Raphelson. "Trucking Industry Struggles With Growing Driver Shortage." Here and Now, *National Public Radio*. January 9, 2018. https://www.npr.org/2018/01/09/576752327/trucking-industry-struggles-with-growing-driver-shortage

regulations mandating compliance with HOS requirements, using electronic logging devices, potentially reducing illegal driver overwork; and, as in so many jobs, stagnant wages. Furthermore, some see younger workers that might have considered truck driving in the past as likely to be discouraged by the anticipated job loss from automation. Other observers see high turnover among the younger workers recruited to truck driving training programs as the real problem, seeing a large gap between what recruits are promised in terms of pay and autonomy and the reality of the jobs they find, which often include many unpaid hours waiting to make deliveries in addition to the stress from being away from home, and the experience of being closely monitored while driving.[100] Indeed, one characteristic of a market where a set of employers have strong bargaining power (called a monopsony) is the persistence of stagnant wages accompanied by labor shortages. With increasing evidence of companies finally offering pay increases and signing bonuses, the immediate shortfall may decline but many of these factors are unlikely to change quickly.

Summary

The key implications of this mini case study of the near-term prospects for heavy-duty truck driving jobs for our broader analysis include:

- Truck driver jobs have already undergone a huge transition from good jobs to bad jobs over the past 40 years, for reasons that have nothing to do with automation.
- The current situation, with the combination of high turnover, stagnant wages, and labor shortages characteristic of a monopsony, is addressable either with better pay and working conditions or with larger investments in automation. We think the latter is more likely but the former would have more short-term potential for increasing the overall capacity of the trucking sector.
- AV options at Levels 1-2 automation supplement what human drivers do—or only partially replace them (Level 3). Hence the direct employment consequences of these technological features will be much less than a broad-brush assessment would indicate.
- Level 4 automation, which does eliminate drivers, is likely to be implemented in only some segments of heavy-duty trucking in the near term, further reducing the set of affected drivers. Gittleman and Monaco identify 310,000 drivers as the most likely to be affected by these AV technology plans.[101]

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[100] Ted Evanoff. "Trucking firms offer up to $8,000 bonus and other deals to lure drivers." *USA Today*. December 26, 2017, updated December 29, 2017. https://www.usatoday.com/story/money/business/2017/12/26/trucking-firms-offer-up-8-000-drivers-ease-shortage/981522001/ ; Steve Viscelli. *The Big Rig: Trucking and the Decline of the American Dream*. University of California Press. 2016. https://www.ucpress.edu/book.php?isbn=9780520278127

[101] Murray Gittleman and Kristen Monaco. "Truck Driving Jobs: Are They Headed for Rapid Elimination?" Bureau of Labor Statistics unpublished paper, October 2017.

- The new business models linked to Level 4 automation will require reorganization that includes a new approach to local deliveries in order to maximize the potential for eliminating jobs for the long-haul exit-to-exit interstate driving tasks.
- Implementation delays, such as technological difficulties to lower-than-expected economic gains (or higher-than-expected costs) and regulatory barriers, will further slow the employment impact.
- Given a current shortage in drivers and a high average age, the diffusion of job-displacing forms of AV technologies in trucking may result in many fewer layoffs/job eliminations than the most negative scenarios indicate. Viscelli sees job loss reaching a maximum of 200,000 drivers over the next 10-15 years, less than 10 percent of the current total.[102]
- Job creation possibilities are evident in the future AV scenarios, particularly from drone-type operation of trucks from remote centers and for lead drivers in a convoy of autonomous trucks. Furthermore, reduction from automation in the required hours of driving may change the mix of what a driver does. Without corresponding automation of the many non-driving tasks included in this occupation, much less full job displacement is likely.

Overall, for the truck driving jobs we consider here—which match what most people think of first for this occupation—the direct job loss and displacement consequences may be quite limited over the period up to 2030, where the AV diffusion rates in the technology scenarios in this broader report really ramp up.

However, truck driving is unlikely to ever again be the source of reliable middle-class jobs for relatively uneducated workers that it was for much of the second half of the 20th century. The best hope for a young-to-middle aged truck driver committed to this career for the long haul is likely going to be found in the "monitoring AV" jobs found either in the "drone operation after exit-to-exit autonomous" or "human-drone platooning" scenarios described above.

To the extent that employers design these jobs so that feedback from drivers/monitors is used to improve AV operation, then these workers may gain some bargaining power (and improvement will likely be faster.[103] How AVs are regulated will also affect labor market impacts. For example, will there be caps on the number of vehicles each remote operator is required to monitor? Will minimum levels of training be specified? Will human drivers be mandated until certain conditions, forcing use of Level 3 rather than Level 4 automation? These final points reinforce our initial statement that the future of autonomous trucking technologies will be designed and chosen, not pre-ordained by the capabilities of the technology proper.

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[102] Steve Viscelli. "Technology and the Future of Work: The Trucking Sector." Forthcoming from Labor Center, UC Berkeley and Working Partnerships USA, U. of California Press.

[103] Susan Helper, Raphael Martins, Robert Seamans. "Value Migration and Industry 4.0", presented to ASSA, 2018. https://www.aeaweb.org/conference/2018/preliminary/paper/H83bQK3y

V. Mitigating the Negative Effects: Recommendations and Future Research Agenda

A. A policy strategy to mitigate negative impacts

In short, AV technology offers large widespread potential economic gains, concentrated costs to some individuals and many possible routes of adoption. Put simply, since the faster the speed of adoption of AVs, the more severe the labor market disruption will likely be, society has three possible AV adoption routes:

1. Accept rapid adoption with substantial costs to workers, at the risk of social disruption and heightened public resistance for further technological change.
2. Impose a slow enough adoption that the current workforce system can handle the transition without high costs.
3. Pursue rapid adoption combined with policies to upgrade our ability to mitigate adjustment costs.

Under the assumption that Option 1 is least preferred and Option 2 is suboptimal, this section discusses the ability of the current workforce development system to mitigate the costs of a rapid adoption of AV, what is known about the effectiveness of mitigation programs and how stakeholders could craft a mitigation strategy on a scale larger than has ever been done before. While it is beyond the scope of this paper to recommend specific policy options from the many available, we outline essential elements of an effective overall strategy.

i. Goals of a policy strategy

Overall, the goal of an AV adoption mitigation strategy is to minimize adjustment costs for workers and their families and communities, that is, to provide the help needed to allow each affected worker to adjust to or move as quickly as possible to his or her most productive, highest wage new job opportunity.

To begin with, the strategy must take into account the issues raised above from previous technological transitions:

- Technology alone does not determine outcomes; policy and employer choices matter.
- Large, widespread impacts are anticipated.
- There is no certainty about timing, the workers and communities affected, or what new jobs will arise.
- Workers' needs vary and certain workers (late career, low education, rural, in particular geographic areas, with criminal records, etc.) will face particularly severe risks from job loss.
- Other transitions are ongoing, including additional applications of artificial intelligence (AI) and rising world trade.

These factors argue for an approach with certain key elements:

First, it needs to be large. We estimate significant impacts from the adoption of AV. The approach taken must be able to cope with those impacts as well as others that may occur at the same time, such as adoption of other applications of AI or changes in trade patterns. In addition, dynamic, free enterprise economies continually create and destroy jobs, imposing significant continual churn. Furthermore, some of the transition may well take place in the context of a recession, which would broaden impacts. Thus, any approach must be large.

Second, the approach must also have multiple treatments and be broad-based. Research shows that unemployed workers vary substantially in their needs and risks, so a single treatment (whether income support, job search assistance, retraining, etc.) is unlikely to be universally adequate. Separately, the approach must not narrowly target a specific population identified according to preset criteria, such as those that purport to determine the "real reason" for displacement. Narrow criteria will inevitably be imperfect; attempts to craft them will fall victim to false precision. Applying those imperfect guidelines will waste administrative resources and delay or deny coverage to people when they need it. For example, ongoing difficulties administering the Trade Adjustment Assistance (TAA) program, which seeks to aid workers affected by trade, illustrate the inherent difficulties in a narrowly targeted approach. Furthermore, we see no rationale for granting more assistance to workers displaced by AV than for some other reason, whether another adoption of AI or an unrelated business relocation or failure. Indeed, worker insecurity about technological change is unlikely to be alleviated by a narrow program that delays or rejects many applicants.

Third, to serve evolving employers and workers, the approach must be adaptable and encourage innovation. To achieve nimbleness, it must continually be informed by the best evidence to guide its decisions. The essential evidence comes in four key forms: (1) Both innovative and ongoing programs must be continually evaluated to help improve service delivery and ensure the best use of resources. (2) Open lines of communication with employers about their needs, perspectives, and plans are also essential. (3) Comprehensive labor market statistics are needed to identify emerging gaps and trends. And, (4) research studies are needed to investigate causes and consequences of labor market outcomes.

To summarize, these factors argue for a policy approach with the following features:

1. Enough capacity to handle multiple large scale disruptions, even during an economic downturn
2. Multiple treatments that can be tailored to workers' situations and risk as well as local conditions
3. Broad-based, rather than applying some criteria that determine the "real reason" for displacement
4. Engaged directly with employers
5. Able to innovate
6. Guided by evidence from program evaluations, robust labor market statistics, and research

ii. Current context

The mitigation strategy need not start from scratch. But neither is the current system likely to be adequate to mitigate the impacts of AV adoption. The U.S. already has a public workforce development system, a partnership among federal, state, and local governments that is charged with providing employment-related services to two customer groups: workers and employers. Through more than 2,000 local One-Stop Career Centers, the system operates a free labor exchange nationwide, offers job search and job matching services, and provides access to a range of services to improve the employability of Americans, including training.

The goal of the system is to help anyone find a job, especially the unemployed and underemployed, dislocated workers, and veterans. Employment services and job training are also provided to workers with disabilities, older workers, youth and other new workers entering the job market, and people lacking skills that employers in their community demand.

In addition, since its establishment by Congress in 1933, the workforce development system is regularly called upon to mobilize during economic recessions and in local areas where unemployment rates or economic dislocation is particularly high, to facilitate the processing of unemployment insurance claims, administer transitional or subsidized jobs when authorized, retrain workers whose regular occupations or industries have disappeared, and assist workers, communities, and regions affected by disasters. The most recent law, the 2014 Workplace Innovation and Opportunity Act (WIOA),[104] is administered by the U.S. Departments of Labor, Education and Health and Human Services and is intended:

> To amend the Workforce Investment Act of 1998 to strengthen the United States workforce development system through innovation in, and alignment and improvement of, employment, training, and education programs in the United States, and to promote individual and national economic growth, and for other purposes.

Operating in conjunction with the system, the U.S. Department of Labor's Unemployment Insurance (UI) program works with the states to provide unemployment benefits to eligible workers who become unemployed through no fault of their own, and meet certain other eligibility requirements.[105] This program provides displaced workers with temporary partial income replacement (usually 26 weeks maximum[106] with an intended average replacement rate of about

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[104] "Workforce Innovation and Opportunity Act," Public Law 113–128, 113th Congress, Government Printing Office, July 22, 2014. https://www.gpo.gov/fdsys/pkg/PLAW-113publ128/pdf/PLAW-113publ128.pdf U.S. Department of Labor, "The Workforce Innovation and Opportunity Act," website. https://www.doleta.gov/wioa/

[105] See a description of the UI program in Chad Stone and William Chen. "Introduction to Unemployment Insurance," Center on Budget and Policy Priorities (CBPP), July 30, 2014. https://www.cbpp.org/research/introduction-to-unemployment-insurance

[106] An extended benefit program (authorized through the Social Security Acts) may be triggered by the state unemployment rate. Congress has often passed temporary programs to extend benefits during recessions. This

50 percent) during job search. It also connects them with One-Stop Career Centers when they file a claim.

Another key input to the workforce development system is workforce information, such as statistics on wages, employment, and joblessness—levels and growth—by occupation, industry, and location. On a national level, three federal statistical agencies—the BLS, the National Center for Education Statistics, and the Census Bureau—as well as the U.S. Department of Labor's Employment and Training Administration (ETA) provide most of the information that state and local agencies use to guide their programs and plans. Some of this data is gathered (from administrative sources and surveys) by the states on behalf of the federal agencies.

Even with all its moving parts and the recent passage of WIOA, the current workforce development system has some serious limitations that are arguably not improving. As part of federal discretionary spending, employment and training and statistical budgets have been shrinking in recent years.[107] The cuts curtail coverage and needed modernization. Thus, fewer people can be served and the guidance they get is not as good as it could be. Furthermore, legal restrictions prevent BLS and DOL ongoing access to administrative wage and employment data from the Unemployment Insurance system. Such access could provide much more timely and detailed information to local workforce development agencies. Program evaluations would also be less expensive, more frequent, and more complete if they could count on access to administrative UI wage and education records.

Also, for a number of possible reasons, unemployed workers' receipt of Unemployment Insurance has been low in recent years. Eligibility rates have declined and, in addition, only about 63 percent of those eligible from 1989 to 2011 received UI benefits.[108] Thus, more unemployed workers and their families go without this income source during challenging times.

As evidence of these and other limitations of the system, measures of U.S. workers' insecurity have risen dramatically over the past several decades, even though incidence of job loss has not risen.[109] This suggests that workers increasingly fear the consequences of job loss. That is, they

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was done with the Temporary Extended Unemployment Compensation (TEUC) program in 2002-2003, which remained in force through June 2, 2010 and with the Extended Unemployment Compensation 2008 legislation.

[107] The proposed budget for "Training and Employment Services" in the Department of Labor for FY2018 is $2.1 million, down from $3.3 million in FY2017. The proposed budget for the Bureau of Labor Statistics (BLS) for FY2018 is $607,842, the same as FY2017. "FY 2018 Department of Labor Budget In Brief," p. 7 and 41. https://www.doleta.gov/budget/docs/FY_2018%20BIB_ETA%20Excerpts.pdf

[108] See Stephane Auray, David L. Fuller, and Damba Lkhagvasuren. "Unemployment Insurance Take-up Rates in an Equilibrium Search Model," Working Paper, February 2013. http://www.fullerecon.com/tupaper_2.pdf Also see Daniel P. McMurrer and Amy B. Chasanov "Trends in Unemployment Insurance Benefits," *Monthly Labor Review*, September 1995. https://www.bls.gov/opub/mlr/1995/09/art4full.pdf

[109] Jacob F. Kirkegaard. "Structural and Cyclical Trends in Net Employment over US Business Cycles, 1949-2009: Implications for the Next Recovery and Beyond." Peterson Institute for International Economics Working Paper No. 09-5. August 13, 2009. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=1448801; Alisha Coleman-Jensen, Christian Gregory, and Anita Singh, "Household Food Security in the United States in 2013." USDA-ERS Economic Research Report Number 173. October 26, 2015.

sense that despite the U.S. workforce development system and safety net, job loss would be very damaging for them. Such fears engender workers' understandable resistance to disruptive economic changes.

All the reasons above suggest strongly that the current workforce system alone will be inadequate to mitigate the labor market costs of a rapid adoption of AV. The system is not adequate now to allay workers' rising anxiety and this system is shrinking.

iii. Information needed for effective evidence-based mitigation policies

Regardless of the policy route taken, it is essential to have accurate and timely labor market information, research, and program evaluation in order to ensure policy effectiveness.

For this reason, we recommend that the U.S. increase its capability in workforce research, evaluation, and official statistics. Fortunately, recommendations by the recent Ryan-Murray Commission on Evidence-Based Policymaking (CEP) point the way for the federal government to better harness administrative data for many uses, including workforce development.[110] The CEP included academic researchers, privacy experts, and program administrators. A concerted effort to support enactment of the CEP recommendations would be an essential step for a strong mitigation policy.

For workforce information purposes, at least three other information enhancements are important. First, though the CEP recommends allowing statistical agencies and program evaluators to access UI wage records—which would be very helpful—it would be even more valuable if UI wage records were enhanced by the addition of just two fields: occupational title and hours worked. These days, most employers have this information already in their automated payroll systems so it is no longer a burden on employers as it once was. BLS can use AI techniques it has already developed to convert job titles to Standard Occupational Classifications efficiently. BLS is currently working with several states, some of which have hours and occupation information, to explore the feasibility of this enhancement. With those data, BLS could redesign a number of its programs to reduce dependence on burdensome surveys.

Second, the U.S. lacks gold-standard data on employer-provided training. We do not know how much training, of what type, is provided by employers and to whom, and who (worker, employer, nonprofit or government) pays for what. The last such data (collected in 1995) showed that large, high-performance, or unionized employers provided more worker training than others.[111] Nearly half of all establishments provided formal job skills training in 1993, while orientation, safety and health, and workplace-related training were provided by 1 in 3 establishments. The three types of job skills most commonly taught through formal training were sales and customer relations, management skills, and computer skills. While about 1 in 4 establishments provided training in these areas, 1 in 12 provided formal training in food, cleaning, protective, and personal services.

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https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2504067; Hacker, Jacob S. *The great risk shift: The new economic insecurity and the decline of the American dream*. Oxford University Press, 2008.

110 See Commission on Evidence-Based Policymaking, "The Promise of Evidence-Based Policymaking: Report of the Commission on Evidence-Based Policymaking," September 2017. https://www.cep.gov/cep-final-report.html

111 See the results from the 1993 and 1995 Surveys of Employer Provided Training: https://www.bls.gov/ept/

These findings point to potential gaps in the types of training available to displaced workers seeking a new career path. Any effective comprehensive workforce strategy requires information about the training activities of employers to round out the information collected from the educational system and workforce training providers.

Third, to more closely track employer needs and activities, BLS is developing the capacity to conduct quick-response one-off surveys. These are key to improving the responsiveness of policy initiatives to fast-developing national, local or sectoral situations. In order to guide resource allocation efficiently, these data must meet a high standard for accuracy and detail.

Fourth, labor market policies should always include a commitment to ongoing evaluation. All too often, policies and programs are implemented without a plan for ongoing evaluation to help determine their effectiveness and inform improvements. Evaluations can be seen by administrators and appropriators as too expensive, disruptive, and slow when needs are great and resources are scarce. Such an approach is certainly short-sighted and undermines efficient use of resources. Moreover, development of administrative data to support program evaluations from their inception can make evaluations cheaper, less disruptive, and faster. For example, the recent Commission on Evidence-based Policymaking recommends that administrative data from federally supported programs always be supplied to the federal government so that it can be used for program evaluations unless there are compelling privacy or legal restrictions that prevent it.

iv. Major policy options

So how can the existing workforce development system and safety net be improved and supplemented so it can handle the challenges of AV and other major transitions?

While it is beyond the scope of this paper to recommend funding mechanisms for the options discussed below, we note that the benefits of AV adoption to the U.S. economy are likely quite substantial, over $1 trillion annually by one estimate.[112] With benefits of this magnitude, diverting some portion to mitigate transition costs appears to be feasible and appropriate, and may indeed be necessary to promote acceptance of further innovations.

As a foundational element of a policy response, we strongly recommend the development of a forum where employers adopting AV and other stakeholders take responsibility to engage with and prepare the workforce development system for upcoming disruptions from AV. The most direct way to begin this engagement would be through the Workforce Information Advisory Council (WIAC). To help administer WIOA, the legislation established WIAC, whose membership consists of workforce and labor market information experts representing a broad range of national, state, and local data and information users and producers.[113] The purpose of the WIAC is to provide recommendations to the Secretary of Labor, working jointly through the Assistant

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[112] Robert Atkinson. "The Coming Transportation Revolution," *Milken Institute Review*. 4th Quarter 2014. https://itif.org/publications/2014/10/17/coming-transportation-revolution

[113] See "Workforce Information Advisory Council Charter," https://www.doleta.gov/wioa/wiac/pdf/WIAC_Charter.pdf and the WIAC webpage https://www.doleta.gov/wioa/wiac/.

Secretary for Employment and Training and the Commissioner of Labor Statistics on information needs and coordination opportunities.

Engaging with a high-level forum, such as WIAC, to help the workforce system to prepare for AV would include

- Educating stakeholders early on trends,
- Connecting affected employers with local workforce system agencies, and
- Advising on information needs to best monitor labor market impacts of AV.

Two related key entrees for more such discussions are the Department of Labor's Employment and Training Administration (ETA), community colleges, and the National Association of State Workforce Agencies (NASWA).[114]

But that is just the easy part. As noted above, WIOA alone is unlikely to achieve the degree of mitigation needed. In recognition of the upcoming challenges, a number of major proposals have been advanced, including:

- Works councils
- Worker training accounts
- Wage insurance
- Public sector employment for infrastructure
- Universal basic income
- Flexicurity (an extensive four-part program)
- Place-based policy; enhanced local economic development

Table V-1 describes these main contenders briefly, with links to further information. They vary substantially in key ways, including who or what they target, what is the nature of the treatment, and which stage of the transition they address.

[114] See Department of Labor's Employment and Training Administration (ETA) https://www.doleta.gov/eta_default.cfm and National Association of State Workforce Agencies (NASWA) http://www.naswa.org/.

TABLE V-1: Sample of Major Policy Proposals to Mitigate Adjustment Costs

Name of Policy	Proposed By or Reference	Concept	Implementation Examples
Works Councils	https://en.wikipedia.org/wiki/Works_council	Encourage or require employers to set up Works Councils of elected employees in companies above a specified size, to enhance workers' and community voices in employer decision-making. Such consultation can encourage and inform national and local employer actions to mitigate costs, such as retraining programs or alternative technology implementation strategies.	European Works Councils in Germany, UK, France, etc.
Worker Training Accounts	"New Deal for the 21st Century," by Edward Alden and Robert Litan, Council on Foreign Relations https://www.cfr.org/report/new-deal-twenty-first-century	Establish "Lifetime career loan accounts" for income-contingent repayable loans accessible to any employee at any point in their careers.	
Wage Insurance	"Wage insurance" by Robert Litan, https://www.brookings.edu/research/wage-insurance-a-potentially-bipartisan-way-to-help-the-middle-class/	Top up the earnings of those who lose their jobs and are forced to take new ones at significantly lower wages.	Provision in Trade Adjustment Assistance Act
Public Sector Employment for Infrastructure	"Marshall Plan for America," by Neera Tanden et al., Center for American Progress https://www.americanprogress.org/issues/economy/reports/2017/05/16/432499/toward-marshall-plan-america/	Create a large-scale, permanent program of public employment and infrastructure investment to increase jobs and wages for those without a college degree while providing needed services to lower-income households and cash-strapped state and local governments. Some workers would be paid as "public apprentices," undergoing intensive, full-time training for in-demand occupations with guaranteed private-sector jobs upon successful completion.	Similar to the Works Progress Administration (WPA) during the Great Depression but modernized for the 21st century

Universal Basic Income	Many variants: basic income guarantee, Citizen's Income, unconditional basic income, or universal "demogrant." See overview in: https://en.wikipedia.org/wiki/Basic_income	Add a form of social security in which all citizens or residents receive a regular, unconditional sum of money from the government independent of any other income. Instead of having numerous welfare programs, it would simply be one universal unconditional income.	Permanent Fund of Alaska. Brazil's Bolsa Família program. US Negative Income Tax Experiments in the 1970s.
Flexicurity	https://en.wikipedia.org/wiki/Flexicurity	Establish integrated strategy to simultaneously enhance flexibility and security in the labor market, implemented across four policy components: 1) flexible and reliable contractual arrangements; 2) comprehensive lifelong learning strategies; 3) effective active labor market policies; and 4) modern social security systems providing adequate income support during employment transitions.	Denmark and various other parts of the European Union
Placed-based policy; Enhanced local economic development	Many variants. http://www.frbsf.org/economic-research/publications/economic-letter/2015/march/enterprise-zone-economic-incentive-tax-subsidy-place-based-policies/; and http://www.socsci.uci.edu/%7Edneumark/1-s2.0-B9780444595317000181-main.pdf ; https://www.brookings.edu/bpea-articles/saving-the-heartland-place-based-policies-in-21st-century-america/	Programs to improve entrepreneurship, develop local industries, attract new employers, subsidize work and upgrade infrastructure or residents' education that will bring more or higher wage jobs to areas with high unemployment.	State and federal Empowerment Zones; European Union Structural Funds; Industrial cluster policies; regionally augmented Earned Income Tax Credits; Kalamazoo Promise

Most are in place elsewhere or have been tried before so, some evidence on their effectiveness and costs are available. Boxes V-1, V-2 and V-3 summarize findings on the impact of previous implementations of mitigation programs. Despite widespread popular impressions that no programs work as intended, many programs actually have a demonstrable positive impact. And, with more innovation and evaluations, there is opportunity to improve on these outcomes.

Note that these policies need not be mutually exclusive. A combination is likely needed, given the breadth of impacts. Indeed, two of these approaches (flexicurity and place-based policy) consist themselves of combinations of programs.

While it is beyond the scope of this paper to recommend which policies should be pursued, we recommend that proponents of AVs engage private and public stakeholders in dialog to find a satisfactory way to mitigate the negative effects of disruption and displacement. These stakeholders include employers, unions, workers with disabilities, state and local agency officials, community colleges, and legislators at many levels.

Box V-1
Impacts of Job Training Programs

Heinrich, et al.[115] found:

> We estimate impacts on earnings and employment of the two primary adult workforce support and training programs under the U.S. Workforce Investment Act (WIA) using administrative data on 160,000 participants from 12 states for up to four years following program entry. We find that participants in the WIA Adult program, who typically enter with poor work histories, realize improved employment levels and increased average quarterly earnings of several hundred dollars. Earnings gains for Dislocated Worker program participants are appreciably smaller, although these participants do experience employment gains.

(Note from the authors: Many participants in the WIA Adult Program are displaced workers. If they are disadvantaged enough to qualify for the Adult Program, local administrators will often assign them there rather than to the Dislocated Worker program.)

From Congressional testimony about evaluations of workforce development programs:[116]

[115] Carolyn J. Heinrich, Peter R. Mueser, Kenneth R. Troske, Kyung-Seong Jeon, and Daver C. Kahvecioglu. "Do Public Employment and Training Programs Work?" *IZA Journal of Labor Economics* 2, no. 6 (October 2013). https://izajole.springeropen.com/articles/10.1186/2193-8997-2-6

[116] Demetra Smith Nightingale. Institute Fellow, Urban Institute. Statement before the Committee on Appropriations, Subcommittee on Labor, Health and Human Services, Education, and Related Agencies, United States House of Representatives. Hearing on "Preparing the Workforce." April 4, 2017. https://www.urban.org/sites/default/files/publication/89426/nightingale_-_testimony.pdf

Training connected to work has the most positive evidence. Not all training is the same, and not all training, whether public or private, is effective, but considerable evidence from evaluations over many years shows that the most effective type of job training is that which is connected directly to work, rather than "stand alone" training not aligned with jobs in demand. Several formal evaluations have found positive impacts on earnings and employment from work-based and work-integrated training models, including registered apprenticeships with particular employers, sectoral and industry-specific training, career pathways, and on-the-job training where a subsidy is offered to employers for a portion of wages for a set period (e.g., six or nine months). Findings from recent evaluations of integrated education and occupational instruction also show promise.

Counseling and customer-focused career services are important. Several different evaluations suggest that the types of intensive services offered in One-Stop Career Centers are important for job seekers and trainees. Veterans who receive assistance from specialized staff have better employment outcomes than veterans who receive general core services. Trainees who receive assistance in selecting their training do better than those who make their own choices without any career coaching. And interim results from the WIA Gold Standard evaluation find that individuals who have staff-supported services, such as workshops and counseling, available to them do better than those who have access to only basic self-service resources. Similar findings about the importance of student supports are coming from evaluations of community college programs.

Comprehensive and integrated models work for youth. Youth, especially those out of school and not working, are much more challenging to serve than adults. Fewer formal evaluations of job training for youth have been done than for adults. However, growing evidence indicates that the programs showing the most positive outcomes for youth have a comprehensive set of integrated services, including education, occupational training, counseling and support services. Residential models such as Job Corps and National Guard Youth Challenge have been found to increase employment outcomes...

Public investment in training fills a "gap." Most job training in the United States is provided by employers. Public funding on training comes mainly from the federal government, although some states invest considerable resources in training, usually in tandem with the federal funding. One Urban Institute study conducted several years ago, but that probably still holds true, estimated that the private sector spends two to three times as much as the public sector (federal and state combined) each year on training. Training at work is clearly important, especially for company-specific purposes. Surveys indicate, though, that employer-provided training is more likely to go to more-educated and higher-level workers. Higher educated and higher paid employees are twice as likely to receive employer-provided training as lower-level and less-educated workers. The 2016 Training Industry Report's recent survey suggests more than 60 percent of those receiving training by employers are executives, managers, and other "exempt" employees. The public workforce system's very limited funding only allows serving a small fraction of the 150 million or so workers in the nation. The public system also tends to serve smaller businesses and newer businesses by identifying available workers and training them, because many of those businesses do not have the resource levels that larger, established companies have. Thus, the public system is training workers who might not otherwise receive it—namely, those with middle and lower skills and wages, and providing training for businesses that might not have the resources to do it on their own. However, the system is constrained by very limited funding in reaching all workers and businesses that could use the services.

Box V-2
Impacts of Place-Based Policies

A recent Brookings paper[117] by Austin, Gleaser and Summers reviews the motivation for place-based policy and finds three plausible justifications for place-based policies: agglomeration economies, spatial equity, and larger marginal returns to targeting social distress in high distress areas. The second justification is stronger than the first and the third justification is stronger than the second. Strong tools, such as spatially targeted employment credits, may be needed in distressed locations. They find that increases in labor demand appear to have greater impacts on employment in areas where not working has been historically high.

Neumark and Simpson report:[118]

> Our overall view of the evidence is that *state enterprise zone programs* have generally not been effective at creating jobs. The jury is still out on federal programs—Empowerment Zones in particular—and we need more research to understand what features of enterprise zones help spur job creation. Moreover, even if there is job creation, it is hard to make the case that enterprise zones have furthered distributional goals of reducing poverty in the zones, and it is likely that

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[117] Benjamin Austin, Edward Glaeser, and Lawrence Summers. "Saving the Heartland: Place-Based Policies in 21st Century America." *Brookings Papers on Economic Activity*, Spring 2018 Edition. https://www.brookings.edu/bpea-articles/saving-the-heartland-place-based-policies-in-21st-century-america/

[118] David Neumark and Helen Simpson. "Do Place-Based Policies Matter?" *FRBSF Economic Letter* 2015-07. March 2, 2015. http://www.frbsf.org/economic-research/publications/economic-letter/2015/march/enterprise-zone-economic-incentive-tax-subsidy-place-based-policies/

For more details see: David Neumark and Helen Simpson. "Place-Based Policies," Chapter 18 in Gilles Duranton, J. Vernon Henderson, and William C. Strange, Eds. *Handbook of Regional and Urban Economics* 5. Amsterdam: Elsevier. 2015. PP. 1197-1287. http://www.socsci.uci.edu/~dneumark/1-s2.0-B9780444595317000181-main.pdf they have generated benefits for real estate owners, who are not the intended beneficiaries. …

... [S]tudies of *discretionary subsidies targeted to businesses in underperforming areas* in European countries and location-based subsidies in the United States… suggest positive effects on investment, employment, and productivity spillovers. The discretionary nature of these subsidies may help explain their success, because applications for subsidies pass through an initial scrutiny, and targeted outcomes can be monitored so that the payment of the subsidy is contingent on job or investment targets being met.

Evidence also suggests that *higher-education institutions* generate productivity spillovers that may be highly localized. Not surprisingly, these benefits are specific to industries with technological links to university research and that employ many university graduates. Some evidence finds that university research facilities attract high-tech, innovative firms to an area, which can help form industry clusters that may deliver longer-term benefits from agglomeration. Much of the evidence is from long-established universities, although research from Sweden points more directly to new universities increasing local labor productivity with benefits that do not appear to create negative effects in other regions.

Finally, analysis of the TVA program and EU Structural Funds indicates that *infrastructure investment* can deliver productivity growth in targeted regions, and can act as a redistributive tool across areas, although questions remain about how long these effects last.

The extensive research on place-based policies indicates that some types of well-designed policies can be effective, while other policies do not appear to be. Policies that subsidize businesses based solely on their location are hard to defend based on the research record. Place-based policies used in a more discretionary fashion seem to work better, perhaps because policymakers can target subsidies where they will do the most good and also hold recipients accountable. And place-based policies that generate public goods such as infrastructure and knowledge appear beneficial, perhaps because these goods are underprovided by the private sector.

But even among the more effective policies, exactly what makes them work is unclear. Past research can provide some guidance, but the lack of consistent evidence means that any such policies need to be continually monitored and evaluated to see whether they actually deliver their intended benefits.

Box V-3
Impacts of Works Councils

Works councils in Germany are correlated with a number of positive effects.

- They are associated with higher wages (above union levels).[119]
- Productivity is higher in companies with works councils.[120]
- They do not appear to reduce investment or innovation.[121]
- Disadvantaged workers benefit disproportionately from working in firms with works councils.[122]
- They are correlated with lower profitability (likely because of paying higher wages) and benefit larger companies more than small ones.[123]

B. Agenda for future research

One important goal of policy with respect to innovation is to achieve a balance between reflexively optimistic and reflexively pessimistic views generated purely from the predictions of what new technologies can do. The aim is for realism about the many factors that affect the use and diffusion of new technical capabilities.

As Section III-B shows, technological transitions can be costly when the new jobs arise too long after the old jobs disappear, appear elsewhere geographically, or require very different skills. Previous major transformations, including the recent introduction of trade with China, have occurred without coordinated engagement of stakeholders to mitigate damage to those left behind. As described in Appendix A, the uncompensated losses from transformations have damaged many lives, families, and communities and, thus helped breed resistance to change. Through research, advance planning, and stakeholder engagement, AVs offer an important opportunity to improve on the past.

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[119] John T. Addison, Paulino Teixeira, and Thomas Zwick. "German works councils and the anatomy of wages." *Industrial and Labor Relations Review* 63, no. 2 (2010): 247–270. http://journals.sagepub.com/doi/abs/10.1177/001979391006300204.

[120] Steffen Mueller. "Works councils and establishment productivity*." Industrial and Labor Relations Review*.65, no. 4 (2012): 880–898. http://journals.sagepub.com/doi/abs/10.1177/001979391206500405.

[121] John T. Addison, Thorsten Schank, Claus Schnabel, and Joachim Wagner. "Do Works Councils Inhibit Investment?" *Industrial and Labor Relations Review* 60, no. 2 (2007): 187–203. http://journals.sagepub.com/doi/abs/10.1177/001979390706000202;

John T. Addison, Claus Schnabel and Joachim Wagner. "Works councils in Germany: their effects on establishment performance." *Oxford Economic Papers* 53, no. 4 (October 2001): 659-694. https://academic.oup.com/oep/article-abstract/53/4/659/2361817

[122] John T. Addison, et al., "German works councils and the anatomy of wages." 2010.

[123] John T. Addison, et al., "Do Works Councils Inhibit Investment?" 2007.

The full impact of the adoption of AVs on the labor market extends well beyond the scope of this paper. Further research will need to grapple with the complexity of the topic, the early stages of transition, time constraints, and data limitations. Going forward, the targeting and effectiveness of cost mitigation efforts will be greatly aided by an ongoing program to track the transition and delve more definitively into particular topics. In this section we describe how to organize such a research agenda.

The research should have at least two important goals: informing mitigation efforts for AVs and providing a case study for the impact of other innovations. By supporting this research agenda, stakeholders can demonstrate their concern and build persuasive evidence to inform policy.

Topics for further work include the following:

1. Conduct industry-level input-output macro analysis to identify other jobs that may be affected by AVs: As a complement to the occupation-based analysis here, an industry-based analysis can track ripple effects through supply chains to identify additional affected sectors and occupations.

2. Estimate the impact of a driving requirement on wages: This estimate would improve precision of the wage impacts of AVs on displaced drivers.

3. Study where unemployed drivers find new jobs by industry and occupation, the duration of unemployment, and the wage change: Analysis of the career paths of former drivers would improve precision of unemployment impacts and inform the design of retraining programs. Although past career paths may not be indicative of a future career path after AV disruption, they are still a good starting point to think about policies to mitigate disruption.

4. Investigate productivity benefits from reducing driving time and increasing other work-related uses of time on the road, size, and incidence by occupation and industry: Sizing these productivity benefits will help identify other beneficiaries of the adoption of AVs.

5. Identify geographic areas and demographic groups at most risk: Refine estimates of the dependence of localities and demographic groups on jobs that are affected by AV to provide early warning to communities.

6. Compare outcomes for workers under different implementations of AVs.

7. Determine the labor market impact of alternative implementation options for AVs: Monitoring the choices and consequences as implementation proceeds will inform future decisions.

This list is far from exhaustive. Experience and engagement with the workforce development system, employers, policymakers, and the technical community (as recommended below) will help identify further important topics.

Ambitious research agendas need external support if they are to be timely, of high quality, and relevant to policy needs. Fortunately, there is already an impressive community of researchers studying the impact of automation and artificial intelligence on the U.S. economy. The best way to tap into these networks is to work with existing research centers at universities or highly regarded organizations such as the National Bureau of Economic Research, the Brookings Institution, or the American Enterprise Institute. AV stakeholders could provide funding for research conferences focused on topics of interest.

Another important step is to ensure that researchers have the data to allow the best possible analysis. To accomplish this we recommend convening research, practitioner, and statistical agency experts to discuss data needs and how to make that data available. It would be all the more useful if this were established in advance of changes. Then the transition could be well-monitored. Sources that can be tapped include government surveys (existing or performed on a reimbursable basis), private surveys (although these tend to have very low response rates), and private and public administrative data.

VI. Conclusion

Our simulations suggest that realizing the vast promise of AV technology will entail straining the U.S. labor market moderately as 1.3 to 2.3 million jobs are eliminated directly over a 30-year time span, depending on adoption scenarios. Although the short-term impacts may be modest, by the mid-2040s, AV adoption may cause the displacement of hundreds of thousands of U.S. workers. As the newly jobless search for work, unemployment rates will likely inch up for a time, starting in the 2030s, with a maximum impact in the mid-2040s of about 0.1 percentage points. Labor force participation will also tick down temporarily by similar numbers as AV-displaced workers spend more time out of the labor force altogether. Wage levels are also likely to change, though the direction is unclear and likely to be affected by policy choices.

U.S. manufacturing has lost 6.7 million jobs since its peak in 1978, or about 1.7 million jobs per decade. Our estimate that AV adoption will disrupt 1.3 to 2.3 million jobs over 30 years amounts to as much as 800,000 jobs per decade—half the size of the manufacturing job loss. Although these effects may be smaller and less geographically concentrated than the manufacturing job losses caused by increased trade with China, they are nevertheless consequential, particularly if incurred during an economic downturn, in already distressed areas, or in the context of job losses from other shocks.

The issue is not if new jobs will arise eventually in the wake of AV displacements (they most certainly will), but whether AV adoption will impose very high costs on displaced workers, and their families and communities. Our estimates suggest that each laid-off worker will lose on average about $80,000 in lifetime income due to the disruption. In addition, when driving is no longer a requirement, many other jobs will change substantially. In total, the jobs whose duties are very likely to change with AV employed 7.7 million people in 2016.

Since the faster the speed of adoption of AVs, the more severe the labor market disruption, Americans will choose whether to slow down adoption enough to avoid high costs to workers, to accept high costs with rapid adoption, or to pursue rapid adoption combined with policies to upgrade our ability to mitigate costs.

If we, as a country, choose to implement the latter, we must plan now so that the promise of AVs (cheaper and more efficient transportation, dramatic reduction in deaths and injuries from accidents, greater mobility for those who can't drive, freedom from tedium for those who can) either does not impose huge costs on those directly affected or compensates them for their loss. With the prospect of these substantial benefits and advance planning, the task is manageable. Indeed, if we are complacent and do not manage the transition well, we risk inviting more resistance to further innovation.

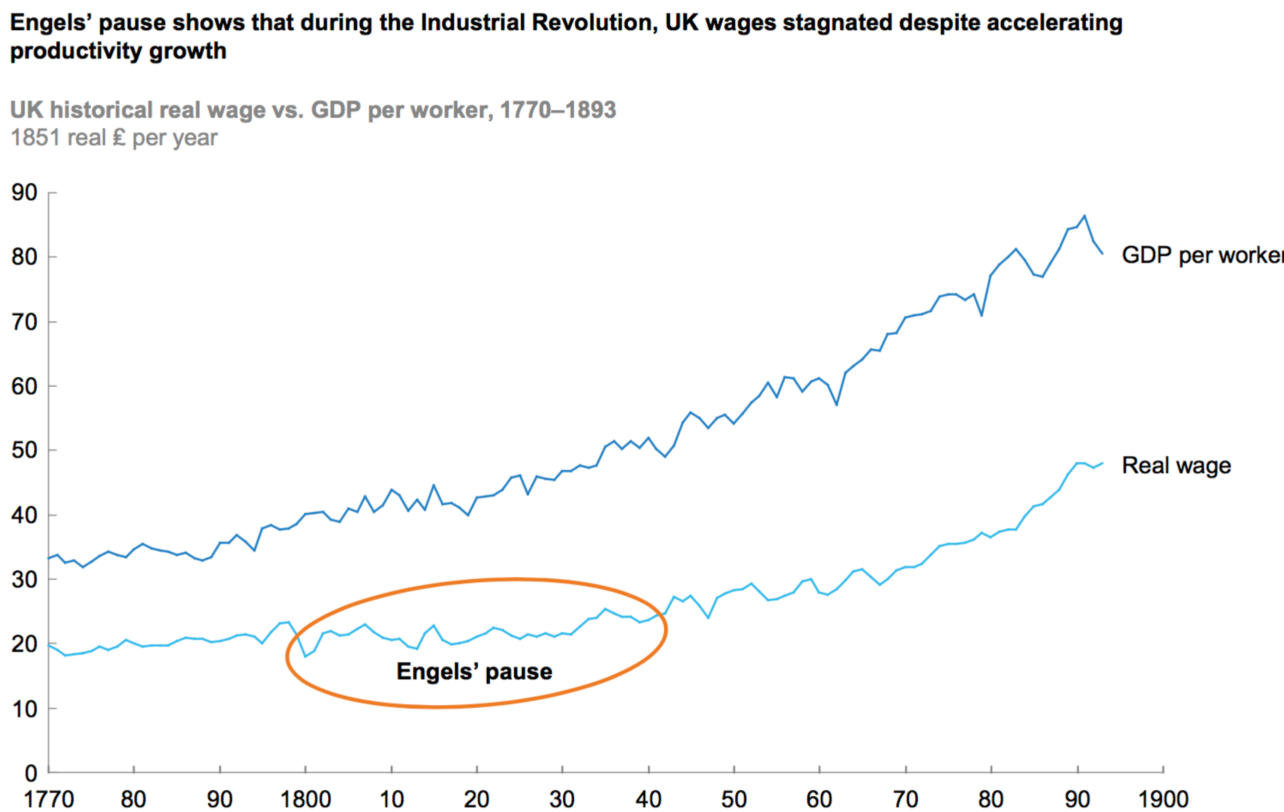
There is no dearth of broad and tailored policy proposals to meet these challenges. To manage policy choices, we offer guidelines for an effective overall strategy to mitigate costs to workers. The issue is whether policymakers and AV stakeholders have the will and foresight to take the needed steps. Going forward, we believe that adoption of a sound mitigation strategy must be recognized as an essential component of promoting adoption of any disruptive innovation in the U.S. There is still time for the transition to autonomous vehicles to help establish this new paradigm.

Appendix A. Case Studies of Economic Transitions

I. The Industrial Revolution

The Industrial Revolution began in England in the late 18th century. The mechanization of industries such as agriculture and weaving led to dramatic increases in output. However, wages stagnated for half a century, from about 1790-1840, and workers' living standards declined. The Enclosure Movement removed small farmers' and grazers' access to land, enabling agriculture to be mechanized on the resulting large holdings; the mechanization also reduced the skills needed for farming. Similarly, skilled hand-loom weavers were replaced by less skilled factory workers (including children), and the weavers' wages fell dramatically.

FIGURE A-1: Engel's Pause



SOURCE: Robert C. Allen, "Engels' pause: Technical change, capital accumulation, and inequality in the British industrial revolution," *Explorations in Economic History*, volume 46, issue 4, October 2009; McKinsey Global Institute analysis

Source: James Manyika, Susan Lund, Michael Chui, Jacques Bughin, Jonathan Woetzel, Parul Batra, Ryan Ko, and Saurabh Sanghvi. "Jobs Lost, Jobs Gained: Workforce Transition in a Time of Automation." McKinsey Global Institute. December 2017, p. 47. https://www.mckinsey.com/global-themes/future-of-organizations-and-work/what-the-future-of-work-will-mean-for-jobs-skills-and-wages

Eventually, wages did grow at a rate commensurate with (and sometimes exceeding) productivity growth, thus enabling workers to share in prosperity. But these changes did not occur automatically. As a recent McKinsey report notes, "The turnaround in the relationship between wages and output came at a time of substantial reform of existing structures including the right to unionize, limitations on child labor, the introduction of public high schools, urban planning to improve public health, elimination of debtors' prison, and the extension of the right to vote to landless workers."[124]

There is extensive research that shows that the average stature (height) of a population is directly related to its socio-economic level.

> Stature is a function of proximate determinants such as diet, disease, and work intensity during the growing years, and as such it is a measure of the consumption of basic necessities that incorporates demands placed on one's biological system. Because family income heavily influences purchases of basic necessities such as food and medical care, stature is ultimately a function of access to resources.[125]

Family income appears to have a strong direct influence on stature because higher income affords better nutrition, housing, and personal hygiene. Stature is also influenced by neighborhood and community effects related to income such as public health and sanitation measures and disease exposure, as well as by work intensity, which in turn, is determined by culture, technology, and methods of labor organization.

Reliable height data has been difficult to obtain for many reasons: sporadic and limited efforts to collect data, especially historically, focused selectivity in who was measured (mostly military recruits, convicts, and slaves), other selection biases of various kinds, minimum height cutoffs, age and height heaping, and ethnic differences in growth potential. Researchers have found ways to overcome these limitations by looking at a wide variety of populations, comparing datasets, and using various clever statistical techniques.[126]

Using stature measurements of English convicts shipped to Australia, who were broadly representative of the working class, Nicholas and Steckel found evidence that English workers experienced falling living standards during the early years of the British Industrial Revolution (roughly 1785-1820).[127] Comparing British workers in urban areas with rural British workers and with Irish workers who were not yet industrialized, the smaller average height of urban workers probably reflect worse health caused by living in substandard housing in an overcrowded disease environment.

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[124] James Manyika, Susan Lund, Michael Chui, Jacques Bughin, Jonathan Woetzel, Parul Batra, Ryan Ko, and Saurabh Sanghvi. "Jobs Lost, Jobs Gained: Workforce Transition in a Time of Automation." McKinsey Global Institute. December 2017, p. 47. https://www.mckinsey.com/global-themes/future-of-organizations-and-work/what-the-future-of-work-will-mean-for-jobs-skills-and-wages

[125] Richard H. Steckel. "Stature and the Standard of Living", *The Journal of Economic Literature* 33, no. 4 (December 1995): 1908. http://www.jstor.org/stable/2729317

[126] Roderick Floud, Kenneth Wachter, and Annabel Gregory. *Height, health and history: Nutritional status in the United Kingdom 1750-1 980*. Cambridge: Cambridge University Press. 1990.

[127] Stephen Nicholas and Richard H. Steckel. "Heights and Living Standards of English Workers During the Early Years of Industrialization, 1770-1815." *The Journal of Economic History* 51, no. 4 (December 1991): 937-957. http://www.jstor.org/stable/2123399

Steckel found that the height of northern European men decreased slightly during the 12th through 16th centuries and even more in the 17th and 18th centuries.[128] By the 1700s, northern European men had lost an average of two-and-a-half inches of height. Not until the early 1900s did they again stand as tall. There are several circumstances that may have caused this: the cooling climate trend from the 1300s to the 1800s (the Little Ice Age) probably made life harder for everyone; urbanization and the growth in trade encouraged the spread of disease; war and other political strife disrupted production and spread disease; and the growth of inequality likely increased stress and decreased nutrition for the lower classes.

Floud *et al.* found that "the early part of the industrial revolution led to an absolute as well as relative increase in the welfare and nutritional status of the working class, but … the impact of urban growth eroded that increase and even led to decreases in average height as large proportions of the working class were subjected to town life."[129]

Komlos found that average stature dropped in the United States for those born from 1830 to 1860—a time when per capita income rose by roughly 50 percent.[130] And in Europe, "The first decrease in physical stature occurred earlier in Europe, coinciding with the onset of the Industrial Revolution (c.1760 to 1800)." He argues that even though industrialization increased overall production, income tended to be more unevenly distributed with the small upper stratum remaining the same height while the much larger lower classes decreased in height. Also, technological change depressed the market value of skilled craftsmen and farmers leading to reductions for both of these groups. Economic growth also led to food losing value compared to industrial commodities which resulted in stagnant food production and lower class people substituting inexpensive starchy carbohydrates for protein rich meat.

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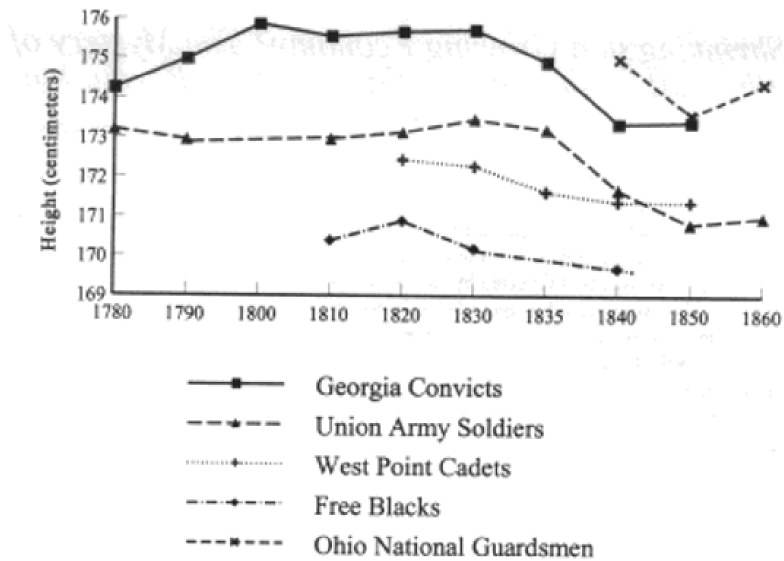
[128] Richard H. Steckel. "New Light on the 'Dark Ages': The Remarkably Tall Stature of Northern European Men during the Medieval Era." *Social Science History* 28, no. 3 (Summer 2004): 211-229. http://www.jstor.org/stable/40267840

[129] Roderick Floud, Kenneth Wachter, and Annabel Gregory. *Height, health and history*, p. 326.

[130] John Komlos. "Shrinking in a Growing Economy? The Mystery of Physical Stature during the Industrial Revolution." *The Journal of Economic History* 58, no. 3 (September 1998).

FIGURE A-2: Change in Average Height of Various Groups during the Industrial Revolution



Source: John Komlos. "Shrinking in a Growing Economy? The Mystery of Physical Stature during the Industrial Revolution." *The Journal of Economic History* 58, no. 3 (September 1998).
Data from: John Komlos, and Peter Coclanis. "On the Puzzling Cycle in the Biological Standard of Living: the Case of the Antebellum Georgia." *Explorations in Economic History* 34, no. 4 (1997): 433-59.
Dora L. Costa and Richard H. Steckel. "Long-Term Trends in Health, Welfare, and Economic Growth in the United States." In Richard H. Steckel and Roderick Floud, eds. *Health and Welfare during Industrialization*. Chicago: The University of Chicago Press, 1997: 47-91.
John Komlos. "The Height and Weight of West Point Cadets: Dietary Change in Antebellum America." *The Journal of Economic History* 47, no. 4 (1987): 897-927.
Komlos, John. "Toward an Anthropometric History of African-Americans: The Case of the Free Blacks in Antebellum Maryland." In *Strategic Factors in Nineteenth Century American Economic History. A Volume to Honor Robert W. Fogel*. Claudia Goldin and Hugh Rockoff, eds. 297-331. Chicago: The University of Chicago Press, 1992.
Richard Steckel and Donald R. Haurin. "Health and Nutrition in the American Midwest: Evidence from the Height of Ohio National Guardsmen, 1850-1910," In John Komlos, ed., *Stature, Living Standards, and Economic Development*. Chicago: The University of Chicago Press, 1994: 117-128.

Industrialization also meant that more people were detached from the land and more directly tied to the business cycle, so they suffered nutritionally during economic recessions such as the American contractions of 1837-43 and 1848-55. Additionally, poor people in urban areas were too far away from farms to get fresh milk and meat. "Furthermore, industrialization and its concomitant, the increased division of labor, in turn unleashed other processes, including the integration of hitherto isolated regions into a larger world market, that magnified their impact on nutritional status. … Yet, once able to sell their products easily, subsistence farmers, lacking full knowledge of the technology of health production, traded away proteins, minerals, and vitamins essential to the health and nutrition of their children. Although such producers gained from the transaction in monetary terms, their children became stunted (and less healthy) as a consequence."[131] Children working long hours in factories may also have needed more nutrition than their pre-industrial counterparts.

However, Bodenhorn, Guinnane, and Mroz argue that most of the studies relying on measurement of living people have selection bias that negates their value in explaining the "industrial puzzle."[132] They show that in countries where all or a random selection of men are conscripted and measured (such as the Netherlands, Italy, France, and Sweden), mean height grows monotonically throughout the 19th century. They argue those joining a volunteer army must have some incentive (such as inferior labor market opportunities) that is related to health/height. This self-selection bias (SSB) is responsible for the "industrialization puzzle" in studies relying on army measurements. They also argue there are similar selection problems for the slaves who were chosen to be measured.

Boix and Rosenbluth summarize what is now generally agreed about average human height over time:

> Both men and women were taller in pre-agrarian societies than in agrarian societies. In Paleolithic and Mesolithic sites, femur lengths seem to indicate a height around 175 cm for men and 165 cm for women. These values are in the range of average heights today. Pre-agrarian individuals were tall as a result of their abundant and diverse diet based on scores of plants and animal species, naturally related to the use of birth control strategies and low human population densities … By contrast, agriculturalists tended to rely on a single cereal stable—rice in Asia, wheat in temperate Asia and Europe, and maize in the Americas—supplemented with vegetables and, particularly among wealthy strata, some fish and meat …
>
> The economic transformation spurred by the industrial revolution had two consequences. In the short run, it led to a decline in average heights as rural dwellers moved to densely crowded, unhealthy urban centers. Transitionally, the opening of markets permitting sales of food for other goods might also have raised the price of food, reducing consumption. In the long run, however, growing per capita incomes and the improvement of public sanitation resulted in better

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131 John Komlos. "Shrinking in a Growing Economy? The Mystery of Physical Stature during the Industrial Revolution." *The Journal of Economic History* 58, no. 3 (September 1998).

132 Howard Bodenhorn, Timothy Guinnane, and Thomas Mroz. "Biased samples yield biased results: What historical heights can teach us about past living standards." *Vox*. July 22, 2015. http://voxeu.org/article/what-historical-heights-can-teach-us-about-past-living-standards; see also Howard Bodenhorn, Timothy Guinnane, and Thomas Mroz. "Problems of Sample-Selection Bias in the Historical Heights Literature: A Theoretical and Econometric Analysis." Yale Economics Department Working Paper No. 114, 2013. https://www.econstor.eu/bitstream/10419/98202/1/74682467X.pdf ; Yale University Economic Growth Center Discussion Paper No. 1023. May 5, 2013. https://ssrn.com/abstract=2261335 or http://dx.doi.org/10.2139/ssrn.2261335

nutrition and health conditions and, eventually, increased heights to the genetic potential—until increased income had no additional effect.[133]

II. Autopilot in aviation

The autopilot function in aviation has a long history, going back to 1914 when gyroscope technology was shown capable of keeping a plane's flight path stable even in the absence of an active pilot at the controls. After refinement, this autopilot technology was licensed for use in 1931; another advance came with the invention of an automatic landing system in 1935.[134] Hence an automatic control capability has been available in commercial aviation for many decades. Yet pilots still routinely staff all commercial airline flights. The minimum required staffing level for a flight crew has shifted down; it was once three (two pilots and a flight engineer) and now only the two pilots are required by FAA regulations. This status quo is, by most accounts, securely maintained under the current regulatory regime.[135]

Still, the public imagination continues to be seized by the idea of "planes without pilots." Pilotless military drones, guided from remote control centers, provide dramatic examples of the potential of automatic controls (although over 150 humans are involved in the average combat mission flown by a drone). In a recent survey, airline pilots reported spending only 4 to 7 minutes per flight in manual control mode. And NASA is investing heavily in a "safe autonomous system operations" project that could potentially remove the on-board co-pilot and substitute a remote ground controller who could serve as co-pilot for multiple flights. [136]

While not contradicting what autopilot technology is capable of doing, accounts from pilots reveal how misleading the "seven minutes of hands-on flying" statement is.[137] Pilots always have hands-on control during taxiing for takeoff and after landing, and they also make the choices among a set of operating parameters that go into a given autopilot configuration. In addition, pilots respond to queries and directives from air traffic controllers and, of course, take over in the case of extreme

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[133] Carles Boix, and Frances Rosenbluth. "Bones of Contention: The Political Economy of Height Inequality." *American Political Science Review* 108, no.1 (February 2014): 1-22. http://piketty.pse.ens.fr/files/BoixRosenbluth2014.pdf

[134] Steven J. Landry. "Human-Computer Interaction in Aerospace," in *Human-Computer Interaction: Designing for Diverse Users and Domains*, Andrew Sears & Julie A. Jacko (eds.), CRC Press, Boca Raton, FL, 2009, pp. 198-213.

[135] In the summer of 2016, National Transportation Safety Board Chairman Christopher Hart reiterated the necessity of human pilots, saying "[o]n the one hand, the human operator is the least predictable part of the system… But a highly trained, proficient human operator can save the day by being the most adaptive part of the system." https://www.c-span.org/video/?411934-1/ntsb-chair-christopher-hart-discusses-driving-cars

[136] John Markoff. "Planes Without Pilots," *New York Times*, April 6, 2015. https://www.nytimes.com/2015/04/07/science/planes-without-pilots.html ; Arnold Reiner, "Towards the End of Pilots." *The Atlantic*, March 3, 2016. https://www.theatlantic.com/technology/archive/2016/03/has-the-self-flying-plane-arrived/472005/

[137] Patrick Smith. "Cockpit Confidential: The Autopilot Myth," 2011, http://freakonomics.com/2011/12/12/cockpit-confidential-the-autopilot-myth/

weather conditions, equipment failures, and other emergencies. Indeed, in one view, pilots should increase their minutes of active flying to avoid the risk of seeing their skills diminished by too much reliance on autopilot.[138]

But perhaps the most important point about the continued presence of pilots in the cockpit is that they are there to reassure both passengers and the society at large that a responsible, competent professional is in charge and monitoring the technology for their safety. Legal philosophers and ethicists, observing this phenomenon, speak of the importance of having a "moral crumple zone" for certain activities that are dangerous and occur in public space.[139] Just as the crumple zone in an automobile provides protection for the occupant in the event of a crash, the presence of a pilot who is responsible for safety provides a kind of moral protection against anxieties that could otherwise render the aviation system less effective as a transportation service open to all. We might find that similar sentiments will preserve a driver role for autonomous trucks, perhaps particularly the big tractor-trailers that can pose such a danger in case of accidents, even when the technology is hypothetically able to function without any human intervention.

III. Computer numerical control of machine tools

Machine tools cut away metal to make a highly precise, durable component. Traditionally, machine tools were operated by highly skilled machinists, who determined how to make a component. The machinist decided what sequence of cuts a machine should make, decided which tools the machine should use (lathe, mill, drill, etc.), made fixtures to hold the part steady while it was being cut, and manipulated cranks and levers to determine the speed at which the machine operated and the speed at which a part was fed in.

From the 1950s to the 1970s, the U.S. Air Force subsidized development of automated machine tools. Initially, instructions were coded into tape guided machines ("numerical control"). In the 1970s and 1980s, firms introduced computer numerically controlled (CNC) machine tools that were programmed using a computer. In both cases, the goal was to enable complex products to be produced without companies needing to depend on skilled labor. The Air Force and defense contractors ended up with a highly abstract programming method which initially was quite complex, expensive, and fault-prone. They rejected a simpler technology, "record playback," which would have simply recorded the actions of skilled machinists to make a repeatable process. The result was a technology that after much tribulation could make more complex parts than even the most skilled machinist could make—but which continued to require the input of skilled technicians. The most effective operation of the technology involves both specialized programmers and skilled technicians on the shop floor who can modify programs to take into

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[138] Tim Harford. "Crash: How Computers Are Setting Us Up for Disaster," *The Guardian*. 2016. https://www.theguardian.com/technology/2016/oct/11/crash-how-computers-are-setting-us-up-disaster

[139] Madeleine Clare Elish. "Letting Autopilot Off the Hook," *Slate.* June 2016. http://www.slate.com/articles/technology/future_tense/2016/06/why_do_blame_humans_when_automation_fails.html

account ever-changing variables such as tool wear.[140] The goal of a “lights out factory” (one with no workers) remains elusive.

Introduction of the same type of automation equipment led to upskilling in some cases and deskilling in other places, depending upon characteristics of both product and labor markets. Once CNC had been adopted, rather than record playback, machinists in some plants gained computer programming skills while computers took over the direct determination of “feeds and speeds.” More often, however, machinists became less skilled, mostly watching for errors by the automated equipment while firms gave programming and problem-solving duties to engineers. The main result was that the jobs were separated; according to the U.S. Department of Labor’s Occupational Information Network (O*NET), two occupations are now involved with CNC machine tools.[141] The median wages of the 146,000 “Computer-Controlled Machine Tool Operators, Metal and Plastic” in 2016 were $18.21 per hour; these workers operate machines – the job description does not mention programming. Conversely, the job description for “Computer Numerically Controlled Machine Tool Programmers, Metal and Plastic” does not mention actually operating a machine; these workers (25,000 in 2016) earned a median wage of $24.32 annually. Finally, there is a “machinist” occupation, employing 396,000 workers, who earned an average of $20 per hour.

Thus, the introduction of computers in most cases led to a separation of operational and programming tasks and a reduction in wages and skills for the former. This separation was not inevitable in that a) machine tools could have been designed to be easier for machinists to program (the “record playback” option), albeit at a cost in the complexity of operations that the machine tool could perform, and b) machinists could have been asked to program as well as operate, a situation that does occur in a significant minority of cases according to Kelley. In both the cases studied by Kelley and by Noble, integration was associated with higher productivity. Noble argues that a desire to minimize worker bargaining power led management to choose the less-productive path.

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[140] David Noble. “Social Choice in Machine Design: The Case of Automatically Controlled Machine Tools, and a Challenge for Labor.” *Politics and Society* 8, nos. 3-4 (September 1978): 313-347. http://journals.sagepub.com/doi/10.1177/003232927800800302

Maryellen R. Kelley. “Organizational Resources and the Industrial Environment: The Importance of Firm Size and Interfirm Linkages to the Adoption of Advanced Manufacturing Technology.” *International Journal of Technology Management* 8 (November 1993): 36-68.

Maryellen R. Kelley. “Productivity and Information Technology: The Elusive Connection.” *Management Science* 40 (1994): 1406–1425. https://pubsonline.informs.org/doi/abs/10.1287/mnsc.40.11.1406

Maryellen Kelley and Susan Helper. “Firm Size And Capabilities, Regional Agglomeration, And The Adoption Of New Technology,” *Economics of Innovation and New Technology* 8, no. 1-2 (1999): 79-103. https://pdfs.semanticscholar.org/3d40/ebf41076da32747f48d4fbbcd078ffc04b60.pdf

Hartmut Hirsch-Kreinsen. “Use of CNC and Alternative Methods of Work Organization.” *Computer Integrated Manufacturing Systems* 6, no. 1 (February 1993): 3-8. https://www.sciencedirect.com/science/article/pii/095152409390022I

P. Timothy Bushnell. *Transformation of the American Manufacturing Paradigm*. New York: Garland, 1994.

[141] U.S. Department of Labor. “O*NET Online” https://www.onetonline.org/

IV. Automotive assembly plant automation

Assumptions that automation will eliminate jobs in their entirety often guide first perceptions—and headlines—about the employment impact of new technologies. But partial automation is far more common. Bessen[142] examines all of the 270 detailed occupations listed in the 1950 U.S. Census and found that only one—elevator operator—was completely eliminated by automation. The automation trend in one of the most capital-intensive settings in heavy industry—the automotive assembly line—offers insights into the reasons partial automation is so prevalent.[143]

An automotive assembly plant is typically comprised of three primary departments – body, paint, and assembly. (Certain plants also have stamping departments; and each of the primary departments can have multiple sub-segments, e.g. trim and chassis lines in assembly.)

The automation trends in each department have been distinct. For many years now, body shops have carried out the majority of needed welds using large multi-welders, with hundreds of welds (up to 80 percent) applied by many robots while the body pieces are held firmly in place by a jig that guarantees structural integrity. Feeder lines that weld small metal stampings into subassemblies typically consist of a mix of automated and manual welds. The development of more sophisticated robots—capable of moving on up to six axes of motion, plus new techniques such as arc welding—has raised the total number of welds applied by automation to upwards of 95 percent in newer assembly plants. With more precise welding, the total number of welds can be reduced. (When many welds were manual, product designs typically required up to 5,000 welds, anticipating that some would be missed or imprecisely placed; a modern design has 2,500-4,000 welds depending on the vehicle type.) OEMs have increasingly been willing to invest in this very high level of weld automation, even when building new plants to produce vehicles in developing countries with low wage rates, because the consistency of body welding and the resulting integrity of the structural design has advantages in selling a vehicle that can meet the regulatory requirements of many different export markets.

Paint automation was similarly divided into highly automated stages in environment-controlled paint booths (by dipping the vehicle body for rustproofing and applying the undercoat, then by paint robots applying the prime and 1-2 color coats) and mostly manual processes to apply sealer for leak prevention and noise control. These sealer jobs were difficult to automate because of the complex motions to apply a precise bead along a curving line, but they were also ergonomically demanding and likely to cause repetitive motion injuries. Eventually the same advances in robotics that allowed further automation of welding—and the reduced price for these capabilities—also allowed automation of many sealing tasks. Hence, the two already-capital intensive departments

[142] James E. Bessen. "How Computer Automation Affects Occupations: Technology, Jobs, and Skills," Boston University School of Law, Law and Economics Research Paper No. 15-49, October 3, 2016. https://ssrn.com/abstract=2690435 or http://dx.doi.org/10.2139/ssrn.2690435

[143] The assembly automation case is supported by research carried out under auspices of the International Motor Vehicle Program at MIT, involving data collected from 70 assembly plants from 20+ countries and companies in 1989, 1995, and 2000. See John Paul MacDuffie and Frits K. Pil. "From Fixed to Flexible: Automation and Work Organization Trends from the International Assembly Plant Survey," 1996, IMVP working paper. https://dspace.mit.edu/handle/1721.1/1623

have moved from 70-80 percent steps performed by automation to between 90 and 100 percent between the mid-1980s and the present.

The assembly department, however, is a completely different story. This is the setting that most people think of when they hear the phrase “assembly plant,” whether their reference point is Henry Ford or Charlie Chaplin. Painted vehicle bodies are stationed on a moving line that passes many workstations where workers carry out a set of standardized tasks on each vehicle with a short cycle time—typically about 1 minute. Assembly is one of the most labor-intensive production processes in any manufacturing setting despite the otherwise high level of capital investment and hence has been a frequent target of efforts to increase automation. In particular, a wave of intense focus on automating assembly took place in the 1980s led by automotive OEMs and equipment suppliers all over the world. Advances in flexible automation, in robots, in logistics (the movement of vehicles and supplier parts within the factory), and in larger automation installations were the proximate cause of this focus. The leading firms in this effort were General Motors in the U.S., Fiat and Volkswagen in Europe, and Mazda and Nissan in Japan, but no firms stayed on the sidelines.

With the benefit of longitudinal data from the International Assembly Plant Study from MIT’s International Motor Vehicle Program (IMVP), the consequences of this wave of investment in assembly automation soon became clear. Certain assembly tasks were well-suited to automation, e.g. the installation of windshields where a heavy object needed to have a same-width bead of glue applied around its edge before precise placement onto the opening in the vehicle body. One robot arm applied the glue bead while another robot arm lifted and placed the windshield, at first with guiding hands from workers insuring precise placement but eventually operating without human intervention. Accordingly, most assembly plants in the IMVP sample implemented automated windshield installation in the period between 1985 and 2000.

However, windshield installation was the exception. Most assembly automation proved not to work well for three reasons: 1) the capital equipment was expensive; 2) the equipment broke down a lot and required frequent maintenance; and 3) the equipment, while hypothetically programmable and able to handle a high degree of model mix and product complexity, was mostly unable to accommodate that level of variety in actual operating conditions. Other problems were specific to the type of automation. Large automation installations, where the vehicle would be fixed in position for a period of time during which multiple tasks were performed, required removing vehicles from the moving assembly line; these often became bottlenecks due to operational problems. Automated Guidance Vehicles (AGVs), detachable platforms that moved vehicles from one section of the plant to another, were guided by fixed metal strips placed in the concrete flooring and hence were hard to move once installed.

Several adaptations to the situation followed, with striking similarities across companies and regions (possibly due to direct knowledge exchange or spillover via suppliers). Large automation installations were often removed and replaced with a more traditional setup of automation stations that could function within the standard cycle time of the rest of the assembly line. Sophisticated multiple-axes programmable robots intended for automating human assembly tasks often could not duplicate the precise maneuvering of the part to the right position/angle for installation nor the precise tightening for the correct torque. Hence those tasks were returned to line workers. But when heavy parts needed to be lifted into place before fastening, simple singleaxis “pick and place” robots were used to relieve the ergonomic strain on workers. This philosophy of “automation assist,” using inexpensive commodity-like robots in combination with human labor, became the dominant approach. Eventually this philosophy found its most creative outlet in the design of work carts to hold bolts and fasteners plus tools, customized by each work team to meet their preferences (with height of the cart and layout of the bins for parts and the holders for tools being the primary design variables). These carts would hook into the moving assembly line so they moved at the same pace as the vehicle and then would disengage at the end of the 1-minute work cycle and roll back to the starting position for the next vehicle. These carts often had decorations on them and were given affectionate, anthropomorphized names.

Technological advances did not cease, of course, but largely adapted to this new philosophy as the appeal of “lean” or “frugal” capital investment caught on. To deal with the problems of inflexible (though programmable) AGVs, new designs emerged with sensors that could read a magnetic strip that could simply be taped on the floor, making a change in routing much simpler. In order to have closer proximity of simple “pick and place” robots and workers while maintaining safety, those robots were increasingly designed with low-voltage power supplies, eliminating the risk of shock. At Toyota, where the principle of continuous improvement (kaizen) is well-established, researchers learned that close proximity of humans and robots was prized as an opportunity for monitoring and learning about machine operations in order to “give wisdom to the machine.” Toyota engineers contrasted this learning-oriented approach with the “monuments of automation” approach embodied in the massive and physically-separated installations favored by Fiat and VW.

Thus even in a setting that favors capital investments for complete automation of tasks, the assembly automation case shows the limits of automation for certain tasks and the ability of firms to adapt to a partial automation strategy that uses less sophisticated equipment designed to complement human activities and capabilities. This partial automation approach has proven to be durable at most OEMs. Tesla’s Elon Musk talks frequently about his intention for robots to carry out the production of a future Tesla model so that the final products have been untouched by human hands. While this vision is appealing to any observers who find the auto assembly line to be the very symbol of alienating work, there is reason to be skeptical of whether Musk can achieve this goal any time soon. Indeed, while ramping up production of the mass-market Model 3, Tesla has faced difficulties with its welding automation, requiring manual welds that have slowed production to a handful of vehicles per day. There’s every reason to expect that Tesla, like all other automotive OEMs, will solve the welding automation problem—but much less reason to expect full automation of assembly tasks. Recent reports from Tesla’s factory for the Model 3 suggest that Musk’s pursuit of full automation in the assembly department is a major cause of both production delay and additional cost. Indeed, Musk is already beginning to concur with the external diagnosis of overautomation in assembly. Overall, this remarkably common experience at most if not all automakers worldwide suggests that “automation assist” in assembly will continue to be more effective for cost, quality, safety, and throughput efficiency that initiatives attempting full automation. This, in turn, greatly reduces the automation threat to employment levels in assembly departments at both new and established OEMs worldwide.

V. Automatic teller machines (ATMs)

The now-ubiquitous Automated Teller Machine (ATM) has become a ready reference point for technology observers on both sides of the question whether automation decreases or increases employment, each side often telling only part of the story. For our purposes, the ATM example is particularly valuable for these reasons:

1) The technology itself diffused relatively slowly at first before a period of explosive growth. This is due less to technical challenges than to regulatory issues and the slowness of customers to change their financial habits;

2) The employment impacts were slow at first. When the period of intense adoption arrived, there was a large first-order negative effect on bank teller employment. Subsequently there was an even larger second-order indirect effect as banks shifted strategy to open many more local branches, reducing tellers per branch but expanding overall teller employment;

3) Banking technology has advanced beyond ATMs, particularly via fintech apps related to mobile or cashless payments. But the ATM is not disappearing; rather, it is being repurposed in ways that promise both direct negative employment effects and indirect employment gains. With respect to the latter, job enhancement will also be enhanced by returning human interaction to non-routine situations arising during routine banking transactions.

According to historians of the ATM, there was no "eureka" moment for the ATM, a complex combination of technologies, but rather an evolution of antecedent technologies (magnetic stripe technology most notably) and several inventors working in parallel.[144] Three different ATMs were launched in 1967, each developed independently: Bankomat in Sweden; Barclaycash in the UK; and Chubb MD2 in the U.S. New technologies were developed specific to the ATM, both hardware (the cash output mechanism) and software (the algorithm creating an encrypted PIN and linking it to a specific account). Exposure of ATMs to weather conditions (intense rain, snow/sleet, extremes of heat and cold) was an early source of operational difficulties that hurt customer trust in their reliability and slowed adoption. According to McRobbie, skepticism was widespread with varied reasons:[145]

One Detroit artist told *The New York Times* in 1977 that she preferred face-to-face banking and that a number of her friends had machines eat their cards: "I'm suspicious," she said. "At least the girl behind the window doesn't die in the middle of a transaction."[146] A dubious banking exec in

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[144] Bernardo Bátiz-Lazo, Tobias Karlsson, and Björn Thodenius. "The Origins of the Cashless Society: Cash Dispensers, Direct to Account Payments and the Development of On-Line Real-Time Networks, C.1965-1985." *Essays in Economic & Business History* 32 (2014): 100-137. http://www.ebhsoc.org/journal/index.php/journal/article/view/274

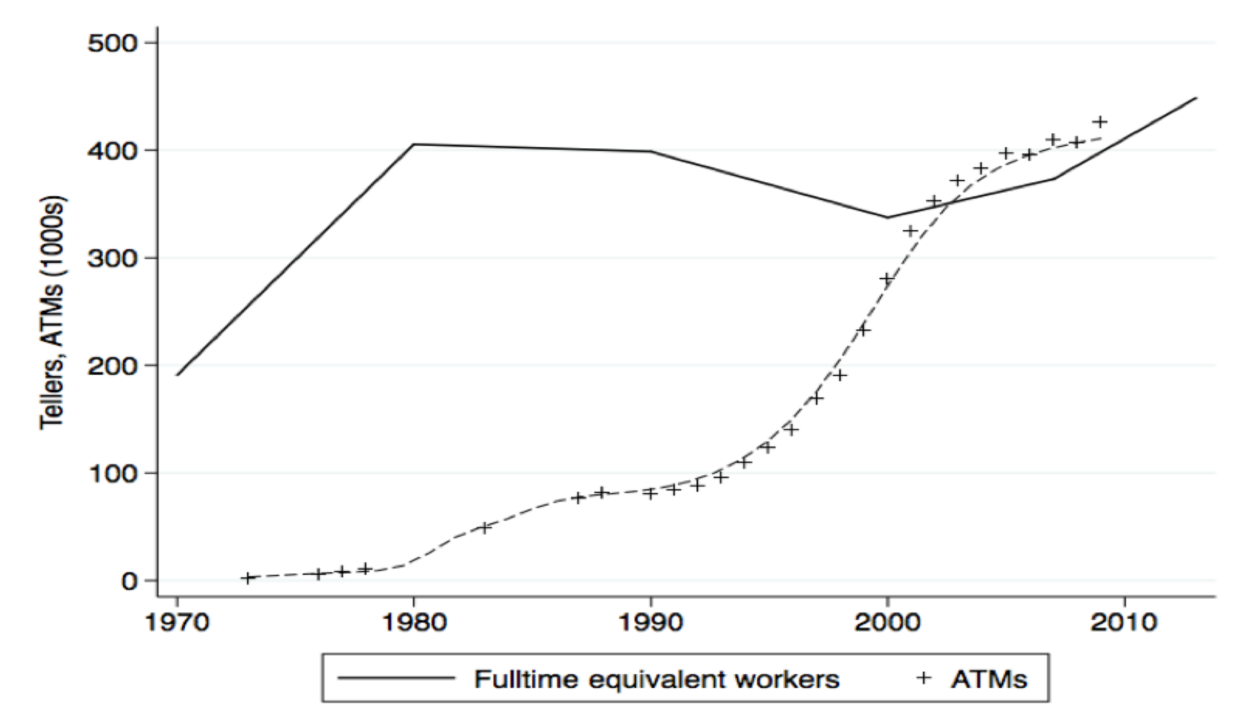
[145] Linda Rodriguez McRobbie. "The ATM is dead. Long live the ATM!" *Smithsonian Magazine*, January 8, 2015: 1–11. https://www.smithsonianmag.com/history/atm-dead-long-live-atm-180953838/

[146] Jerry Flint. "Quick Electronic Banking Slowed By the Public's Habits and Fears." *The New York Times*, May 31, 1977. http://query.nytimes.com/mem/archive/pdf?res=9900EFDF113FE334BC4950DFB366838C669EDE

New York City told the paper that it was great that a customer could bank at 3 a.m., but "Where are you going to spend it at 3 a.m.?"

Employment consequences of ATMs tracked diffusion levels quite directly for a time. Statistics from the Bureau of Labor Statistics show that employment in commercial banking declined by 70,000 from 1986 to 1996, dropping to 1.5 million even as the economy expanded. Of the service-producing sector, only savings institutions and railroad transportation lost more jobs than commercial banking from 1986-96.[147] But this pattern reversed beginning in the mid-1990s. According to James Bessen, "The number of full-time equivalent bank tellers has grown since ATMs were widely deployed during the late 1990s and early 2000s."[148] (See Figure A-3). "Why didn't employment fall? Because the ATM allowed banks to operate branch offices at lower cost; this prompted them to open many more branches (their demand was elastic), offsetting the erstwhile loss in teller jobs."

FIGURE A-3: Fulltime-Equivalent Bank Tellers and Installed ATMs in the U.S.



Regulatory changes also played a role in the diffusion of ATMs and a shift in bank strategies vis-à-vis branches. In 1984, the Supreme Court ruled that an ATM did not count as a bank branch, allowing more density of ATMs without violating regulations on geographic concentration of

[147] Teresa L. Morisi. "Commercial Banking Transformed by Computer Technology." *Monthly Labor Review*, Bureau of Labor Statistics, August 1996. https://www.bls.gov/opub/mlr/1996/08/art4full.pdf

[148] James E. Bessen. "How Computer Automation Affects Occupations: Technology, Jobs, and Skills." Boston University School of Law, Law and Economics Research Paper No. 15-49, October 2016. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2690435

banks. The freedom to do routine banking transactions at any hour increased use of banking services and encouraged banks to reach out to potential customers who hadn't had a bank account previously. Branches were reconceptualized as places to connect directly with customers in order to sell high-margin products and services such as credit cards, mortgages, home equity lines of credit, and insurance. Deregulation of banking that allowed more different entities to enter these new lines of business increased this new cross-selling approach and also spurred competition, with the physical presence of branches seen as valuable for building overall consumer awareness of a bank's brand. Fishman provides these comparative statistics: "… in 1985, the U.S. had 60,000 ATMs and 485,000 bank tellers. In 2002, the U.S. had 352,000 ATMs—and 527,000 bank tellers. ATMs notwithstanding, banks do a lot more than they used to and have a lot more branches than they used to."[149]

VI. International trade

Though not directly connected to automation, the rapid change in trade patterns in the 1990s and 2000s offers some important lessons about how change can severely hurt some communities and spark widespread fear and anger.

Studies such as those by MIT economist David Autor[150] and Yale economist Peter Schott[151] have found that China's entry into the World Trade Organization (WTO) led to large losses in income and employment for U.S. workers. Autor's findings suggest that one quarter of U.S. manufacturing job loss can be attributed to this cause, and the impact was not limited to the manufacturing sector. According to this research, the median working age adult lost $1,200 in annual income from 2000 to 2007 as a result of China's entry into the WTO.

Autor, Dorn, and Hanson analyzed the effect of rising Chinese import competition between 1990 and 2007 on U.S. local labor markets ("commuting zones", or CZs). Some CZs had high exposure to Chinese imports because in 1990 they specialized in industries (e.g. furniture) in which Chinese imports by other rich countries grew a lot, while other CZs had less exposure. The median CZ saw an increase of Chinese imports per worker of $890 from 1990-2000, and $2,110 between 2000 and-2007. They found that the impact of increased Chinese import exposure was large and was not limited to the manufacturing sector. A $1,000 /worker increase in a CZ's import exposure led to a $549 loss in wage/salary income per working age adult per year in that CZ, due to reduced employment (mostly in manufacturing), reduced labor force participation, and reduced non-manufacturing wages.

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[149] Charles Fishman. "The Toll of a New Machine." *Fast Company,* May 1, 2004. https://www.fastcompany.com/49359/toll-new-machine

[150] David H. Autor, David Dorn, and Gordon H. Hanson. "The China Shock: Learning from Labor-Market Adjustment to Large Changes in Trade." *Annual Review of Economics* 8 (2016):205–40. https://www.ddorn.net/papers/Autor-Dorn-Hanson-ChinaShock.pdf

[151] Justin R. Pierce and Peter K. Schott. "The Surprisingly Swift Decline of U.S. Manufacturing Employment." NBER Working Paper No. 18655, December 2012, Revised January 2014. http://www.nber.org/papers/w18655

Most of these losses were not compensated. For every dollar of income that workers lost due to China's entry into the WTO, they received on average only 10 cents in compensation.[152] A $1,000/worker increase in a CZ's import exposure led to only a $58/year increase in government transfers. Most of these transfers of income occurred through the disability system or food stamps; the impact of Trade Adjustment Assistance was very small. The deadweight loss due to inefficiency of transfer payments and to involuntary unemployment was about $142 per capita for 1990-2007. One estimate of gains from this increased import exposure was $32–$61.[153] Others argue this estimate is too small, and ignores potential long-term gains. Also, deadweight loss will fall over time as adjustment occurs.

VII. Australian mining

Much of Australia's mining industry is located hundreds of miles away from population centers.[154] In some quarries and mines, workers are flown into tent camps from which they work for two weeks and are then flown back home. These working conditions are hard on workers and expensive for the mining companies.[155] So the Australian mining industry has been rapidly developing and deploying automation and remote-controlled equipment including autonomous (self-driving) trucks made by Komatsu and Caterpillar for hauling raw rock from the quarry face to crushers.

Currently mining giant Rio Tinto operates 73 driverless trucks at four mining sites (West Angelas, Yandicoogina, Nammuldi, and Hope Downs 4) in Western Australia from an operations center in Perth.[156] The trucks can run 24 hours a day throughout the year without a driver who would need lunch and bathroom breaks. They are also more precise and consistent in where they pull up for loading. Company officials estimate that each of the trucks can replace about 500 work hours each

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[152] David Autor, David Dorn, and Gordon Hanson. "The China Syndrome: Local Labor Market Effects of Import Competition in the United States." *American Economic Review* 103, no. 6 (2013): 2121–2168. https://economics.mit.edu/files/11643 ; David Autor, David Dorn, Gordon Hanson. "The Geography of Trade and Technology Shocks in the United States." *American Economic Review Papers and Proceedings* 103, no. 3 (2013): 220–225. https://economics.mit.edu/files/11641

[153] Costas Arkolakis, Arnaud Costinot, Andrés Rodríguez-Clare. "New Trade Models, Same Old Gains?" *American Economic Review* 102, no. 1 (February 2012): 94-130. https://economics.mit.edu/files/7571

[154] Australia has a population of 24.13 million people. This is just 87 percent that of the state of Texas (27.86 million), but Australia covers an area of 2.97 million square miles, which is about 11 times as large as Texas (268,597 square miles). Most of Australia's population resides in coastal cities: Sydney, Brisbane, Gold Coast, and Newcastle on the east coast (with Canberra just slightly inland), Perth on the west coast, and Melbourne and Adelaide on the south east coast. Large iron and copper mines are often over 1,000 km from these population centers.

[155] Spencer Kelly. "Robot trucks do the jobs Australians shun." *BBC News*. November 18, 2014. http://www.bbc.com/news/technology-30098772

[156] Tom Simonite. "Mining 24 Hours a Day with Robots." *MIT Technology Review*. December 28, 2016. https://www.technologyreview.com/s/603170/mining-24-hours-a-day-with-robots/

year.[157] Rio Tinto's productivity leader, Rob Atkinson, says driverless trucks are roughly 15 percent cheaper to run than human-operated trucks.[158]

Fortescue Metals Group (FMG) is currently operating 54 driverless trucks and drills at the Firetail and Kings Valley iron ore mines in North West Australia, which have increased productivity 20 percent and saved $100 million on the capital cost of 20 trucks.[159] Pit to port costs have been cut 43 percent. To support the trucks, Caterpillar's dealer, Westrac, has hired 100 people with skills in robotics, data analytics, radio networks, and GPS technologies.

Rio Tinto also operates robotic rock drilling rigs and will have driverless trains for hauling the ore to port by 2018.[160] BHP Billiton has also deployed driverless trucks in Western Australia that it operates from Perth. In addition, the mining industry is exploring automated rock breakers, semi-autonomous crushers, and remotely-operated ship loaders.[161] Auto-tunable robotic loading (ATRL) technology, which can sense how much rock has been scooped up by a loader as it moves its scoop forward, is being developed for underground mines.[162] Where jobs are too complicated for autonomous machines to work, remotely controlled machines may be possible.

Beyond the mining industry, Australia is developing automated milking machines that enable a cow to be milked whenever she wants and an autonomous weed-removing robot powered by on-board photovoltaic solar collectors.[163]

While providing substantial productivity benefits, automation and remote control means fewer jobs for miners and local suppliers, many of them Aboriginal/indigenous people. It also means less tax-revenue for government tax agencies.[164] These local low-skill workers are often replaced by high-skill workers who manage and service the autonomous machines from remote operation centers located in far-away cities.

"If you're moving from mines that employ 5,000 to 10,000 people down to 500 or 1,000, then you're obviously not going to get the same amount of local jobs," says Howard Mann, senior

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[157] Kathryn Diss. "Driverless trucks move all iron ore at Rio Tinto's Pilbara mines, in world first," *ABC News*, October 18, 2015. http://www.abc.net.au/news/2015-10-18/rio-tinto-opens-worlds-first-automated-mine/6863814

[158] Simonite. "Mining 24 Hours a Day with Robots." 2016.

[159] Paul Wallbank. "Caterpillar's driverless dumpsters drive disruption in Australian mines." *Diginomica*. April 17, 2017. https://diginomica.com/2017/04/17/sending-disruption-mines/

[160] Simonite. "Mining 24 Hours a Day with Robots." 2016.

[161] Oliver Balch. "Automated mining will cost jobs and tax income: it's time for governments to act." *The Guardian*. January 19, 2017. https://www.theguardian.com/sustainable-business/2017/jan/20/autonomous-mining-will-cost-jobs-and-tax-income-its-time-for-governments-to-act

[162] Gary Peters. "Mine automation clears giant hurdle." *Mining Technology*. March 19, 2017. http://www.mining-technology.com/features/featuremine-automation-clears-giant-hurdle-5760844/

[163] Spencer Kelly. "Robot trucks do the jobs Australians shun." 2014.

[164] Oliver Balch. "Automated mining will cost jobs and tax income: it's time for governments to act." 2017.

adviser on international law at International Institute for Sustainable Development (IISD) and co-author of a recent study[165] on the impact of automation in the mining sector.[166]

The situation could be even worse in resource-rich developing countries as multinational mining corporations deploy automation to extract resources that are primarily used in the developed world. Local employment in mining, support, and supplier industries may dry up, and the GNP of some of these countries might be reduced by as much as 4 percent. Large mine operators in low-income countries make 21 percent of their purchases locally whereas in OECD countries, they spend closer to 91 percent.

“The ‘shared value’ paradigm was intended to reduce that gap and give developing countries the opportunity to close those ratios. What automation is going to do is just step in the way and block that from happening in a significant way,” says Mann.

Peter Knights, head of the mining engineering department at Australia’s Queensland University, argues that host governments in developing countries should require that skills be transferred to local workers just as U.S. defense companies that have sales contracts with Australia must currently do.

James Cook University professor Ian Atkinson said it was likely some jobs would be lost but expected it to happen over a long period of time. “It may happen that as people retire or leave the industry they won't be replaced by a person,” Professor Atkinson said. “It's not just taking workers out and putting a machine in, it's going to happen really quite gradually for a long time yet.”[167]

And automation might also make mining easier so that new mines are developed that would employ additional people, as Professor Atkinson said:

> If you apply machines and actually have a mine where you normally wouldn't maybe you’ll be developing new mines.

A recent study found that computers will reshape the labor market in Australia in two ways:

> 1. Directly substitute for labor, with a high probability that as much as 40 per cent of the jobs in Australia could be replaced by computers within a decade or two; and

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[165] Aaron Cosbey, Howard Mann, Nicolas Maennling, Perrine Toledano, Jeff Geipel, and Martin Dietrich Brauch. *Mining A Mirage? Reassessing the shared-value paradigm in light of the technological advances in the mining sector*. International Institute for Sustainable Development (IISD) and the Columbia Center on Sustainable Investment. 2016. http://www.iisd.org/sites/default/files/publications/mining-a-mirage.pdf

[166] Oliver Balch. “Automated mining will cost jobs and tax income: it's time for governments to act.” 2017.

[167] Eric Barker. “Mining industry looks towards a new wave of automation.” *ABC News*. May 23, 2017. http://www.abc.net.au/news/rural/2017-05-23/the-future-of-automation-in-the-mining-industry/8550636

2. Disrupt the way work is conducted, expanding competition and reducing the costs to consumers but also reducing the income of workers.[168]

The study estimated that up to 5 million jobs are likely to be automated by 2030 and nearly 40 percent of Australian jobs that exist today are at risk, with more than 60 percent at risk in parts of rural and regional Australia.[169]

University of Sydney mechatronic engineering Professor Hugh Durrant-Whyte designed and implemented the stevedore automation system in Port Brisbane and Port Botany so that these terminals are now completely operated from Sydney. He was also responsible for automating Rio Tinto's mines in Western Australia—14 mines in the Pilbara, six in the Hunter Valley, three in Mongolia, and four in the U.S., all from "a single room in Brisbane." He argues that the worst consequence of automation will be further polarization of the workforce—the number of high-skill jobs for managers and professionals would grow as would low-skilled, interactive jobs in the service industry, but those in between will shrink drastically.

> "That's what technology is doing that's different from previous industrial revolutions," Durrant-Whyte said. "And I do think that this is very, very concerning because it really does show the type of inequalities on a global scale that are going on." He said this polarization hadn't quite hit Australia yet but warned "it is heading that way without any doubt at all."

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[168] CEDA – Committee for Economic Development of Australia. *Australia's future workforce?* June 2015, p. 8. http://www.ceda.com.au/CEDA/media/ResearchCatalogueDocuments/Research%20and%20Policy/PDF/26792-Futureworkforce_June2015.pdf

[169] David Marin-Guzman. "Use of automation has 'profound' impacts for Australia." *Thomson Reuters*. June 30, 2016. http://sites.thomsonreuters.com.au/workplace/2016/06/30/use-of-automation-has-profound-impacts-for-australia/

Appendix B. Simulating Labor Market Status and Earnings Impacts

This appendix details how we convert the job loss patterns shown in Table II-2 into displacements and changes in unemployment, labor force participation, and earnings through our simulation exercises.

To summarize our approach for labor market status, first we derive displacements from job losses to displacements by adjusting for projected turnover. Once we have determined the number of workers we expect to be laid off, we then project their subsequent labor market status in the years after layoff. To do so, we use the recent experience of displaced workers to estimate a path for the group going forward. That is, these paths allow us to convert a surge in expected layoffs from occupations affected by AV into implied elevations of unemployment and declines in labor force participation. To construct these paths, we rely heavily on data from the 2012, 2014, and 2016 Current Population Survey (CPS) Displaced Worker Surveys (DWS) conducted by the U.S. Bureau of Labor Statistics, augmented as needed by assumptions that we explain below.[170] We use this same process to construct post-displacement paths for several demographic and geographic subgroups.

I. Displacement simulations: from jobs lost to displacement

To estimate displacement from the number of jobs we expect to be eliminated, it is important to consider the number of potentially laid-off workers who might never receive a pink slip because they retired or left the labor force for other reasons, or they transferred to a different occupation first.

Occupational turnover occurs when workers leave an occupation. For example, a worker may retire, become disabled, take a job in another occupation, go back to school, be promoted, take on family responsibilities, be fired for cause, or pass away. An occupation's annual turnover reflects the rate at which jobs in the occupation would decline if no exiting workers were replaced. Factors that influence occupational turnover include the average age of the workforce, injury rates, whether it is an entry-level job, and if experience in that job applies to other occupations. These estimates do not count workers who change jobs but remain in the same occupation.

Table III-1 presents occupational turnover projections for AV affected occupations derived from BLS Occupational Openings and Separations projected for 2016-2026.[171] The table also presents ranges for the total number of jobs that are eliminated in each occupation across the four scenario combinations. BLS projects occupational turnover using two different models, one for labor force exits and another for occupational transfers. Both models use a regression analysis of historical data to identify the characteristics of a worker, such as age and educational attainment that make

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170 Bureau of Labor Statistics, "Worker Displacement" survey. https://www.bls.gov/news.release/disp.toc.htm

171 These are described in Bureau of Labor Statistics. "Occupational Separations and Openings." https://www.bls.gov/emp/ep_separations.htm

them likely to separate from their occupation. These patterns from historical data are then applied to the current distribution of employment for each occupation to project future separations.

Our simulations are turnover-adjusted in the sense that to calculate the expected number of displaced workers in each scenario we reduce the expected job losses by the turnover percentages shown in Table III-1.

II. Unemployment simulations: from displacement to being re-employed or unemployed

Once we know the expected pattern of displacements, we use the DWS to simulate laid-off workers' labor market experience in subsequent years, beginning with unemployment and re-employment.

The DWS includes workers with three or more years of tenure on the job before they were laid off. We used the DWS from 2012, 2014, and 2016 because these are the most recent surveys and they occur during an economic expansion, but when unemployment was still relatively high. So, these years are neither boom not bust years. Because the sample is representative of all displacement in the U.S. during those years, its composition reflects the particular cyclical and structural trends at play at the time. The paths followed after displacement reflect the composition of the workers as well as the impact of current mitigation efforts. [172]

The finished path for the most general cohort of workers appears in Table B-1. It covers the period from the year before displacement until six years afterward. Table B-2 describes the source or formula for each element in Table B-1, while the text below presents the rationale for the assumptions taken. Discussion of Tables B-1 and B-2 focuses on re-employment and unemployment impacts. Labor force participation impacts are considered further below.

First, how to read Table B-1: In this table, we follow a group of workers displaced from their jobs for five years to register their labor market status in each subsequent year. The left-hand column gives us the year relative to the year when they lose their jobs. The first row (year -1) gives their status before the layoff year. In that year, all are employed (so employment =1); none are out of the labor force or unemployed (so out of labor force and unemployment=0). In subsequent years, the table shows the share of the original laid off cohort that fall into the three possible labor market statuses in columns 2, 3 and 4. Also shown is the unemployment rate for this group of workers in column 5 and the difference between their unemployment rate and a baseline rate calculated as explained below.

[172] We partially adjust for potential differences in the composition by isolating and examining demographic and geographic subgroups. Future simulations could be refined to make more complete adjustments.

TABLE B-1: Path of Labor Market Status after Displacement

Years after displace-ment	Share of displaced workers employed	Share of displaced workers out of labor force	Share of displaced workers unemployed	Unemploy-ment rate of displaced workers	Baseline* unemploy-ment rate	Unemploy-ment rate gap between displaced workers and baseline*	Share of displaced workers adding to unemploy-ment
-1	1	0	0	0%	0%	0.0%	0
0	0.597	0.065	0.338	36.1%	0.00%	36.1%	0.338
1	0.483	0.130	0.387	44.5%	1.08%	43.4%	0.378
2	0.681	0.126	0.192	22.0%	2.17%	19.9%	0.174
3	0.723	0.133	0.144	16.6%	3.25%	13.4%	0.116
4	0.763	0.120	0.117	13.3%	4.33%	8.9%	0.079
5	0.802	0.110	0.088	9.9%	5.42%	4.5%	0.040
6	0.842	0.100	0.059	6.5%	6.50%	0.0%	0.000

Source: Bureau of Labor Statistics Displaced Worker Survey (DWS) for 2012, 2014, and 2016 for columns 2-5 for years 1, 2, and 3. Estimates provided by Henry S. Farber. See
B-2 and Appendix B text for detailed description of the authors' assumptions and calculations that complete the table.

*In years -1 and 0, this figure compares laid off workers to employed workers. To simulate normal employment turnover, for years 1-6, it compares them to linearly increasing unemployment, until reaching the year 6, which compares them to the overall average unemployment during the DWS months.

TABLE B-2: Sources and Assumptions for Table B-1

Years after displace-ment	Share of displaced workers employed	Share of displaced workers out of labor force	Share of displaced workers unemployed	Unemploy-ment rate of displaced workers	Baseline unemployment rate for the year	Unemployment rate gap between displaced workers and baseline*	Share of displaced workers adding to unemploy-ment
-1	1, by construction	0, by construction	0, by construction	0, by construction	0, by construction	0, by construction	0, by construction
0	Implied by unemployment rate and out of labor force estimates	(1/2)*DWS average exit rate for years 1-3	Implied by unemployment rate and out of labor force estimates	(1/4)*(1+year 1 unemployment rate)	By construction	Unemp. rate for year 0	(Unemp. rate)/(baseline unemp. rate)* unemployment, all for year 0
1, 2 & 3	DWS average employment share for same year	DWS average exit share for same year	DWS average unemployment share for same year	DWS average unemployment rate for same year	(1/6), (2/6) or (3/6)*baseline unemployment rate for year 6	(Unemp. rate for same year)-(baseline unemp. for same year)	(Unemp. rate)/(baseline unemp. rate)* unemployment, all for same year
4 & 5	Implied by unemployment rate and labor force exits	(12/13 or 11/13) *(DWS average exit share for years 1-3)	Implied by unemployment rate and labor force exits	(Unemp. rate in year 3) + ((1/3) or (2/3)) * (unemp. rate in year 6 –unemp. rate in 3)	(4/6) or (5/6) *baseline unemployment rate for year 6	(Unemp. rate for same year)-(baseline unemp. for same year)	(Unemp. rate)/(baseline unemp. rate)* unemployment, all for same year
6	Implied by unemployment rate and labor force exits	(10/13)*(DWS average exit share for years 1-3)	Implied by unemployment rate and labor force exits	Baseline unemployment rate for year 6	DWS weighted average unemp. rate (Jan. 2012, 2014 and 2016).	0, by assumption	0, by assumption

Sometime during the next year (year 0), all in the group lose their jobs. At the moment of the layoff, all displaced workers become unemployed, but then over time they look for new jobs, start work at new jobs, or exit the labor force, so they leave the ranks of the unemployed. Thus, workers begin year 0 (the year of the layoff), with a job and end it after their layoff. Layoffs can happen at any time throughout the year. So, for the year 0, we assume that the average layoff takes place halfway through the year.

We take into account that some workers will exit the labor force after displacement, that is, about 13 percent of displaced workers are not working or looking for work. This is reflected in the third column of Tables B-1 and B-2. Perhaps surprisingly, the DWS data suggests that virtually all of displacement-induced labor force exits take place during the first year. That is, about 13 percent of displaced workers are not working or looking for work. For three years after the layoff event, that share neither rises nor falls. (Specifically, the average rates are 13.0, 12.6 and 13.3 in years 1, 2 and 3 respectively.) If all the exits occur quickly after the layoff, then to reflect the partial year, the share of the laid-off workers that were out of the labor force would be about half of the 13 percent or 6.5 percent. To the extent that workers may delay their exits during the first few months, this number will be biased upward, but for year 0 only.

Columns 2 and 4 of the tables show employment and unemployment shares respectively. The DWS provides these shares for years 1-3, from which we calculate the unemployment rates in column 5, using the following formula:

Unemployment rate = (Unemployed share)/(Unemployed share + Employed share)

To construct an unemployment rate for year 0, we start by assuming, on average, the layoffs occur halfway through the year and that all workers are unemployed at least briefly once during the year. If they stayed unemployed for the whole time after layoffs until the end of the year, their unemployment rate would be 50 percent for the year. However, according to the DWS, the unemployment rate for displaced workers is not 100 percent, but 44.5 percent by a year out. Assuming the path from 100 percent to 44.5 percent is not too far from linear, we take a quarter of the sum of 100 percent and 44.5 percent as average unemployment for this cohort of workers to get 36.1 percent for the average unemployment rate for displaced workers during year 0. That is, we multiply by one half to reflect the partial year and another one half to reflect their average unemployment rate during that time. If we knew that the layoffs would be early or late in the year, this rate would be higher or lower accordingly, for year 0 only.

Thus, we see that the unemployment rate rises rapidly in year 0. But because all of the cohort was employed at the beginning of year 0, annual average unemployment peaks the year after, in year 1. After that it declines steeply in year 2 and further in year 3.

Since the DWS does not ask workers to recall back more than three years earlier than their layoff, we must make reasonable assumptions about outcomes of layoffs for years 4 and 5. In the DWS, unemployment at year 3 is still elevated (higher than 6.5 percent, the average rate at the time of the DWS surveys), and it is not declining fast enough to close the gap by year 4, so we assume that it takes at least another two years, until year 6, to close the gap. That is, we impose year 6 as the end date when the unemployment rate of the displaced workers converges to the national rate.

We make the path linear rather than curved (perhaps hyperbolic) to balance out some very long spells that we may be truncating. We also note that the share of workers who linger in unemployment beyond year 6 is surely quite small.[173]

At this point, it is important to emphasize that we don't expect unemployment to decline to zero for laid-off workers, but rather to converge to the U.S. average. Before displacement, they were all employed, but over time, their unemployment status would be expected to approach the labor market average, not zero unemployment. This means that our baseline for comparison needs to change by year. It increases over time from zero to the average when the DWS surveys were conducted. Normal turnover (assuming it occurs at a constant rate) would have caused a linear rise in unemployment for this set of workers, converging to the national average for the years the DWS covers by year 6. [174]

This moving baseline allows us to track two measures of displacement's impact on joblessness: the unemployment rate and the share of unemployed. The impact on the unemployment rate is the gap between the DWS unemployment rate for each year above the baseline unemployment. Then we multiply the ratio of the unemployment gap to the DWS unemployment rate by the share unemployed to estimate the share of displaced workers unemployed as a result of displacement.

For demographic and geographic sub-groups, we use the DWS shares in the same way as discussed above. We also use their specific unemployment rates for the baselines.

III. Participation simulations: from displacement to leaving the labor force

As noted above, the DWS also shows that some displaced workers exit the labor force altogether. So, another impact to track is how much the adoption of AVs could reduce the size of the labor force. That is, what share of the workforce laid off from AVs is likely to be neither working nor looking for a job? Our strategy is to take the Displaced Worker Survey (DWS) estimates of decline

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[173] We know that the share unemployed due to displacement will decline over time until it reaches the new steady state, but not how fast it declines. It is also likely (because we see this in Years 1-3) that the pace slows every year, reflecting accumulating scarring from long-term joblessness, skills gaps, or other barriers. So, the path should be concave. By adopting a linear path ending in Year 6, we almost certainly overestimate unemployment effects in Years 4 and 5, and underestimate those effects for Years 6 and beyond. Whether these effects balance out depends on how many people continue actively looking for work and are unable to find it seven or more years after displacement. For the full sample, the overall remaining divergence in unemployment rates in Year 3 is 10.1 percent (16.6 percent minus 6.5 percent, see Table B-1), far lower than in Years 0 through 2. Future work on simulations such as these should tap into longitudinal studies to refine such calibrations and the concept of the year-by-year baseline.

[174] That way, at year 6 we compare unemployment for this set of workers to that for the whole country, but for earlier years, we take account of their lower unemployment than the average worker because they all had jobs at the beginning of year 0. We call this the baseline unemployment for each year. It begins at zero and converges to the national average by year 6. Note that in the Job Openings and Labor Turnover Survey, average monthly turnover (also called the separation rate) across the U.S. from December 2000 to September 2017 was 3.5% per month. At that rate, if displaced workers have an equal and typical chance of separating each month without displacement, then over 78 months (six years plus half of year 0), over 94 percent of workers would have left their jobs "normally" (without being displaced by AV).

in participation in years 1 to 3 after displacement and project them forward beyond the six years covered in the unemployment simulations.

To begin with, it is important to note that the pool of people out of the labor force is not composed of the same people every year. A steady average can mask a considerable amount of cycling in and out the labor force. For example, some workers (especially young ones—and displaced workers are typically younger than average) will opt to get more education or training and re-enter the labor force after they finish. Others may take time off to attend to family responsibilities for a while, caring for children or parents, and return after that. On the other hand, some displaced workers may exit if they fail to find suitable work after a long search. They may stop searching for an extended time or permanently. So, the decrease in labor force participation should be seen as an increased tendency for many to spend some time not working as well as premature retirement by a smaller number.

Simulating participation decline for displaced workers poses some challenging questions. How long does the decline in participation persist beyond the three years we observe in the DWS and the six years we model for unemployment impacts?

The starting point is the unemployment simulation described in Table B-1, which shows how we expand the participation effects to years 0 and to years 4-6. As noted, we find a flat effect of displacement on labor force participation for years 1-3 for the sample as a whole and for all subgroups other than the oldest workers (age 55-64). That is, we model the participation effect as a discrete jump in workers' tendency to be out of the labor force compared to full participation before. Then, for years 1-3 we take DWS shares.

Going beyond the three years raises the question of how long the average displaced worker could have been expected to work without displacement. It is far too extreme to assume that the whole labor force shrinks a bit, permanently, with each displacement event. Laid off workers do not work or live forever; they all leave the labor force eventually. Thus, the impact on the labor market must surely taper off over a longer span as the group ages. This does not contradict the lack of a decline in the DWS samples over a short time.

To project the period of impact forward, we estimate the average remaining worklife of the DWS sample (using forensic worklife expectancy estimates from Krueger and Slesnick[175]—a standard resource for forensic economists), adjusted for the sex and age of the DWS sample to be 16 years. Midway between assuming that the impact of displacement on workers is permanent and assuming it disappears after three years is taking a linear decay after three years for the remainder of expected worklives. This implies that we expect the labor force participation of displaced workers to converge to that of non-displaced workers after 16 years. This pattern is shown in Table B-3 and in Figure III-1.

[175] Kurt Krueger and Frank Slesnick. "Total Worklife Expectancies." *Journal of Forensic Economics* 25, no. 1 (2014), pages 51-70

TABLE B-3: Impact of Displacement on Labor Force Participation

Years after displacement	Increase in share of workers not in the labor force after displacement		
	All	Men	**Women**
-1	0	0	0
0	0.067	0.051	0.085
1	0.130	0.103	0.166
2	0.126	0.089	0.180
3	0.133	0.111	0.165
4	0.123	0.103	0.152
5	0.113	0.095	0.139
6	0.102	0.087	0.127
7	0.092	0.079	0.114
8	0.082	0.071	0.101
9	0.072	0.063	0.089
10	0.061	0.055	0.076
11	0.051	0.048	0.063
12	0.041	0.040	0.051
13	0.031	0.032	0.038
14	0.020	0.024	0.025
15	0.010	0.016	0.013
16	0.000	0.008	0.000
17		0.000	

Source: See Table B-2 for source of years -1 and 0. Years 1, 2 and 3 are taken from the BLS Displaced Worker Survey. For all and women workers, Years 4-16 are a linear decline from the year 1 to year 3 average to zero. Year 16 is the average expected worklife of all and women workers in the labor force with the same age and sex distribution as the combined 2012, 2014, and 2016 Displaced Worker Survey samples, using expectancies from Kurt V. Krueger and Frank Slesnick, "Total Worklife Expectancy," *Journal of Forensic Economics* 25, no. 1 (April 2014): 51-70. http://www.journalofforensiceconomics.com/doi/abs/10.5085/jfe.25.1.51 For men, the average expected worklife is 17 years, so the impact stretches over an additional year.

Weighting those worklife estimates by the DWS yields an average expected remaining worklife of 16 years for the DWS sample. We take a linear path of declining impact that ends in the sixteenth year after displacement. For men the worklife length is 17 years, while for women it is 16.

The DWS makes clear that participation effects are longer-lived than unemployment effects. Davis and von Wachter[176] also state that:

> Previous research also finds that job displacement leads to other adverse consequences. Lasting post-displacement earnings shortfalls occur alongside lower job stability, greater earnings instability, recurring spells of joblessness, and multiple switches of industry or occupation…Lower job stability and higher earnings volatility persist up to 10 years after displacement. Thus, there is no indication that laid-off workers trade a lower earnings level for a more stable path of employment and earnings.

This is consistent with the fact that many workers find lower wage jobs after displacement. That is, as the wages offered to many workers will be lower or more volatile than their previous job, some of them choose not to work. The alternatives of early retirement or taking on family responsibilities are more rewarding. Long-lived impacts on participation are also consistent with these workers not finding stable employment, so they cycle in and out of the labor market more often.

IV. State occupation location quotients

To complement the analysis of regional impact in our simulations, Table III-2 summarizes information from BLS state Occupation Location Quotients. That table is built on the state location quotients provided in Table B-4.

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[176] Steven Davis and Till von Wachter. "Recessions and the Costs of Job Loss." *Brookings Papers on Economic Activity*, 2011 no. 2. https://www.brookings.edu/bpea-articles/recessions-and-the-costs-of-job-loss/

TABLE B-4: Occupation Location Quotients (LQs) for Primary Driving Occupations*

State	Heavy and Tractor-Trailer Truck Drivers	Light Truck or Delivery Services Drivers	Bus Drivers, School or Special Client	Driver/ Sales Workers	Taxi Drivers and Chauffeurs	Bus Drivers, Transit and Intercity	Ambulance Drivers and Attendants, Except Emergency Medical Technicians
AL	1.37	0.99	1.34	0.99	0.47	1.00	**2.04**
AK	0.70	0.89	0.87	0.67	0.86	0.81	
AZ	0.72	0.90	0.74	1.07	1.38	1.14	0.85
AR	**2.30**	0.87	1.42	0.82	1.04	0.25	0.34
CA	0.67	1.02	0.5	0.83	0.83	1.21	0.76
CO	0.77	1.11	0.65	0.86	0.74	1.10	0.53
CT	0.69	1.03	**1.68**	0.65	**1.71**	0.82	0.48
DE	0.73	0.85	1.34	1.19	0.89	0.90	1.04
DC	0.06	0.39	0.48	0.21	0.45	0.30	
FL	0.78	1.01	0.67	1.04	0.98	1.04	0.15
GA	1.10	1.01	1.16	1.13	0.51	0.69	**1.71**
HI	0.46	1.21	0.61	0.89	**1.57**	**3.00**	
ID	1.48	0.79	1.10	1.27	0.70	0.88	1.11
IL	0.93	1.27	1.04	0.73	1.02	1.16	1.01
IN	1.45	0.94	1.29	1.27	0.61	0.50	0.40
IA	**2.02**	0.99	0.95	0.87	0.81	0.85	1.46
KS	1.19	0.99	1.32	1.08	0.71	0.24	
KY	1.19	1.09	1.48	0.97	0.71	1.04	0.24
LA	0.97	1.23	1.17	0.57	0.86	0.51	0.89
ME	1.16	1.22	1.00	1.33	1.02	0.56	**3.73**
MD	0.73	1.35	1.18	0.92	1.34	**1.88**	0.54
MA	0.59	1.05	1.08	0.91	**2.13**	1.08	1.50
MI	1.04	1.07	0.87	1.03	0.75	0.71	0.76
MN	1.01	0.86	**1.52**	1.03	1.04	1.08	
MS	**1.66**	1.04	1.28	1.10	0.59	0.54	1.08
MO	1.27	0.91	1.16	1.27	0.79	0.68	0.15
MT	1.18	1.20	1.20	1.25	0.73	0.98	1.13
NE	**2.29**	0.81	1.01	1.23	0.82	0.77	0.85
NV	0.69	0.94	0.49	1.08	**6.88**	**1.67**	
NH	0.82	1.15	1.10	1.16	1.37	0.31	
NJ	0.9	1.11	1.21	0.61	1.55	1.30	**1.59**
NM	1.01	0.94	0.92	1.05	0.96	0.78	**1.75**
NY	0.52	0.79	**1.51**	0.08	1.24	**1.90**	**1.72**
NC	1.06	0.97	1.07	1.23	0.67	0.63	0.47
ND	**2.36**	1.05	0.91	1.43	1.10	0.32	**7.37**

OH	1.09	1.07	0.57	1.37	1.05	0.91	1.43
OK	1.21	0.92	0.79	0.98	0.73	0.53	0.75
OR	1.00	0.83	0.97	1.18	0.70	1.01	0.30
PA	1.12	0.98	**1.50**	0.99	0.99	0.78	**3.23**
RI	0.55	1.29	1.11	0.99	0.85	0.27	1.12
SC	1.10	1.11	0.78	1.25	0.61	0.34	**3.57**
SD	**1.53**	1.01	1.02	0.88	1.12	0.43	
TN	**1.65**	1.06	1.05	1.03	0.71	0.73	0.43
TX	1.23	0.92	0.80	1.36	0.68	0.91	0.55
UT	1.34	1.00	0.48	0.73	0.74	0.51	0.64
VT	0.96	1.14	1.3o	0.72	**1.67**	1.17	
VA	0.89	0.92		0.94	0.91	1.07	0.62
WA	0.83	0.97	1.07	0.84	0.88	**1.62**	**0.77**
WV	1.28	1.13	**2.11**	1.1	0.73	0.59	**2.83**
WI	1.44	0.95	1.10	0.92	1.44	0.57	0.59
WY	**1.85**	0.90	1.40	**1.89**	1.45	0.57	
Minimum LQ	**0.06**	**0.39**	**0.48**	**0.21**	**0.45**	**0.24**	**0.15**
Maximum LQ	**2.36**	**1.35**	**2.11**	**1.89**	**6.88**	**3.00**	**7.37**
Standard deviation of LQs	**0.475**	**0.158**	**0.336**	**0.268**	**0.901**	**0.500**	**1.313**
Total US employment, in thousands**	1,532	781	212	383	300	75	10
Jobs eliminated in AV scenarios, range in thousands**	919-996	351-430	106	77	60-210	53-56	1

*Occupation location quotients (LQs) measure whether a state specializes in providing a certain type of labor. They are defined as the ratio of an occupation's share of jobs in a state to the occupation's share of jobs in the U.S. as a whole. LQs greater than one signify that the state has a higher concentration of jobs in that occupation than the U.S. as whole. LQs less than one indicate that the state has a lower share than in the nation. An LQ of two indicates that the state has double the share of jobs in that occupation as the country as a whole. The standard deviation of LQs for an occupation is lower if that occupation has a consistent share of jobs in most states. LQs of 1.5 or greater are shown in boldface.

**See Table II-2 for sources.

Source: Authors' calculations from Bureau of Labor Statistics Occupational Employment Survey 2016. https://www.bls.gov/oes/tables.htm. Missing values indicate a very small number of jobs and/or data suppressed to preserve confidentiality of survey respondents. Note that self-employed workers are not included in these statistics.

V. Earnings losses simulations: from displacement to lost wealth

As noted in the framework, AV's transition costs will be borne largely by workers displaced from their jobs by AV. This is a small group compared to those who benefit from AV, which includes all transportation consumers, along with the firms who become early AV adopters and their suppliers. Suppose that some of those benefits could be used to defray the losses likely to be suffered by the displaced workers, what would the bill come to? This exercise aims to answer that question.

A layoff can affect workers' annual earnings in various ways, including causing a period of unemployment, changing the number of hours worked and affecting their wage rate. To simulate earnings losses, we apply an estimate of losses to the layoffs we identified in the unemployment estimates. While there have been many estimates of earnings losses from displacement before, a recent one stands out as particularly valuable for our purposes.

Our earnings simulations are based on a recent careful study of the impact of displacement by Davis and von Wachter.[177] Using longitudinal Social Security records from 1974 to 2008, they calculate, in present value terms, the lifetime wealth costs to workers of being displaced from their jobs. This study has the merits of being based on administrative data (which is very reliable), looking at a large sample, and estimating cumulative lifetime impacts. Overall they find large effects. They state:

> In present-value terms, men lose an average of 1.4 years of pre-displacement earnings if displaced in mass-layoff events that occur when the national unemployment rate is below 6 percent. They lose a staggering 2.8 years of pre-displacement earnings if displaced when the unemployment rate exceeds 8 percent. These results reflect discounting at a 5 percent annual rate over 20 years after displacement. We also document large cyclical movements in the incidence of job loss and job displacement and present evidence on how worker anxieties about job loss, wage cuts, and job opportunities respond to contemporaneous economic conditions.

The results we use are taken from Table 2 of Davis and von Wachter, which we reproduce here in Table B-5. We use the estimates for women and for men with three years of tenure or more (by age group for men), to maximize consistency with the Displaced Worker Survey. This is also the more conservative approach, since losses for men with six years of tenure are much higher. The relevant column is the present discounted value of average loss at displacement "as a multiple of predisplacement annual earnings."

To estimate predisplacement earnings for the occupations affected by AVs, we use occupational average annual earnings for full-time, full-year workers in the American Community Survey (ACS). We apply the multiples in Table B-5 to the ACS annual earnings to estimate the wealth loss to individuals and sum them up for the number of workers we estimate will be displaced by AV adoption.

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[177] Steven Davis and Till von Wachter. "Recessions and the Costs of Job Loss." *Brookings Papers on Economic Activity*, 2011 no. 2. https://www.brookings.edu/bpea-articles/recessions-and-the-costs-of-job-loss/

TABLE B-5: Reproduction of Table 2 from Davis and von Wachter (2011): Present-Discounted Value (PDV) of Earnings Losses after Mass-Layoff Events, 1980–2005[178]

Group[179]	Present discounted value (PDV) of average loss at displacement		
	Dollars	**As a multiple of predisplacement annual earnings**	**As percent of PDV of counterfactual earnings[180]**
Women 21–50, 3 or more years tenure			
All years	38,033	1.5	10.9
Expansion years only	33,164	1.3	9.5
Recession years only	68,782	3.3	20.6
Men 21–50, 6 or more years tenure			
All years	106,900	2.0	12.9
Expansion years only	100,543	1.8	11.9
Recession years only	148,400	3.0	20.0
Men 21–30, 3 or more years tenure			
All years	50,240	2.1	9.8
Expansion years only	39,639	1.7	7.8
Recession years only	117,322	4.0	22.0
Men 31–40, 3 or more years tenure			
All years	49,599	1.2	7.7
Expansion years only	42,555	1.0	6.5
Recession years only	93,833	2.2	16.0
Men 41–50, 3 or more years tenure[181]			
All years	98,519	1.8	15.9
Expansion years only	95,716	1.7	15.1
Recession years only	116,515	2.2	21.9
Men 51–60, 3 or more years tenure[182]			
All years	99,288	1.8	24.0
Expansion years only	97,934	1.7	23.1
Recession years only	108,248	2.1	31.1

Source: Reproduced from Steven Davis and Till von Wachter. "Recessions and the Costs of Job Loss." *Brookings Papers on Economic Activity*, 2011 no. 2. https://www.brookings.edu/bpea-articles/recessions-and-the-costs-of-job-loss/

[178] Present discounted values (PDVs) are calculated over the 20 years following displacement as described in table 1 of Davis and von Wachter (2011), except as noted below. Dollar figures are in dollars of 2000.

[179] Ages and years of tenure are as of time of displacement. Values for years containing both expansion and recession months or monthly unemployment rates that fall in different ranges are calculated as described in table 1 of Davis and von Wachter (2011).

[180] Counterfactual earnings are what the displaced worker would have earned over the same 20 years had he or she not been displaced.

[181] PDVs are calculated over 15 years.

[182] PDVs are calculated over 10 years.

We consider these estimates rough for a number of reasons. First, not all the AV displaced workers will be working full-time, year-round, as the ACS wage estimates assume. Second, Davis and von Wachter's estimates cover only workers with three years of experience, whereas some AV workers will have less than that. This analysis does not take into account that employers may lay off workers with lower or higher wages on average or with more or less experience, or if there will be any shift to part-time or less-than-full-year working arrangements. Any of those decisions will affect the eventual magnitude of losses to AV workers. Third, we do not know the stage of the business cycle during which layoffs will occur. As Table B- 5 shows, layoffs during recessions are far costlier (about twice) to workers than those during expansion years. Thus, actual losses could be much higher or lower.

VI. Summary of sources used for impact simulations

For easy reference, Table B-6 provides a comprehensive list of the sources we use in all parts of the simulations in this paper.

TABLE B-6: Sources and Uses of Inputs for Impact Simulations

Simulation	Input	Source	Notes
Unemployment and labor force participation	Labor market status of displaced workers with 3+ years of tenure before displacement, by sex, age, region, education, and race	Displaced Worker Surveys for 2012, 2014, 2016, Current Populations Survey, Bureau of Labor Statistics	Tabulations provided by Henry Farber, Princeton University and downloads from BLS website.
	Unemployment rate, seasonally adjusted, by sex, age, region, education, and race	Current Population Survey, Bureau of Labor Statistics, for January 2012, 2014, and 2016	Downloads from BLS website
	Expected worklife by sex and age	Kurt Krueger and Frank Slesnick. "Total Worklife Expectancies." *Journal of Forensic Economics* 25, no. 1 (2014), pages 51-70	Table 3
	Participation rate by sex, age, region, education, and race	Current Population Survey, Bureau of Labor Statistics	Downloads from BLS website
	Occupational turnover projections	Bureau of Labor Statistics Employment Projections 2016-2026	Downloads from BLS website
Earnings	Net present value of earnings losses for displaced workers by sex and age	Steven Davis and Till von Wachter. "Recessions and the Costs of Job Loss." *Brookings Papers on Economic Activity*, 2011 no. 2.	Table 2
Driving-related Injuries and fatalities	On-the-job injuries from traffic accidents by occupation	Survey of Occupational Illnesses and Injuries, Bureau of Labor Statistics, 2016	Downloads from BLS website
	On-the-job fatalities from traffic accidents by occupation	Census of Fatal Occupational Injuries, Bureau of Labor Statistics, 2016	Downloads from BLS website
All	Employment, wages, and demographics by occupation	American Community Survey, Census Bureau, 2015	Downloads from Census website
	Proportion of jobs that require driving	Occupational Requirements Survey, Bureau of Labor Statistics, 2016 and 2017	Downloads from BLS website
	Occupations affected by AV	David Beede, Regina Powers, and Cassandra Ingram, "The Employment Impact of Autonomous Vehicles" ESA *Issue Brief* #05-17, Office of the Chief Economist, Economics and Statistics Administration, U.S. Department of Commerce. August 11, 2017. Consultation with SAFE transportation experts	