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Introduction

Transportation innovations and investments have contributed significantly to U.S. economic growth. They have enabled households to optimize their residential and workplace locations and their choice of employers; encouraged firms to increase the size and scope of their markets, reduce their inventories, and expand their choice of workers; and allowed consumers to benefit from greater competition among domestic and international firms and from more product variety. The motor vehicle, which has contributed greatly to those socially desirable activities, has been listed among the greatest human inventions of all time (Bowler 2017; Winston 2010).

The increasing dominance of cars and trucks for transporting passengers and freight has evolved with the development of the U.S. public road system, which represents the nation's largest civilian public investment and has become the arterial network of the U.S. economy. Today, some 90 percent of commuters use cars to get to work, 70 percent of travelers use cars for intercity trips, and 30 percent of shippers of intercity freight (measured in ton-miles) and nearly all of their urban freight is shipped by truck—all of those movements rely on a federal-highway capital stock that is valued at roughly $3 trillion (Winston 2013).[1]

Given the importance for the U.S. economy of motor-vehicle transportation and the infrastructure that it uses, significant changes in the performance of either could have a large effect on economic growth. To date, however, the road network has been characterized by growing traffic congestion, deteriorating pavement, crumbling bridges, and a staggering number of crashes. The annual cost of congestion, vehicle damage, and injuries and fatalities runs in the trillions of dollars.

Some economists have argued that the decades-long underfunding of highway infrastructure is the cause of those problems. They have called for policymakers to increase expenditures to repair pavement, renovate bridges, build new roads, and modernize signaling.[2] Other economists have highlighted the inefficiencies in government highway pricing and investment policy, arguing that the public sector has wasted hundreds of billions of dollars by failing to charge road users for their contribution to congestion and their damage to pavement and bridges and by neglecting to make investments that maximize social benefits.[3]

Those calls for reform have largely gone unanswered. Federal efforts to improve our nation's highway system have stalled for decades. Although nineteen states have raised their gasoline taxes since 2015, they have done so only because improvements in the fuel economy of the nation's automobile fleet—together with a federal gasoline tax that has been fixed at its 1993 level of 18.4 cents per gallon—have led to shortfalls in federal money available from the federal Highway Trust Fund (Langer, Maheshri, and Winston 2017).[4] Both major political parties agree that the United States has been experiencing an infrastructure crisis for years. However, they have yet to take any major steps to address it.

The Emergence and Potential of Autonomous Vehicles

Notwithstanding those bleak conditions, there is still hope for the highway transportation system. Self-driving or autonomous vehi-

cles, a long-awaited catalyst for change, are quickly emerging from the private sector. As this book argues, autonomous vehicles represent a watershed moment in the development of transportation. If properly encouraged, this innovation promises not only to vastly improve road travel and generate huge benefits to travelers, shippers, and delivery companies but also to benefit the entire economy by reducing congestion and virtually eliminating vehicle accidents. In addition, although autonomous vehicles' effects on land use, employment, other modes of travel, and public finance are likely to be mixed, the negative effects are generally overstated, because they ignore plausible adjustments by the public and policymakers that could ameliorate them.

As Bowler (2017) notes in the case of air transportation, as late as the 1920s skeptics still scoffed at the whole idea of a commercially viable aviation industry. Rapid technical developments soon allowed their arguments to be discounted. Still, as late as 1937, Sir Harold Harley told a BBC audience that no major innovations could be foreseen in aviation technology (Bowler 2017).

Similarly, autonomous vehicles have attracted vocal naysayers, who assert that the technology may never work effectively enough to improve highway transportation significantly or that it will take a long time before those vehicles are in regular use and that even then, they are likely to increase road travel and to worsen congestion. Litman (2019) summarizes various doubts about autonomous vehicles. The popular press also feeds negative views with pieces titled "Cars Are Death Machines. Self-Driving Tech Won't Change That" (Arieff 2019) and "Silicon Valley Pioneered Self-Driving Cars. But Some of Its Tech Savvy Residents Don't Want Them Tested in Their Neighborhoods" (Siddiqui 2019).

We and others are optimistic about the likely success of autonomous vehicles in the long run for a number of reasons. The competition and cooperation that is evolving in the autonomous-vehicle industry is unprecedented in its global scope. The technology has greatly progressed and continues to advance at a rapid rate. The in-

centives for industry participants to succeed and the cost of failure are enormous. And it is plausible that competition among cities, states, and even countries will develop and provide incentives for policymakers to enact policies that expedite the adoption and efficient operations of autonomous vehicles.

Nonetheless, doubters are likely to modify their views only if and when autonomous vehicles are widely adopted and are operating safely and efficiently. In the meantime, policy analysts can play an important and constructive role by identifying and analyzing some important policy issues that must be addressed effectively to ensure that autonomous vehicles will be safe and efficient when the public begins to adopt them to replace nonautonomous vehicles.

A Global Effort

In 2011 two top engineers for Google traveled to Detroit in the hope of working with a car company to build and sell a fleet of self-driving cars (Burns and Shulgan 2018). But when no one in Detroit was interested, Google (and subsequently Waymo, its self-driving car project) took the lead in introducing autonomous vehicles to the world. A few years later, U.S. and foreign automakers, other technology firms, and various start-up ventures were in hot pursuit, either by themselves or in a partnership.[5] Now, nearly all major car companies in the world, as well as technology, cargo, and startup companies, are engaged in developing autonomous vehicles.[6] Hundreds more companies have emerged to develop various components of the technology.

Various partnerships between foreign firms, governments and firms, and universities and firms abound. Waymo has struck a deal with Renault-Nissan to bring driverless cars to Japan and France; Ford and Argo.ai are in talks with Volkswagen about building self-driving car fleets; GM Cruise is partnering with Honda; Uber is growing closer with Toyota; and Fiat-Chrysler and Amazon are partnering with Aurora. China and South Korea have indicated their intention to support the efforts of their companies to become world

leaders in autonomous-vehicle technology and adoption. Other countries are likely to follow suit. And America's leading technology universities, including but not limited to MIT and Carnegie Mellon, are aiding the autonomous-vehicle industry by researching ways to improve the vehicles' performance in complex driving environments and by training the computer-science talent that the industry is employing.[7]

Today, total global investment in autonomous-vehicle technology exceeds $100 billion, and that figure is increasing rapidly as competition intensifies (Kerry and Karsten 2017). For example, Hyundai announced that it is planning to invest some $35 billion in autonomous-vehicle technology by 2025.[8] Atkinson and Foote (2018) notes that global growth in autonomous vehicles is expected to be fastest in North America. Foreign automakers and technology companies have been investing in U.S.-based R&D and are locating in the United States, underscoring U.S. leadership in this emerging field.

At the same time, countries throughout the world are investing in infrastructure to facilitate autonomous vehicles production and adoption. China is building a new highway with dedicated lanes for autonomous vehicles that will be used by their leading autonomous-vehicle companies, Baidu, Pony.ai, and WeRide. The highway connects Beijing and the Xiong'an New Area in Hebei Province, some sixty miles away. In addition, China's leading telecommunications equipment manufacturer, Huawei, is building technology that could take on a large part of the processing required to run an autonomous vehicle.

Although firms are partnering with one another, they are also competing intensely to offer a reliable autonomous vehicle to the public because their very existence is at stake. In the United States, General Motors survived even though the Chevrolet Bolt was not the successful electric vehicle it had hoped for, while Tesla developed an electric vehicle that is selling nearly 200,000 units annually. However, General Motors and Ford will face much more competition in

the market for autonomous vehicles, with far greater implications for their market shares. These companies are transforming themselves by closing plants that produce passenger cars, slashing their workforce to save billions of dollars annually, and using these savings to invest in new technologies that they hope will propel them to the forefront of the autonomous-vehicle industry of the future.[9] Although the U.S. government has helped domestic automakers in the past by providing them with bailouts and protection from foreign competition, financial assistance will not transform a U.S. firm that falls behind in the highly competitive global autonomous-vehicle industry into an industry leader, and it is therefore unlikely to be provided by the government.[10]

As a result of industry competition and cooperation, vehicle technology is progressing at such a rapid rate that the relevant question in America is no longer whether its surface-transportation system will be made up entirely of autonomous vehicles in the foreseeable future. The question is when will the transformation occur. And that question cannot be addressed without understanding the pervasive role of government in the adoption process.

In any case, recent testing has moved beyond operating the vehicle in good weather and in a low-risk environment to identifying and overcoming atypical but challenging conditions that could arise in practice, such as driving in blinding snow and combating terrorists' efforts to cause a vehicle to crash into other vehicles or to run over pedestrians. In addition, automobile and technology companies are developing the capacity to promptly fix any technical problems in their autonomous-vehicle fleets, and they are increasingly aware of the liability issues that surround autonomous vehicles.

The Role of Government

Government policymakers do not simply need to stay out of the way to facilitate autonomous vehicle transportation. They must take a number of important steps, which include establishing a framework

for vehicle testing and conditions for adoption, making appropriate investments in highway-network technology to facilitate communication between autonomous vehicles and between such vehicles and highway infrastructure and operators, and reforming pricing and investment policies to enable the safe and efficient operation of autonomous vehicles.

Accordingly, policymakers pose a greater risk than industry participants regarding when, if ever, U.S. society realizes the huge potential benefits of autonomous vehicles. They could delay implementing guidelines for testing of autonomous vehicles and ensuring their timely adoption. They could put off the costly investments in technology that facilitate communications between vehicles and from vehicle to infrastructure and network, some of which public authorities will have to install and manage effectively to facilitate mass use of autonomous vehicles on the U.S. road system. And they could fail to remedy inefficiencies in highway-infrastructure pricing, investment, and production policy, which have compromised nonautonomous-vehicle travel for decades and must be reformed to enable autonomous vehicles to operate efficiently and to raise revenue from highway users to help finance the investments in new infrastructure technology.[11]

A Brief Roadmap

The main purpose of this book is to present an overview of the potential benefits of autonomous vehicles, providing empirical estimates wherever possible, and to assess the current technological challenges and public-policy concerns. Its goal is to encourage industry participants and policymakers to make constructive use of the time between the current period, when autonomous vehicles are being tested in selected locales, and the transition period, when the public starts to adopt autonomous vehicles for their actual travel, to significantly address the potential problems. Although the book focuses primarily on the United States, the substantive and policy

issues raised here are relevant for all countries that seek to adopt autonomous vehicles expeditiously and successfully.

This book draws three primary conclusions.

The potential benefits from autonomous vehicles are extensive and enormous. In particular, the benefits to the economy from reducing congestion could raise annual economic growth by at least 1 percentage point. In addition, the gains from virtually eliminating fatalities, injuries, and collision damage would be very large. Finally, the alleged costs of autonomous vehicles in terms of land use, employment, other modes of transportation, and public finance are likely to be overstated. In fact, they could be turned into positive effects through plausible adjustments by the public (for example, in housing and labor markets) and through the implementation of efficient public policies by transportation officials.

The major obstacles to realizing most of the potential benefits are primarily policy related, rather than technological. The federal government has already delayed vehicle testing and adoption, and it seems unable to understand that current inefficiencies in highway policy pose a serious threat to the success of autonomous vehicles. Some local and state governments have shown an interest in upgrading their infrastructure technology so that their roads could be used efficiently by autonomous vehicles, but they have not turned their attention to reforming inefficient highway policies.

In the long run, despite the failure of policymakers to implement efficient highway infrastructure policies in the past, competitive forces at the city, state, and even country level may spur policymakers to reform their highway policies to enhance autonomous vehicle operations. Given that policymakers have time to adjust their policies, cautious optimism that trillion-dollar bills will not be left on the sidewalk in the coming decades is warranted.

As this book went to press, a global pandemic had broken out, caused by a coronavirus (COVID-19) that was first detected in Wuhan, China. The outbreak quickly manifested an unforeseen benefit of autonomous vehicles by spurring China to expedite pro-

duction and adoption of autonomous delivery services provided by small vans. Autonomous delivery services enabled medical providers and consumers to reduce their human exposure and address labor shortages caused by quarantines. As the coronavirus spread to the United States and other countries, public health professionals stressed the importance of "social distancing"—maintaining physical distance from others—to curb the virus's spread and to "flatten the curve," meaning that people would become infected more gradually, thus preventing surges in the need for medical services that would overwhelm hospitals. In the short run, autonomous vehicle companies are likely to focus more of their efforts on autonomous deliveries. In a post-coronavirus world, autonomous vehicles carrying passengers and cargo will gain significant attention as a vital way to flatten the curve associated with future viruses and to reduce the disruption of economic and other activities. Accordingly, the book's focus on governments taking actions to expedite the adoption and efficient use of autonomous vehicles has even greater urgency and importance.

Part 1 of this book discusses autonomous vehicle operations and the process of vehicle adoption. The various potential effects of autonomous vehicles on travel conditions and the economic environment are addressed in part 2. Given autonomous vehicles' potential to reduce congestion, and the difficulty of establishing a causal relationship between congestion and various economic performance measures, we devote considerable attention to developing and executing an approach to provide a rough estimate of the effect that autonomous vehicles could have on economic growth by reducing congestion. Congestion is an important example of a negative effect of traditional or nonautonomous vehicles that autonomous vehicles could reduce. We also discuss the other negative effects of automobiles that autonomous vehicles could reduce, including threats to travelers' health and safety, and examine how autonomous vehicles could affect accessibility, land use, the overall U.S. transportation system, employment, and public finance. Fi-

nally, in part 3 we assess the technological and public-policy issues that could impede the success of autonomous vehicles and draw preliminary conclusions about whether competition among cities, states, and countries to enable consumers to realize the benefits of autonomous vehicles could influence policymakers to address those issues adequately.