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Review

The impact universe—a framework for prioritizing the public interest in the Internet of Things

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THE BIGGER PICTURE Digital technologies are fundamental to the world we live in. Internet-connected systems and devices are a critical infrastructure: they run power and water systems, they drive cars, planes, and trains, and they have changed how we do business. They provide a platform for social interaction—targeting and modulating a mindboggling set of options.

The increasing ubiquity, decision-making capabilities, and far-reaching impacts of connected technologies have profound implications for individuals and society. They mandate new social controls—policy, regulation, law, standards, recommended practice—that promote the public interest in a rapidly changing environment. Developing effective social controls requires a holistic appraisal of their potential impact on society and the environment.

The "impact universe" is a framework that exposes a broad set of impacts—both quantifiable and qualitative—to assess the benefits and risks of connected systems and devices. Developing an impact universe framework requires a stakeholder to identify benefits and risks in aggregate; it encourages them to focus beyond the single metric valuation that often characterizes the development of social controls for connected systems. It provides a tool for stakeholders to more effectively guide technological innovation, so that the design, development, use, and standardization of connected products and services advances the public interest and promotes social responsibility in a tech-powered world.

SUMMARY

The connected technologies of the Internet of Things (IoT) power the world we live in. IoT systems and devices are critical infrastructure—they provide a platform for social interaction, fuel the marketplace, enable the government, and control the home. Their increasing ubiquity and decision-making capabilities have profound implications for society. When humans are empowered by technology and technology learns from experience, a new kind of social contract is needed, one that specifies the roles and rules of engagement for a cyber-social world. In this paper, we describe the "impact universe," a framework for assessing the impacts and outcomes of potential IoT social controls. Policymakers can use this framework to guide technological innovation so that the design, use, and oversight of IoT products and services advance the public interest. As an example, we develop an impact universe framework that describes the social, economic, and environmental impacts of self-driving cars.

INTRODUCTION: MANAGING CONNECTED TECHNOLOGIES TO PROMOTE THE PUBLIC INTEREST

It is hard to fathom just how fundamental technology has become in the world we live in. Internet-connected systems and devices are critical infrastructure—they run power, water, and communication systems, they drive cars, planes, and trains, and they have changed how we do business. They provide a platform for social interaction—targeting and modulating a mindboggling set of options. They power the marketplace, manage the organization, enable the government, and control the home.

The increasing ubiquity, decision-making capabilities, and far-reaching impacts of connected technologies, also called the Internet of Things (IoT), have profound implications for individuals and society. When humans are empowered by technology and technology learns from experience, a new kind of social contract is needed, one that specifies the roles and rules of engagement for a cyber-social world. Creating this social contract requires promoting the public interest in a rapidly changing environment driven by technology innovation and the business opportunities it provides. It requires social controls—policy, regulation, law, standards, recommended practice—that promote human benefits and mitigate the risks and dangers of a tech-powered world.

The goals of this paper are 2-fold: (1) to describe a framework—the "impact universe" —for thinking holistically about the potential impacts of social controls for systems and the devices in the IoT, and (2) to demonstrate by example—through development of an impact universe framework for self-driving cars—how complex it is to balance distinct public-focused goals and strategies to promote beneficial outcomes. In general, creating and employing an impact universe framework proceeds in three phases: first, a stakeholder (a policymaker for our purposes) identifies relevant public interest goals and key strategies that promote them. Second, she identifies synergies and incompatibilities between the chosen strategies and goals and revises them as necessary. Third, she develops targeted social controls that promote the synergies of the chosen strategies and goals and minimize their incompatibilities. This must be done with respect to the context in which the social controls will be deployed, and targeted to time frames specific to this context.

This is not straightforward. Different policymakers working on the same issues often have competing goals and strategies and varying abilities to control/guide public outcomes. Moreover, the complexity of developing socially responsible policy is exacerbated by the complexity of architecting (or re-architecting) technology to support public versus private interests. This is especially true for the heterogeneous, decentralized IoT that underlies much of the technological world we live in.

The IoT is a deeply integrated ecosystem of devices and systems that commonly exchange information, make decisions, and manage and monitor in the background. Everyday devices and systems—baby monitors, phones, home appliances, cars—increasingly connect to the Internet and collect information, modulate choices, and autonomously take on decision-making responsibilities.

These technologies have tremendous benefits and sometimes dangerous risks. Smart medical devices can efficiently regulate insulin or monitor heartbeats, alerting the individual and medical professionals when, or before, there is a problem. But without adequate cybersecurity protections, smart medical devices can be easily hacked, with potentially catastrophic or fatal results. This presents a challenge for manufacturers: How much safety and at what price? Beefing up cybersecurity increases the time and effort spent on product design, development, and testing, potentially making products more expensive and/or increasing time-to-market. Fixing vulnerabilities after product release may also be problematic, as technical architectures can be difficult and expensive to reverse-engineer. Facebook's iconic motto—"move fast and break things" —increases economic competitiveness, but it is an irresponsible approach for IoT products and services used as critical infrastructure, or when "breaking things" has potentially catastrophic results.

The lifeblood of the IoT is data—data that are often collected and retained for competitive advantage by private entities who fully control all aspects of its access, stewardship, preservation, and use. Lack of transparency and access to these data can work against the public interest: accident statistics from tests with self-driving cars are needed to gauge their level of safety, yet many states do not require private companies to report this information. Consumer data used for pricing or assessment may exacerbate social inequities, yet their algorithms, data, and training sets are often unavailable for public scrutiny. Effective IoT policy must focus not just on products and services, but on complex issues regarding the stewardship, preservation, access, and use of the valuable data that drives them.

For technology to advance society, the design and development trajectory of the IoT must be managed. Creating social controls that ensure that IoT products incorporate adequate safety and security, and other public protections requires leadership from the public sector, whose mission it is to promote and protect the public interest. Moreover, it is easier for companies to incorporate public protections when everyone has to do it. With leadership and social controls from the public sector, the current culture of tech opportunism can begin to move toward a culture of tech in the public interest.

Creating social controls is complex, to say the least. Effective standards, policy, and regulations must be crafted that promote individual, community, and environmental protections during design, development, deployment, use, interaction, and disposal of IoT devices and systems. New laws, policy, and regulations must be created to deal with decision-making technologies, and to assign liability when autonomous systems fail. Many potential impacts of IoT devices and systems are unclear and need to be formally studied. Good social controls must be specific and enforceable, promote well-defined public objectives, and coordinate multiple strategies to achieve desired outcomes. Creating them is not an exact science.

The emerging field of Public Interest Technology (PIT) can help. PIT focuses on the development and use of technology in a socially responsible manner, with the goal of promoting the common good. PIT strategies include public-focused product design, standards that promote safety, security, and other public interests, and public interest-focused policy and regulation. These strategies are important because, without them, profit, market leadership, and other private sector goals may prevail, often leaving consumers and citizens at increased risk. PIT strategies provide a way to rein in tech and reduce catastrophic outcomes. They help regulators, policy makers, and technologists think holistically about the social impacts of tech products and services, using multi-disciplinary perspectives from computer and information science, law, policy, ethics, social science, science and technology studies, and domain disciplines. These perspectives can be synergized into a holistic framework—the impact universe—that provides a PIT-focused way of looking at the broad and important social effects of the IoT.

We define an impact universe framework for an IoT device or system ("thing") T as a set of goals for T, the strategies that promote these goals, and the interdependencies between all of them. The impact universe exposes T's potential benefits and risks in the larger ecosystem, where human behavior, the characteristics of the natural world, and existing social controls and cyberinfrastructure all influence T's realization. Innovation is not stand-alone; the success and usefulness to the public of IoT device or system T is dependent on its ability to navigate this larger ecosystem.

Creating an impact universe framework is *contextual*—it is dependent on which device or system, which goals, and which strategies are identified to achieve a stakeholder's desired outcomes. It is dependent on whether the target environment is a local, state, or federal jurisdiction. It may also vary based on the population for whom the controls are intended. The impact universe framework is also *holistic*—the framework helps expose trade-offs within the larger cyber-social context in which goals and strategies must be achieved.

An impact universe framework is an abstract construct and, as with many things, the devil is in the details. To illustrate, we describe in this paper an impact universe for the development of social controls for connected autonomous vehicles (CAVs)—self-driving cars. Our purpose is to demonstrate by example how complex it is to identify effective goals and strategies that promote technology in the public interest. Self-driving cars are an ideal focus for this case study—there is already considerable experience with their benefits and challenges, and they have captured the imagination of both industry and the public. Their development trajectory is complex, and the stakes in creating appropriate policy, law, and incentives to guide their development are high. They are expected to become ubiquitous over the next few decades, and they are coming to a highway near you.

But self-driving cars are just one example of how the creation and deployment of the IoT will change the world we live in far more than we expect. The impact universe framework—examination of the synergies and incompatibilities of potential goals and strategies in context—can be used to frame conversations about the development of social controls for any IoT device or system—a connected baby monitor, an implantable insulin pump, a smart refrigerator, a surveillance system, and the like. We briefly describe using the impact universe framework approach for IoT devices and systems other than CAVs in "Beyond CAVs: creating an impact universe for other IoT devices and systems" and discuss the challenges of subjectivity and potential next steps in "The impact universe framework—continuing the conversation."

In the following sections, we focus on CAVs. We describe how policymakers, auto manufacturers, businesses, and the public will influence the trajectory of CAV design, development, and use. The impact universe framework helps focus close attention on the larger social, economic, and environmental context in which this trajectory will evolve. It is both challenging to steer this trajectory toward the public interest and also critical, because ultimately how IoT systems, such as CAVs, are managed matters if we want to ensure that humans thrive, the planet is protected, and society is advanced in an IoT-powered world.

An impact universe framework for CAVs

The development of automobiles has always focused on multiple overarching goals—safety, environmental sustainability, economic growth, etc. Consider the two overarching goals of safety and environmental sustainability. Both are currently the focus of a broad spectrum of transportation-related laws, regulations, policy, and standards, many developed by stakeholders who are public policymakers.

Reducing natural resource depletion is one specific goal that promotes environmental sustainability. As CAVs become more prevalent, manufacturers predict that next-generation CAVs will be lighter, more energy efficient, use algorithms to drive safely, and will not need as much protective safety equipment as current vehicles. The strategy of building lighter-weight CAVs with less safety equipment and more sustainable materials will help achieve the goal of reducing natural resource depletion.

However, the strategy of building lighter CAVs that travel in close, automated eco-platoons at high speeds will be a mixed bag for the overarching goal of safety. While the predictability of CAV platoons will likely reduce the overall number of accidents (one specific safety goal), the accidents that do occur at higher speeds and in lighter cars may be more dangerous to the CAV's occupants, working against the goal of decreasing the percentage of severe accidents (another specific safety goal).

Understanding how the strategy to build lighter-weight, environmentally friendly CAVs may result in both positive and negative safety outcomes raises specific policy issues: How much and what kind of safety equipment should be required? Should there be minimum weight requirements for cars? How fast and close should CAVs travel? Should investments in research be increased to explore safer and more sustainable materials for next-generation CAVs? By taking into account the universe of potential impacts, policymakers can gain important information to assist them in creating effective social controls that achieve their desired outcomes.

For our case study, consider a stakeholder policymaker whose overarching goals are environmental sustainability, public protections, and economic growth. Her specific goals in these areas and the potential strategies that promote them are generalized for illustration, and to demonstrate how complex and contextual developing effective social controls can be. It will be important for our policymakers to partner with technical and industry experts whose deep knowledge is needed to create realistic and effective strategies and specific social controls. This multi-sector, multi-disciplinary approach, a PIT approach, is critical to ensure that social goals are promoted, human benefits are maximized, and the risks of ever more capable and prevalent technologies are mitigated.

Self-driving cars in the cultural imagination

In 1966, one of the Oscar-nominated short-animated films was "What on Earth! The Automobile Inherits the Planet" from the National Film Board of Canada. As per the Film Board: "The animated short proposes what many earthlings have long feared—that the automobile has inherited the planet. When life on Earth is portrayed as one long, unending conga-line of cars, a crew of extra-terrestrial visitors understandably assume they are the dominant race. While humans, on the other hand, are merely parasites."[1]

The film, a bit over 9 minutes long, shows Earth's inhabitants—cars—traveling together, dictating the form of the built environment, "learning," "playing," and "reproducing," all with hilarious and often prescient results. It is not until the last minute of the film that humans are introduced as parasites of the vehicle "earthlings," and ones that do not matter very much.

The film is over 50 years old, but not so far from the future envisioned for CAVs 30–40 years from now (except for the whole "humans as parasites" part …). As vehicles become more and more independent and autonomous, the notion that cars will be driving around on their own, platooning in groups, dictating the development of roads and cities, and changing the transportation economy provides another perspective on how we will experience the social and environmental impacts of future transportation.

In this film and a host of other creative projects, society has imagined a world in which technology dominates. This world is increasingly possible, and the stakes continue to rise with technological innovation, more sophisticated artificial intelligence, and few public protections, all of which encourage tech opportunism, rather than tech in the public interest. The challenge of prioritizing tech in the public interest falls to policymakers, who must help re-orient tech to advance society, and the public, who must both advocate for change and deal with its consequences. Yet the road ahead must be traveled, and social controls that promote tech in the public interest will serve as our best way forward.

But today, in the early 2020s, true self-driving cars have yet to be built. Like many technologies in the IoT, the self-driving car industry has a long way to go before it achieves the full autonomy expected by 2050–2060. As with human-driven cars, the future of CAVs will be driven by both technological innovation and social controls; and, at this juncture, the public sector and the automotive industry have a tremendous opportunity to evolve them in a way that creates far-reaching and beneficial public impacts by the 2050s, when they are expected to be ubiquitous. Before we describe an impact universe framework that can guide future CAV development, we describe the state of the industry and current technological challenges in creating self-driving cars.

State of the automotive industry: True self-driving cars do not yet exist

The first thing to understand about CAVs is that fully operational self-driving cars do not yet exist. In 2016, the US National Highway Transportation Safety Administration adopted a classification system developed by the Society of Automotive Engineers (SAE) that characterizes various levels of vehicle autonomy based on the amount of human intervention and attentiveness needed.[2] According to the SAE classification, the most autonomous cars you can buy in 2020 are level 3 cars. Level 0 cars have no self-driving capabilities. A Model T was a level 0 car, but so are some used pre-adaptive cruise control cars today. Level 5 cars can perform all driving tasks in all conditions—they are true self-driving cars and are still an aspiration. At level 5, the car is the driver, and no human driver is required. You currently cannot buy new cars at either level 0 or level 5.

You still need a driver in level 3 cars and drivers must be ready to take control at any time, but the car can take on many of the responsibilities of monitoring the environment and operation. Many automakers, including Audi, Nissan, Volvo, GM, and Tesla, are beginning to build more and more capable level 3 cars for the consumer market. On a recent road trip with a friend who drives a high-end Tesla, both she and her car shared driving responsibilities. It was an interesting partnership. My friend knew she could rely on the car to navigate itself in highway conditions, but that she needed to take over when driving on poorly marked, narrow residential streets. This knowledge was critical to her understanding of what her car could and could not do, and to driving it safely and effectively.

A level 4 car can essentially drive itself under certain conditions. The catchphrase is "certain conditions" —self-driving models cannot yet handle all the situations the car will encounter and so have not yet reached 100% autonomy (the so far mythical level 5). The transportation industry talks about the scope and limits of the car as its ODD—operational design domain. ODD describes the "operating conditions under which a given driving automation system or feature thereof is specifically designed to function."[3] This means that unusual weather conditions, obstacles that the algorithms do not recognize, or unfamiliar road conditions may all be outside of a level 4 car's ODD and require human intervention. Moreover, some errors may be a consequence of the gap between the assumed limits of an ODD and the environment the ODD actually describes.

Today, level 4 cars are being developed largely for commercial use by both tech and commercial car companies. We expect to see them on the road and available for sale to consumers sometime in the next decade. By 2060, it will be hard to buy a car that is not self-driving.[4] We are not there yet though. In 2017, Forbes predicted that there would be 10 million "self-driving" cars in 2020.[5] That is less than 1% of the 1.4 billion cars on the road in 2020.[6] A lot of innovation, planning, and development has to happen before all transportation becomes smart transportation. And that is not just a challenge but a great opportunity to steer things in the right direction.

How self-driving cars work

The development of self-driving cars has broad social, environmental, and economic repercussions. To understand these repercussions, it is useful to first explore how CAVs work.

Self-driving cars are known in the industry as Connected Autonomous Vehicles and each of these terms has a specific meaning. *Connected*, because data are collected wirelessly from sources external to the car (satellites for weather prediction, information from other cars, signals from highway sensors) as well as sources internal to the car. Data are also sent to external sources (information for other cars, data for the company, data for crowd-sourced functions). *Autonomous*, because sensors in and out of the car provide information to computers that plan and provide instructions to actuators that operate the car.

CAVs are essentially "regular" (human-driven) cars enhanced with cameras and sensors that "see" the environment, computers that *plan* operation, and actuators that *do* the driving. They drive essentially the same way human drivers do—through a sense/plan/act approach—but CAVs do it with sensors and computers rather than human brains. And, like human drivers, they have to perform all these operations in a split second. My friend's Tesla has a variety of screens showing data on the prevailing environment and potential obstacles—almost like a driving video game where the reward is safe and efficient arrival at your destination.

The complexity of the programs used by CAVs to accomplish these self-driving tasks is extraordinary. The car must continuously form a 3D representation of its environment: what is the speed limit, what do road signs say, where is construction? Is the person in the road a pedestrian or police rerouting traffic? What is the weather like? What are cyclists and other cars doing?

To get this information, the CAV uses a variety of sensing systems. These include GPS (global positioning system) to determine location information and LIDAR (light detection and ranging) to "see" things at short distances (up to 450 ft) and assist with emergency braking, pedestrian detection, and collision avoidance. Cameras provide additional details that help with lane departure warnings and traffic sign recognition. Ultrasound (sound wave mapping) helps with adaptive cruise control and obstacle detection. Inertial movement detectors keep track of how many times the wheels rotate for relative distance calculations. Radar (radio wave mapping) helps with blind spot detection, rear collision warning, cross-traffic alerts and other functions.[7]

Why so many sensing/seeing systems? Because each of them has different benefits, ranges, liabilities, and errors. We use different sensors and perspectives to help the car "see" the same landscape robustly and to minimize the weaknesses and errors of any one system. Because the sensors provide multiple perspectives and often information backup for each other, the CAV's computers can more robustly assess the ever-changing environment in which the car is operating.

As the CAV's computers receive information from sensors and elsewhere, algorithms continuously model the surrounding environment to determine how the car should proceed. The CAV's algorithms must detect objects, recognize what those objects are, place them in the environment, and predict how they will move.[8] They do that through a complex and coordinated set of machine learning algorithms. Regression algorithms develop an image-based model for prediction and feature selection. Pattern recognition algorithms filter images in preparation for classification. Clustering algorithms discover structures from data points for hard-to-identify images. Decision matrix algorithms systematically analyze and rate the image algorithms, based on confidence of correctness and other values.[9] The outputs of the data-driven analysis and ranking of these algorithms are instructions that allow the car to drive on its own—braking, accelerating, changing lanes, and doing everything a human would do.

For level 3 and 4 "drivers," the car they are dealing with is always changing. Data from previous drives of theirs and others is used to help algorithms learn and improve performance, i.e., the car is regularly getting "smarter." My Tesla-owning friend receives software upgrades roughly every 3 weeks that improve her car's ability to drive autonomously. Recent software updates included enabling the DashCam to automatically save video clips when a safety event is detected, addition of Disney+ to the car's streaming options, and language support for car passengers who speak Romanian.[10] Tesla drivers are essentially driving a different car with every update and must learn and adapt to new capabilities.

Even now, when they are far from perfect (almost), self-driving car cars are breathtakingly complex and surprisingly safe. (There have been roughly a half dozen fatal accidents involving autonomous vehicles, although determining cause is challenging. Determining safety statistics that compare fatalities in autonomous vehicles for a set number of vehicle miles traveled to fatalities in non-autonomous vehicles for the same number of vehicle miles traveled is still premature because not all of the relevant data are available.)

A decade ago, the typical CAV program was around 100 million lines of code. In contrast, the program that flies the Boeing 787 Dreamliner was around 6.5 million lines of code.[11] One reason for this is that the ambient conditions for planes are easier to model—although planes need to take into consideration a broad scope of weather conditions and some other planes, CAV's need to take into consideration many more interactions with objects that behave unpredictably. Over the last decade, CAV programs have become even more complex. It is no surprise that CAV companies are considering the development of Jetsons-like VTOLs (vertical take-off and landing vehicles) that fly, in addition to terrestrial cars that drive themselves.[12] (In the 1960s, "The Jetsons" TV show featured a family of the future who used flying cars—a common mode of transportation.)

CASE STUDY OF A CAV IMPACT UNIVERSE FRAMEWORK THAT PROMOTES ENVIRONMENTAL SUSTAINABILITY, PUBLIC PROTECTIONS, AND ECONOMIC GROWTH

To illustrate how nuanced the impact universe framework can be, we now develop an impact universe framework for CAVs. Although today true self-driving cars do not yet exist, consider self-driving cars in 2050–2060, when they will be prevalent. Our cars will be lighter (hundreds of pounds), go father (hundreds of miles per charge), and travel in groups or "platoons."[13] They may look more like the pod-shaped cars in the Jetsons cartoon show than they will resemble the cars of today. We will see changes in the way CAVs are built, the way they are used, and the transportation economy. CAVs will influence where we live and how we think about our commute to work. They will provide new opportunities for long-distance travel, mobility, land-use, and create new and different jobs. And they will impact the development of infrastructure, use of resources in the natural environment, and lifestyle choices.

Social controls deployed now will greatly influence the way current and future CAVs are designed, developed, utilized, commercialized, and managed. In the following sections, we describe specific goals and strategies for creating an impact universe framework for CAVs with the overarching goals of environmental sustainability, public safety, and economic growth.

Goals for promoting environmental sustainability

We often think about the environmental impact of automobiles in terms of emissions and air pollution, but the manufacturing, operation, and disposal of cars during their automotive "life cycle" have even broader affects. Natural and other resources are used during the manufacture ("birth") of a vehicle as well as to power it (through fuel or electricity) during its operation ("life"). After a CAV stops operating ("death"), recycling and repurposing, rather than disposal, of CAV components can reduce e-waste.

Complicating this is the expected use model for self-driving cars (e.g., owner-deployed or used as a commercial service), which greatly impacts wear and tear and the calculation of the lifespan of electric components used in the CAV. This means that, without additional information about the social and economic environment in which CAVs operate, it is hard to accurately predict how long they will last and whether components can be recycled. Design and maintenance must also be considered—can CAV components be upgraded in software, or must they be swapped out for new hardware? All of these influence calculations of the sustainability of CAVs.

In addition to impacting the natural environment, CAVs will also impact the design of the built environment—roads, support facilities, land-use, parking, etc. —accommodating new modes of operation and passengers' expanded lifestyle choices. Because the entire life cycle of the car should be taken into account, various specific goals can be used to promote environmental sustainability. These include:

- Reduce emissions from present levels during the manufacturing and operation of CAVs (E1)
- Promote sustainable materials usage for manufacturing and operation of CAVs (E2)
- Minimize additional planetary e-waste through the recycling and repurposing of CAV parts and systems (E3)
- Build transportation infrastructure that promotes environmental sustainability (E4)

We describe strategies for goals E1–E4 below.

Strategies to reduce emissions (E1)

Emissions depend on both vehicle design and vehicle use. In the transportation industry, the relationship between car use and its level of emissions is often captured by the ASIF formula.[14] The formula models emission level as a product of activity level (use), modal share (fraction of travel conducted in the usage mode), and carbon intensity of fuels used in that mode.[15]

$$\text{Emissions (ASIF)} = \text{activity level (A)} \times \text{modal share (S)} \times \text{energy intensity (I)} \times \text{fuel carbon content (F)}$$

As the formula shows, there are multiple ways to reduce emissions. Many strategies fall into the general categories of (1) building cars that are more energy efficient (i.e., build cars with electric batteries versus fuel-injected engines), relevant to lowering I and F in the ASIF formula, and (2) driving cars in a more energy-efficient manner, also known as eco-driving strategies, relevant to lowering the A and S parts of the ASIF formula.

With respect to building more energy-efficient cars, there has been a growing shift toward plug-in electric vehicles (PEVs),[15] with recent announcements of large investments by Ford and notice that all GM vehicles will be all-electric by 2035. By 2040, it is expected that it will no longer be possible to buy a non-electric new car.[16] Federal emission standards[17] guide the design of today's vehicles but have also been a cause for controversy. Many auto manufacturers want these standards loosened, while environmentalists want them strengthened.[18] Adding to the mix is the existence of different standards in different jurisdictions; for example, California law is tougher on emissions than federal law. Public officials looking to lower emissions more aggressively may want to encourage specific jurisdictional controls that incentivize exceeding or strengthening current standards.

With respect to driving cars more sustainably, *eco-driving* can help lower emissions during vehicle operation. Eco-driving techniques include smooth acceleration and deceleration, maintenance of a steady speed when possible (think cruise control), minimizing idling, anticipation of traffic flow, etc. Basically, eco-driving is what we think of as "good driving habits," and they can be algorithmically programmed in autonomous vehicles. Current level 3 and 4 cars incorporate eco-driving techniques, and 2050 promises close platoons of coordinated CAVs, all of which incorporate eco-driving strategies.

Studies show that eco-driving can reduce emissions by up to 9%.[19] Efforts to promote human eco-driving focus primarily on training and practice (see the report by Shaheen et al.[20] for an analysis of public education programs), rather than regulation. (There is some regulation to limit poor driving strategies such as excessive idling.[21]) This will be different for CAVs, where algorithms will do the driving and more research and development are needed to define and incorporate autonomous eco-driving techniques. A policymaker's strategy to reduce emissions through eco-driving might be to invest in further research exploring improved CAV eco-driving approaches. There is precedent for this, both for eco-driving and other transportation-related areas, as demonstrated by the important state investments in research made by the National Cooperative Highway Research Program.[22]

Based on this discussion, strategies to reduce emissions may include:

- *Strengthen federal emission standards*
- *Create incentives for auto manufacturers to cut emissions in CAVs*
- *Invest in research to improve eco-driving*

Strategies for promoting sustainable materials usage for CAV manufacturing and operation (E2)

The desire for more energy-efficient vehicles with reduced emissions has led to the increasing prevalence of PEVs. It is currently predicted that, by 2025, 70% of PEVs will have lithium-ion batteries.[23] Lithium-ion batteries are rechargeable and attractive for electric-powered vehicles because they have a high energy density (can store a great deal of energy per volume) and little energy leakage.

Lithium-ion batteries include other materials as well: Tesla's lithium-ion battery is also composed of nickel, cobalt, and aluminum. The Nissan Leaf's lithium-ion battery is also comprised of magnesium.[23] But many of the materials in modern PEV batteries—lithium carbonate, graphite, and cobalt—are expensive, considered to be in limited supply, or may not keep up with demand.

To promote sustainability, both researchers and manufacturers must explore new materials and battery designs that can be used with next-generation CAVs. What will future CAV batteries look like? Each potential combination of materials must be viewed from multiple perspectives: chemical and materials properties, safety and performance, cost and availability, etc. Each battery design will dictate the type and amount of natural materials used and potentially depleted. It will also have implications for infrastructure in the built environment as recharging stations and other services will need to be planned and sited with power generation in mind. Successful new battery designs will be the result of both research and market forces. Investment in research will be important to manage the supply of lithium carbonate and other materials currently in use.

Other CAV materials will need to be monitored and managed as well. In vehicles with autonomous capabilities, computers and LIDAR commonly require rare-earth materials in small amounts.[19] Although not all 17 rare-earth elements are actually rare (some are plentiful in the Earth's crust and on the ocean floor),[24] they are often diffuse or environmentally damaging to extract and refine.[25] They are none-the-less critical at this point in time. According to experts, "rare-earth metals, when looked at anatomically, seem to be inseparable from each other, in that they are all almost exactly the same in terms of their chemical properties. However, in terms of their electronic properties [and] their magnetic properties, each one is really exquisitely unique, and [can] occupy a tiny niche in our technology, where virtually nothing else can."[26]

The availability of rare-earth elements is complicated by geopolitical issues.[27] China has systematically captured the rare-earth market and used it as a strategic advantage. Current US efforts to partner with other countries as well as rebuild the US domestic supply chain have important business, environmental, and political consequences. All must be factored into plans for design, production, and prevalence of CAVs and other IoT products.

We do not quite have a model with the specificity of the ASIF formula to estimate materials depletion, and this will also depend on the prevalence of CAV uptake. However, policymakers can work to mitigate the depletion of materials used in the manufacture of CAV components and processes just as we do now with non-autonomous vehicles. They can do this by exploring and incentivizing the use of sustainable, energy-efficient materials, and developing economic and social controls that promote the reduction of the number of vehicles on the road through incentives for public transportation or other alternatives. Strategies to promote sustainable materials usage may include:

- *Invest in electric battery research that focuses on sustainable materials*
- *Incentivize the use of sustainable electronic components for CAVs*

Strategies for minimizing e-waste (E3)

Dealing with the "death" and "afterlife" of a CAV's many electronic components will be a critical strategy for promoting environmental sustainability. The world currently produces more than 50 tons of e-waste per year,[28] only 20% of which was documented and recycled in 2018.[29] Landfill e-waste may contaminate soil and groundwater and/or expose workers to hazardous and carcinogenic substances. Moreover, data on e-waste is not universally collected, making it hard to estimate the size of the problem. Increasing prevalence of CAVs will exacerbate these current challenges.

CAV recycling and repurposing can minimize e-waste and extend the economic value of automotive components. We currently recycle conventional vehicle components, such as aluminum, copper, scrap metal, and tires. In total, around 80% (by weight) of a conventional vehicle is recycled and the rest is often sent to the shredder.[30]

A primary focus for recycling and repurposing will be PEVs. PEVs are currently assumed to last at least as long as their vehicles, and battery repurposing can extend the life of still-useful batteries. When a battery is removed from a PEV, it may still retain 75%–80% of its original capacity.[31] This still-functional battery can then provide an alternative to traditional lead batteries for purposes such as automotive starting and ignition, telecommunications backup power, grid connected energy storage, etc.[32] Moreover, dissembling and recycling battery components and materials creates fewer emissions than producing new batteries from natural sources.[31] As CAVs become more prevalent, the recycling industry for rare or expensive materials (like the ones used in lithium-ion batteries) is also expected to grow.

Recycling and repurposing other components that give CAVs their autonomy—sensors, processing computers, and other non-battery components—may, however, be a mixed bag. It is not clear whether the life of various components will be useful past the life of the car. Even if there is useful life in them, advances in hardware technology may make it inefficient to reuse them. The development of strategies to reduce the negative environmental impacts of CAV electronics may require further study and must take both the potential for further functionality and the problems with disposal into consideration.

Note that the lifespans of CAV components and CAVs themselves are dependent on how CAVs are used. Conventional owner-operated vehicles are often assumed to have a 15-year lifespan, during which they are parked 95% of the time. Recently, Ford's AV operations chief conjectured that future CAVs that are used more extensively for ride-hailing services may last around 4 years.[33] CAVs as a service will have different component lifetimes than CAVs dedicated to individual use. The interplay of CAV use, ownership, economics, and other aspects of the social environment in which CAVs will be deployed is critical to accurately calculate their environmental, business, workforce, infrastructure, and production impacts.

While policymakers may need to wait for more experience and information to specifically guide the disposal and afterlife of CAV components, they can continue to promote today's guidance on repurposing and recycling.[34,35] Moreover, they can begin to collect the data necessary to help calibrate environmental e-waste from CAV autonomous components. Gathering useful data and incentivizing recycling and repurposing of CAV electronic components are two strategies that can help promote a policymaker's objectives.

- *Incentivize the recycling and repurposing of CAV electronic components*
- *Collect information on the levels and amount of CAV e-waste*

Strategies for promoting a sustainable built environment (E4)

CAVs will also impact land-use and the built environment—urban and suburban density, roads, parking and way stops, facilities for maintenance, repair, disposal, etc.

Consider parking. A typical vehicle may be parked for 95% of its lifetime and a recent study estimates urban land-use to include between 10 and 54 parking spaces per acre in 5 major cities.[36] But self-driving cars will not really need to park nearby when we arrive at our destination. They can go pick up other riders or shelter far away, autonomously coming to pick us up when needed. This means that we can allocate real estate to other things: more residential or office units, bike paths, parks, and pedestrian walkways, etc.

CAVs may promote dispersed land-use around metropolitan areas and will change how we think about commuting. When you do not have to drive, you can work in your car, visit with friends, read, sleep, or take meetings. An hour commute to a much farther workplace can add 2 hours of work time. A long CAV trip on highways that accommodate higher speeds and platooning may replace some trips that we presently take by train or air. With prevalent CAVs responsible for the driving, and outfitted to accommodate other activities, the way we use and think about vehicle transportation will change.

This will lead to significant changes in the built infrastructure—roads, transportation facilities and services, land planning for evolving changes in population density, etc. It will also impact the economics of the transportation ecosystem—who owns and who uses, who works and at what job, what kind of companies are needed to support the automotive ecosystem, who their customers are, etc. Decisions about the built environment are deeply connected to business models, sharing, workforce, planning, and other areas. (See "Promoting economic growth goals," for more details about this.) Our policymaker is aware of the many ways that things will change, but experience and planning expertise will be needed in advance of policy and infrastructure development. Her strategy may be to create a request for study and convene an expert group to get ahead of potential changes, charging this group to recommend ways to structure infrastructure and develop a built environment that promotes strong communities and environmental sustainability:

- *Create a request for study to recommend planning guidelines for the built environment*

Beyond CAVs, sustainability is a key impact for almost all IoT devices and systems. The CAV-focused discussion here will be similar to a life-cycle discussion for smart appliances, Fitbits, or iPhones. What electronics should be included and how do we deal with them at the end of the life of the product or component? How will the product impact the natural and built environments? The impact universe framework for these products may expose different priorities and relationships but will likely be equally nuanced.

Promoting public protections—safety, security, and privacy goals

In 1965, Ralph Nader published the book "Unsafe at Any Speed,"[37] exposing the defects and dangers of the Chevrolet Corvair. The book, and the recognition that vehicle accidents were the leading cause of death for Americans under 44, spurred legislation on vehicle safety and established the National Highway Traffic Safety Administration.[38] Since then, vehicle safety, security, and more recently privacy have been critical priorities for the public and the transportation industry. The development of CAVs—more complex, more autonomous, and more likely to blur social and technical boundaries—exacerbates all challenges with public protections.

For policymakers, embedding public protections in the design, use, and, oversight of CAVs will be critical to promote the public interest. Common goals to promote public protections for autonomous transportation include:

- Promote CAV safety through design and construction (passive safety) and driving and operation (active safety) (P1)
- Promote CAV cybersecurity through designs that meet and contribute to best practice standards and approaches (P2)
- Provide consumers the right to know what personal data are being collected and how the data are used in CAVs. Create opt-in options for collection and use of consumer personal information not needed for CAV operation, maintenance, or safety (P3)

Strategies for promoting safety (P1)

It is hard to imagine anyone in the transportation ecosystem for whom human safety is not a primary objective. The commitment to safety is echoed in every stakeholder group, from vehicle manufacturers to auxiliary industries, such as insurance providers, to the United States Department of Transportation, who named safety as their highest priority.[39]

Two common ways of promoting safety are passive safety and active safety. *Passive safety* focuses on making the "hardware" of the car—materials, design, components, body—better able to avoid, withstand, and minimize accidents. *Active safety* focuses on promoting safety through the driving and operation of the car.

Passive safety approaches—standards, design, research into materials, aerodynamics, energy efficiency, and other contributors—will evolve with increased prevalence of CAVs. As described earlier, future CAVs are expected to be much lighter and "right-sized" in comparison with today's cars, and new designs may achieve this goal by jettisoning safety equipment and varying the materials chosen for construction (potentially replacing heavier materials, such as steel, with aluminum, carbon fiber, or other lightweight synthetics). As these designs evolve, policymakers and the automotive industry will need to carefully consider the impact of the new designs on safety.

But CAVs will also bring new venues for passive safety. In the future, CAVs will operate on streets and highways by joining and leaving platoons of vehicles.[40] They will draw information from V2V (vehicle-to-vehicle) sources and sources in the road infrastructure and the built environment (V2I [vehicle-to-infrastructure]). They will need to process almost instantaneous alerts of V2V and V2I systems to improve their approach to braking, turning, lane changing, and more. Potential safety risks for vehicles traveling in a platoon will need to be factored into future CAV standards and regulations. Effective strategies may focus on the creation of studies and advisory groups to gather data, study, and envisage needed standards, regulation, and protections for V2V and V2I environments.

Active safety focuses on driving and operation. For CAVs, promoting active safety shifts the focus from the human driver to the autonomous driving system: making a CAV actively safe essentially amounts to making the algorithms and sensors accurate, responsive, fault tolerant, and robust.

Active safety in CAVs is a game changer. With over 90% of car crashes due to human error,[41] it is widely believed that removing humans from the driving equation could dramatically improve the safety of road transportation. Data show that accidents in human-driven cars are often a result of distraction, misjudgment, or impairment. One way to beef up safety for human drivers has been to restrict scenarios in which drivers are more likely to make these kinds of mistakes, for example, by prohibiting drinking and driving, texting and driving, etc. However, it is rarely the case that a human driver will misclassify a cyclist as a trash can. CAV systems are highly susceptible to these kinds of errors.

Autonomous systems eliminate the distraction and impairment mistakes that plague humans, but they can introduce new errors not common to humans. Potential sources of system errors include existence uncertainty, state uncertainty, and class uncertainty. *Existence uncertainty* describes the uncertainty around whether the system "sees" an object—a stop sign, road marking, etc. *State uncertainty* refers to uncertainty in a measured physical variable or characteristic (e.g., size, position, speed), and can reduce data integrity. *Class uncertainty* describes confusion about the correct identification of an object—cyclist or trash can? —and can be caused by limitations or problems with CAV identification algorithms. Not surprisingly, humans trounce autonomous systems when it comes to class certainty.[42]

To improve the safety of CAVs, data must be gathered on the types and impacts of algorithmic and system errors that will be critical to improving their safety. Policymakers can promote active safety by requiring independent collection and analysis of errors that lead to CAV accidents, much like the Federal Aviation Administration collects data in assessing airplane crashes.[43]

Note that there are always trade-offs between safety and other goals, e.g., economics and environmental sustainability. Policymakers must determine the right balance for these competing goals to promote the public interest in the transportation ecosystem. Moreover, safety trade-offs will be different in a world where there is a substantial number of both CAVs and human-driven vehicles—the midway point between today's environment (mostly human driven), and the environment we will see as we approach 2050 (mostly autonomous). As we transition to a virtually all-autonomous environment, safety trade-offs will need to be continually re-assessed.

Note that sometimes these trade-offs will be counterintuitive. A study by the Rand Corporation contrasted safety, measured by the number of fatalities, with prevalence and maturity of CAV systems. The study's results indicate that early release and prevalence of less mature (and more accident-prone) CAVs may actually save more lives.[41] One possible explanation is that replacing unpredictable human drivers with less mature CAV systems creates more predictability in the overall system and safer roadways.

In addition to strategies currently being utilized to promote automotive safety, CAV-specific strategies to promote safety may include:

- *Create a request for study to recommend best practice and standards for V2V and V2I engagement*
- *Require and coordinate data collection on accidents for autonomous vehicles driving on public roads*

Strategies for promoting cybersecurity (P2)

As a "computer that drives,"[44] the security of the CAV can be a direct contributor to its potential for safety. Security is a system's protection from theft, damage, and disruption or misdirection of the services provided by its hardware, software, or electronic data. As CAVs evolve, their sensors, hardware, software, and data provide new attack surfaces and new ways to threaten the safety of passengers and others. Since 2016, the number of annual cybersecurity incidents involving CAVs has increased by 605%.[45] Over the last two decades, cybersecurity, and the risks of cyber-physical systems, have been an increasing focus of the US National Academies Computer Science and Telecommunications Board, the National Institute of Standards and Technology, the Department of Transportation, and other groups.

The high-profile remote hacking of a Jeep Cherokee[46] (Box 1) raised public awareness that security of the software and hardware of CAVs can be a serious risk to safety. Cars and systems that can be hacked are cars that are unsafe.

Many CAV security vulnerabilities are similar to those found in other computer systems, and good practice for CAV cybersecurity will mirror good practice for other connected digital products. Common types of attack include unauthorized software updates, password and key attacks, network protocol attacks, denial of service attacks, and more.[47] These attacks could come from short-range or local means, through networks produced by V2V and V2I connectivity, and even physical access.[47] Additional vulnerabilities may come from nefarious activity, inability to deal with network outages, interception, or hijacking of information, failures and malfunctions of digital devices, systems, or power, loss, or leakage of information, as well as traditional physical threats to conventional automotive components.[48] In CAVs, any system may have security vulnerabilities, from the connected GPS, Bluetooth, WIFI, and media systems, to the physical LIDAR, cameras, or other sensors.

Good security practices include the ability to patch/upgrade CAV software, use of standard protocols and implementations, ensuring that the CAV can function offline, use of encryption and authentication for CAV data, segmentation—the ability to isolate systems to reduce vulnerabilities, and layering—monitoring data traffic and isolating the effects of malware.

For example, security segmentation involves protecting CAVs by creating closed circuits whenever possible, so that the corruption of one system will not lead to the corruption of the entire vehicle. Security breaches are most dangerous when remote access to a less important system can serve as a gateway to a more important one, as in the Jeep remote hijacking scenario. In the same way that connectivity can increase the hacking surface, segmentation and independence of components can reduce the hacking surface, allowing the lack of connection between different components to function as a built-in barrier. This can help prevent accessing driving functions through infotainment systems, a common source of vulnerabilities.[49]

Good security is a win for everyone. It is important to recognize that responsibility for this will largely be in the hands of the auto manufacturers, rather than the regulators. To create a culture of security best practices for CAVs, the transportation industry formed an Auto-ISAC (Information Sharing and Analysis Center) in 2015, following the model of cybersecurity information sharing in aviation and other industries.[50] The goal of the group is to "share and analyze intelligence about emerging cybersecurity risks to the vehicle, and to collectively enhance vehicle cybersecurity capabilities and the commercial vehicle sector." Just as in aviation, industry proactivity is critical to promote the safety and

Box 1. Hacking a Jeep Cherokee

One of the most high-profile examples of a security breach of a semi-autonomous vehicle is a 2015 "white hat" remote hacking demonstration of a Jeep Cherokee. To demonstrate security flaws, hackers took over the vehicle while a journalist was driving down an interstate at 70 mph.

By remotely accessing the vehicle's onboard entertainment and navigation system, the hackers gained control over every vehicle feature from windshield wipers to the accelerator to demonstrate vulnerabilities in the car's computer system. They used the vehicle's cellular network, connected to the entertainment system, to hack the vehicle from a remote location. This resulted in the first massive security-related vehicle recall, with 1.4 million vehicles being recalled.

This was a demonstration, but the risk of security breaches is likely to increase as vehicles evolve toward full autonomy. Many of the features of CAVs, such as platooning and sharing of training data, will require constant connectivity and will also provide new points of entry for attackers.

security of vehicles at the design and implementation stage, when strategies can be most effective.

A policymaker may choose to promote her security objectives as we do now—by monitoring security problems and expecting or requiring that security systems for CAVs meet best industry practice. In addition to supporting current cybersecurity efforts, she may promote more long-range strategies, for example, increasing researcher access to security breach data (see the strategies in the last section) and increasing funding for CAV cybersecurity research. A strategy in this vein would be:

- *Invest in cybersecurity research that improves security practice and standards for CAVs*

Strategies for promoting personal privacy (P3)

Although, from an operational perspective, CAVs are computers that drive, from a privacy perspective, CAVs are essentially smartphones with wheels.[51] McKinsey estimates that modern cars collect as much as 25 gigabytes of data per hour from sensors, including data on web browsing, video and music streaming, biometrics, driving behavior, smartphone usage, etc.[51,52] Currently there is little restriction on what can be done with these data, and whom it can be shared with or sold to.

Occupants of a car typically know neither the extent of the data collected nor what is done with it. Moreover, sensors and cameras also collect data about individuals outside the car—bystanders—to make planning and operational decisions, and privacy protections must cover them as well. Complicating things is the fact that personal data (location and travel history, images of someone walking across the street, etc.) may be used for CAV operation as well as commercial opportunities, so prohibiting the collection of some personal data can negatively impact performance and safety.

Like other connected digital products and services, CAVs will require proactive policy and regulatory restrictions and oversight to protect personal privacy. Some CAV privacy restrictions will resemble privacy restrictions for other connected digital consumer products. Some may need to be targeted to the CAV environment, for example. prohibition of "take it or leave it" terms that endanger CAV occupants who have not opted-in to personal data collection. All of this both mandates and complicates the deployment of effective CAV privacy protections.

Vehicle privacy has been discussed for over a decade—much in advance of today's autonomy innovations—with the Vehicle Information Infrastructure Report,[53] convened by the Department of Transportation, providing an early look. Today, various reports and gatherings by the Federal Trade Commission[54] and industry-wide consortia, such as the Auto-ISAC,[50] focus on privacy and security issues for CAVs.[55] Following FTC guidelines and the Consumer Privacy Principles of the Alliance of Automobile Manufacturers,[56] design principles and practices that promote personal privacy in CAVs may include:

- Requirements for transparency about the collection, use, and sharing of personal information. Provision of access to data subjects for reasonable review and correction
- Data minimization, de-identification, and retention policies that focus on the use of personal data only for business purposes and only as long as is needed
- Choice and control of data subjects about the collection, use, access, and sharing of personal information beyond operational purposes
- Incorporation of Notice and Consent policies for use of CAV personal data
- Securing of personal data and promotion of data privacy when possible, including encryption, anonymization, differential privacy, etc.
- Development of monitoring and accountability mechanisms to ensure compliance with privacy policies and the commitment of industry to comply
- Design requirements to build strong privacy (and security) protections into vehicle designs at the outset, rather than an afterthought

All of these provide specificity to the general promotion of transparency and consumer control for non-operational use of personal CAV data. In developing specific social controls, a policymaker may need to extend existing privacy protections to CAV environments or specify targets and practices similar to those above in new policy or legislation. Her proactivity will be important, as greater privacy protections are unlikely to come from industry. A strategy that serves as placeholder for the above recommendations and those similar to them is

- *Require transparency and consumer control of personal data for non-operational use*

Some of the most effective strategies for promoting privacy, safety, and security are to make these protections part of the hardware and software architecture design of the device or system itself, and to limit unsafe use through standards, policy, regulation, etc. This is true for virtually all IoT products and services, but the balance of priorities one might consider for a Fitbit, where a worst-case outcome is much less likely to be catastrophic, versus for a car or connected pacemaker, whose worst-case outcomes may be fatal, must reflect that. The level of risk of various prioritizations of goals and strategies can be exposed by their impacts and inter-relationships in the impact universes for each of these devices.

Promoting economic growth goals

Today, most American families own a car, with 91.3% of households in 2020 reporting having access to at least one vehicle.[57] But use of car services such as Lyft and Uber are on the rise. What happens when transportation moves from a durable good to a service? Economists expect that CAVs will broadly transform the transportation industry including its players, its workforce, and its impact on other sectors.

Although early indicators show that the changes are likely to be dramatic—the current ride-hailing service industry, which did not exist a decade ago, was recently valued at 61.3 billion USD.[58] It is also expected that changes will evolve over the next few decades. Getting ahead of the game will help a public-focused policymaker steer the transportation economy in the right direction. Her policy goals may be to

- Gather information and accurately model CAV impacts on the economy (Econ 1)
- Use policy to incentivize and promote economic growth and stability (Econ 2)

These are accomplished now by gathering data and convening expert groups to research, model, report, and predict the economic impacts of technologies and industries, and this information is used to inform economic policy. This approach will be important to assess the economic implications of CAVs as well.

To understand the economic implications of the CAV industry, a good place to start is three areas in which economists expect dramatic changes in the automotive ecosystem—market leadership, vehicle-related services, and the transportation workforce. To demonstrate the wide-ranging economics of CAV development, we briefly discuss these areas below.

Leadership in the CAV marketplace

Today, the automotive industry is one of the largest in the global economy, with automobiles and auto parts making up 20% of all US retail sales,[59] and worldwide sales amounting to over 1.5 trillion USD.[60] Most of these sales benefit around a dozen powerful conglomerates. Moreover, automotive manufacturers can control almost the entirety of the process—design, manufacturing, sales, and service.

With the emergence of CAVs, new players are entering the transportation industry: tech companies. Tech companies are creating cars from the inside out, focusing on the complex software systems that will allow cars to drive themselves. Whether automobile-focused companies (building cars with smart systems) or tech companies (building smart systems surrounded by driving hardware) will prevail impacts the character of the market, who benefits, and when.[61]

The stakes are high. In the automotive industry, research and development into CAV technology has already reached over 100 billion USD.[62] But the spending may not come from the companies you think—Google's Waymo or GM's Cruise, for example. In 2019, Volkswagen spent the most of any company on CAV technology, followed by Samsung, Ford, Toyota, BMW, and Audi. Spending the least on CAVs that year were Apple, GM, and Uber.[62] Recently, Tesla poured $1.5 billion in just one year into the research and development of its most advanced cars. It may also be the most synergistic tech/automotive company of the bunch, focusing on both the hardware (car) and the software (smart system).[63]

A shift in dominance from traditional automobile manufacturers to tech companies would have a tremendous impact on the economy. If traditional manufacturers become secondary or partners to tech companies, there will be repercussions throughout the supply chain and economic environment. It may also be true that CAVs, thought of as software products, may be subject to different kinds of policies and legislation, as is beginning to happen with smartphones and medical device apps. Tech companies also bring different corporate and professional cultures and business models (e.g., the commoditization of collected data) into the auto industry. The economics of transportation will shift, not just with new technology, but with new players and approaches.

Ride-hailing and vehicle-related services

One of the most dramatic shifts in the transportation economy in recent years has been the rise of ride-hailing services, and companies such as Lyft and Uber. CAVs may have an equally dramatic effect on who provides these services. In contrast to today, CAV ride-hailing vehicles will likely be owned by companies. Costs for these companies will include not just the cost of vehicles but other costs of vehicle ownership—car cleaning, maintenance, and insurance, as well as customer-focused coordination and services. The cost model of ride-hailing as a service may increasingly resemble that of today's rental car companies.

The commercialization and privatization of ride-hailing will also impact the need for, and prevalence of, public transportation. If CAVs as a service move into the private sector, as air transportation has today, the need for public vehicle transportation may diminish. We currently do not know how the balance of public transportation, private ownership of vehicles, and commercial ride-hailing options will shift. Modeling these shifts as they occur, as well as their economic repercussions, will be critical to inform economic policy and incentives with respect to CAVs.

The data collected by CAVs will also bring new economic opportunities. As with other connected systems, some collected CAV data can be sold and used for purposes other than driving. One can imagine fleets of CAVs collecting all kinds of data—images, audio, video, environmental information, etc. —for a wide variety of applications, just as Google Earth data are used for more than maps.

Imagine new services that might use CAV data: car companies collecting weather information for their internal autonomous systems could sell it to weather services that could share near-perfect and real-time weather information across any CAV-populated location. In the absence of restriction, CAV passenger data could be used for marketing, enabling the purchase of strategically placed ads, sponsored destinations, etc. In particular, the availability of dynamic surveillance data from CAVs may allow CAVs to double as surveillance systems, capturing everyday movement and patterns that were previously private. Doing so sets up incompatibilities between strategies that promote individual privacy and strategies that promote economic growth, requiring prioritization and risk mitigation from policymakers developing CAV social controls promoting the public interest.

Traditional transportation-related industries will also be impacted by increasing vehicle autonomy. As CAVs usher in a shift from private ownership of vehicles to ride services, insurance for individuals may look more like today's renter's insurance than owner's insurance, with primary costs moving to the ride service industry. The models used by insurance companies to determine premiums will change as well. Insurance companies currently collect premiums based on how "costly" they believe a driver to be, i.e., how much they would need to pay if there were some kind of accident. CAV technology promises more safety and, with it, the potential for less expensive premiums under the current model. KPMG predicts that autonomous systems will reduce accident frequency by 90% by 2050.[64] On the other hand, the accidents that do happen could involve more costly repairs. For example, sensors, already becoming common for rear end detection, are much more costly to replace than a simple bumper. The upshot is that while these accidents may be less frequent, they may be much more expensive.

All of this means that the economic impact of CAVs on insurance will be subject to competing influences: fewer accidents, more expensive repairs, possibly greater medical costs because accidents may be more severe (from lighter cars and higher speeds). Combining these influences with plausible model instantiations indicates that overall losses from accidents could fall by 63%—22 billion USD—by 2050.[64] Similar modeling by Deloitte predicts that auto insurance premiums will decrease by almost 30% of current levels.[65]

Workforce evolution

Not surprisingly, CAVs will greatly impact the transportation workforce. In addition to those employed in the manufacture, maintenance, repair, sales, and other aspects of the automotive industry, many Americans today are employed as drivers. Truck drivers, delivery services, chauffeurs, bus drivers, taxi drivers, and others may be replaced in the near-to-longer term with CAVs and last-mile robotic delivery options—an estimated 5 million jobs in the current economy would be lost if CAVs were prevalent today. But it will take a decade or more for level 5 CAVs to be prevalent and they will bring new jobs as well as eliminate current jobs. Both trends will impact the economy, as will the local and federal political environments in which workforce planning and related decisions are made.

Consider trucking. Currently, the trucking industry, which moves 71% of all freight in America, is valued at $700 billion USD.[66] Truck drivers spend days on long-haul drives across the country, with the average professional long-haul trucker logging more than 100,000 miles per year, or 274 miles per day.[66] The majority of these miles are accumulated on long, straight stretches of highway. These portions of roads and driving are currently the easiest and safest for CAVs. They have consistent speeds, fewer distractions, such as pedestrians and stops, and little complicated maneuvering. Moreover, such roads are ideal for platooning.

The delivery industry is beginning to see more and more semi-autonomous trucks navigating the highways. At the end of 2019, California's Department of Motor Vehicles announced that they would permit testing and deployment of driverless trucks for commercial use.[67] In 2021, after testing operations with "supervised autonomy" (autonomous runs with a driver on board who can take over) in several states, companies, such as TuSimple, are beginning to deploy autonomous trucks without drivers on board.[68] Over the next decade, semi-autonomous and autonomous trucks will become more and more prevalent.

Passenger trips will also shift CAV-related jobs with some new CAV-related jobs reflecting traditional jobs in current rental companies: maintenance, repairs, regular cleanup, etc. Ride-hailing services of the future may provide concierge services that cater to passengers who want food, rest, work options, or entertainment on their trips.

As software design, computation, and robotics become a more dominant part of CAV manufacturing, automotive companies may also shift their workforces to include a larger proportion of data and computer scientists, roboticists, engineers, materials scientists, and others, with a corresponding impact on budgeting, salaries, and needed skills. CAV mechanics may focus on the software and robotics aspects of ailing CAVs at least as much as the hardware, expanding needed skills. It is only 30–40 years away, but it is a brave new world.

Market leadership, services, and workforce are only three areas of economic impact for CAVs. There are many more that will have economic repercussions—changes to land-use and the built environment, economic impacts of new commuting and travel patterns, use of CAVs for work and entertainment, etc. Public-focused policymakers and their academic colleagues will need to employ expanded and accurate models and data to inform economic policy for a future in which CAVs are prevalent. An excellent example of how complex this modeling can be and how many stakeholders must be involved is found in a report by Shaheen et al.[69] Strategies that help lay the groundwork for accurate economic modeling and to promote economic growth include:

- *Gather and make accessible CAV-related economic data that can be used for economic modeling by academics and the public sector*
- *Convene expert groups to research, model, predict, and report economic impacts of CAVs*
- *Encourage the development of new services that utilize CAVs*

SYNERGIES AND INCOMPATIBILITIES IN THE CAV IMPACT UNIVERSE FRAMEWORK

"Case study of a CAV impact universe framework that promotes environmental sustainability, public protections, and economic growth" describes a diverse set of goals and strategies that a policymaker seeking to create CAV social controls in the public interest might consider. Structuring them as an impact universe provides a tool for understanding their trade-offs by putting diverse goals and strategies into a single framework and weighing them in context, instead of considering one goal at a time.

Table 1. Goals and strategies in the CAV impact universe

Overarching goals	Goals	Strategies
Environmental sustainability	reduce emissions (E1)	strengthen federal emission standards
		create incentives to cut emissions
		invest in eco-driving research
	promote sustainable materials usage (E2)	invest in electric battery research
		incentive use of sustainable components in CAVs
	minimize e-waste (E3)	collect information on levels and amount of e-waste
		incentivize recycling and repurposing of CAV electronic components
	promote a sustainable built environment (E4)	create a request for study to recommend planning guidelines for the built environment
Public protections	promote CAV safety (P1)	create a request for study to recommend best practice and standards for V2V and V2I engagement
		require and coordinate data collection on accidents for autonomous vehicles driving on public roads
	promote CAV cybersecurity (P2)	invest in cybersecurity research that improves security practice and standards for CAVs
	promote personal privacy in CAVs (P3)	require transparency and consumer control for non-operational CAV data
Economic growth	gather and closely model CAV impacts on the economy (Econ 1)	gather and make accessible CAV-related economic data that can be used for economic modeling by academics and the public sector
		convene expert groups to research, model, predict, and report economic impacts of CAVs
	use policy to promote economic growth and stability (Econ 2)	encourage the development of new services that involve CAVs

This helps the policy maker avoid heading down a path based on a single goal only to find out that her strategies undermine another goal in unanticipated ways.

The goals and strategies described in "Case study of a CAV impact universe framework that promotes environmental sustainability, public protections, and economic growth" are exemplars that would underlie more specific and targeted social controls. But even at this level of generality, it is clear that some goals and strategies are synergistic, and some are incompatible. The goals and strategies from "Case study of a CAV impact universe framework that promotes environmental sustainability, public protections, and economic growth" are listed in Table 1.

Given a set of goals and strategies, a policymaker can determine which are synergistic and which potentially work against each other. Some synergies in Table 1 include:

- Investing in eco-driving research (strategy for E1) will promote public safety (goal P1). This strategy will also promote environmental sustainability (goal E3) by reducing emissions (strategy for E3) as well as reducing e-waste (strategy for E3) in that eco-driving promotes a longer life for CAVs
- Collecting data on CAV accidents (strategy for P1) will inform better cybersecurity (goal P2), as well as increase the accuracy of economic models (strategy for Econ 1)
- Minimizing e-waste (strategy for E3) will create new CAV services (strategy for Econ 2) and promote more sustainable materials usage (strategy for E2)

When goals and strategies work against each other, it will be important for policymakers to tailor or revise their strategies and the operational social controls that affect them to minimize incompatibilities. For example, in Table 1.

- Promoting personal privacy (goal P3) may translate into more complex software architectures, more testing, and additional mechanisms to support user control and transparency. This may increase costs and time-to-market for manufacturers, slowing the potential for economic growth (goal Econ 2)
- Increased privacy controls (strategy for P3) and strengthened security standards (goal P2) may also limit new avenues for CAV services, such as dynamic surveillance (strategy for Econ 2), impacting the growth potential of the CAV economy

Note that all strategies will need to be prioritized, and different stakeholders working on the same policy interventions may prioritize them differently. The process of making sausage out of these perspectives, priorities, and dependencies is hard to systemize, which makes the development of an impact universe necessarily non-deterministic. But visualizing critical information that describes synergistic and incompatible dependencies and then trying to minimize the "friction" in the system can help.

One way to visualize the synergies and incompatibilities of a set of goals and strategies is to represent them as interacting gears: each gear is a goal or strategy, and movement of one gear (indicated by an arrow) may impact the movement of other gears. When various goals and strategies are synergistic, they drive one another (i.e., interacting gears can move forward simultaneously); when they are incompatible, their movement is mutually limiting (i.e., forward motion of one gear deters forward motion of another). In Figure 1, synergistic movements for some goals and strategies in Table 1 are visualized by two sets of gears, and incompatible movement is visualized by the gears in Figure 2.

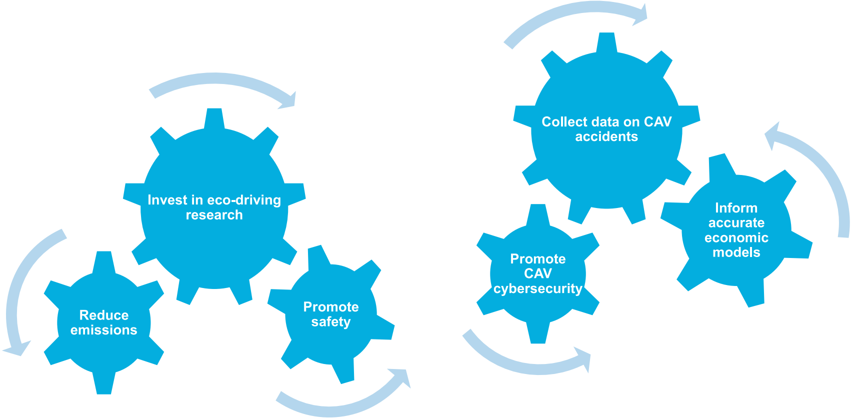

Figure 1. Compatible CAV goals and strategies
Optimization of the central goal or strategy can promote other goals and strategies in each set of gears.

As with other parts of the digital world, assessing the information presented by the impact universe framework must be done by humans. Their choices about which goals are important, which strategies should prevail, and how to target specific social controls that affect them will, and should, subjectively reflect their priorities and the context in which their approaches must be effectively deployed.

BEYOND CAVs: CREATING AN IMPACT UNIVERSE FOR OTHER IoT DEVICES AND SYSTEMS

The purpose of an impact universe framework is to provide an integrated, contextual, multi-disciplinary, and holistic view of the interdependencies of the goals and strategies that underlie potential social controls for connected technologies. After examining an impact universe framework, specific social controls can better leverage the context and time frames in which they will operate, and deployed to promote the stakeholder's desired outcomes.

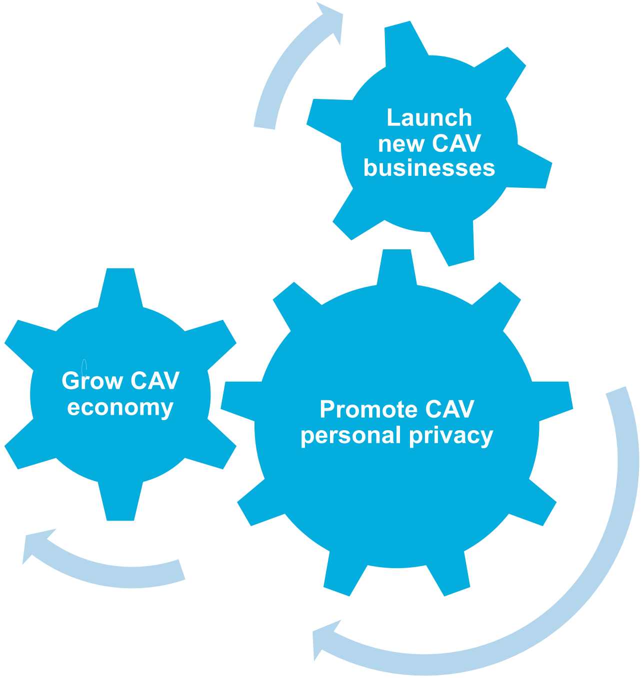

Figure 2. Incompatible CAV goals and strategies—optimization of promotion of personal privacy limits potential economic growth and some new businesses

The impact universe framework for CAVs demonstrates how complex and nuanced the impacts of an IoT device or system may be and how complex it is to understand them holistically. However, CAVs are only one example. Impact universe frameworks can be developed for any IoT "thing" and can also be developed for any type of stakeholder (not just policymakers) and any set of stakeholder goals (not just those described here). Although the impact universe framework for a smart toaster, a Fitbit, or a smart grid will look different than the impact universe we have described for a CAV, the same approach will provide critical insights needed to better evaluate the benefits, risks, and implications of social controls for the target IoT device.

Clustering and scoping may help. There are classes of IoT things for whom security vulnerabilities can lead to catastrophic results. Hacking a car or a pacemaker in the worst-case can kill a user. The impact universe for these devices must expose the relationships between security and all other interests and rank priorities in a way that promotes risk mitigation above all else. Other IoT devices could be considered together to promote specific interests. Take user privacy. Smart doorbells, smart home assistants, CAVs, etc. all collect personal data. Opt-in standards, access policies that restrict sharing without user consent, and product and system design alternatives that do not collect personal information could all be explored to promote user privacy. Creating an impact universe for classes of products or services with respect to a specific public interest profile can help create needed social controls in the IoT.

Complicating it all is the need to create these controls while technologies are dynamically evolving. As we saw for CAVs, we often do not immediately know the implications of new technologies. If we are lucky, we may have experience with some strategies that promote a stakeholder's goals. For example, the ASIF model and experience with current emission standards provide a solid footing from which to develop strategies and targeted social controls that promote environmental sustainability goals for CAVs.

On the other hand, many of the specifics needed to develop effective social controls may be unavailable, premature, or hard to quantify when decisions must be made. For example, many of the specifics needed for good economic growth models for CAVs may not be known. This is true for many IoT products, not just CAVs: the prevalence, uptake, and specifics of use and ownership for a wide variety of products will be important in developing accurate assessments of their lifetime, their potential for spawning additional goods and services, their potential contribution to planetary e-waste, and their economic trajectory.

The impact universe framework demonstrates that both known and unknown, easily quantifiable, and hard-to-specify impacts matter, and that all are needed to assess the benefits and risks of devices and systems in the IoT. Developing an impact universe framework provides a useful approach for assessing these benefits and risks because it requires a stakeholder to identify them in aggregate. It encourages them to focus beyond the quantifiable information before them, and beyond the single metric valuation that often characterizes the development of social controls for the IoT. In this, the impact universe framework provides a tool for stakeholders to more effectively guide technological innovation, so that the design, development, use, and standardization of IoT products and services advances the public interest, and ultimately a better IoT.

THE IMPACT UNIVERSE FRAMEWORK—CONTINUING THE CONVERSATION

The challenging and sometimes frustrating aspect to developing the impact universe framework as a structured approach is that all terms are subjective and open to interpretation: What is the public interest? What kinds of impacts? Which priorities matter most?

All of these questions must be addressed in context, and all depend on the priorities and perspectives of the stakeholders. What is considered in the public interest varies per group, per government, per worldview. The importance of individual privacy is different in the EU, US, and China. Safety is defined differently by companies and consumers. Impact is hard to define, and hard to calibrate in terms of the effect an action will have on an individual's life.

In developing the impact universe as a way to expose the relationships between potential actions in a real-world environment, we lack deterministic methodology. Our challenges to navigate the "messiness" of the real world of decision making and not oversimplify the nuanced relationships between various impacts are shared with other approaches—value sensitive design, systems engineering, and various models from operations research. In that sense, this paper contributes to the conversation about the need for context, the need to prioritize with partial information, and the development of tools that can help stakeholders manage potential tangible and intangible outcomes in the IoT.

Going forward, it would be useful to add new case studies of impact universe frameworks for additional IoT things (or classes of things) to explore the benefits and limitations of this approach. It would also be useful to explore how the impact universe framework might be combined with other methodologies and tools for analysis.

In seeking to define tools for policymakers, we also need to advance the goals of the policies we are creating. What is in the public interest for the IoT? Are there fundamental digital rights that need to be articulated for citizens and that can form the basis of the social controls we develop? Considerable work has been done in the EU to define the digital rights of its citizens, with multiple digital rights initiatives leading to the General Data Protection Regulation. A core set or "bill" of digital rights does not currently exist within the US. It is only when we define which digital rights are fundamental, that we can then begin to articulate the responsibilities of the public and private sectors to promote those rights.

We are just at the beginning of this discussion, particularly in the US. Continuing the conversation is critical if we want to derive the benefits and leverage the opportunities of the IoT, minimize its risks, and empower a public who can thrive in our cyber-social world.

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AUTHOR CONTRIBUTIONS

F.B. wrote, conceptualized, and directed the research for this paper. E.C., A.J., and W.M. were undergraduate Radcliffe Research Partners during 2019–2020, engaged in discussions on the topic, and developed briefings that contributed to the paper.

DECLARATION OF INTERESTS

Francine Berman is a member of the advisory board for *Patterns*.

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