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Liability and Regulation of Autonomous Vehicle Technologies

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ABSTRACT

Autonomous vehicle technologies and advanced driver-assistance systems have the potential to significantly improve transportation safety and efficiency, and, collectively, they may offer tremendous social, economic, and environmental benefits. As these technologies increasingly perform driving functions, they also create a shift in responsibility for driving from the driver to the vehicle itself. This motivates a new look at liability and regulatory regimes because of the increasing uncertainty about what should happen when the inevitable crash occurs and the implications for the adoption of these technologies. This research is an initial step toward understanding these issues and creating an integrated collection of policies to address them.

In this work, we first evaluate how the existing liability regime would likely assign responsibility in crashes involving autonomous vehicle technologies. We identify the controlling legal principles for crashes involving these technologies and examine the implications for their further development and adoption. We anticipate that consumer education will play an important role in reducing consumer overreliance on nascent autonomous vehicle technologies and minimizing liability risk. We also discuss the possibility that the existing liability regime will slow the adoption of these socially desirable technologies because they are likely to increase liability for manufacturers while reducing liability for drivers. Finally, we discuss the possibility of federal preemption of state tort suits if the U.S. Department of Transportation (US DOT) promulgates regulations and some of the implications of eliminating state tort liability.

Second, we review the existing literature on the regulatory environment for autonomous vehicle technologies. To date, there are no government regulations for these technologies, but work is being done to develop initial industry standards. It will be particularly important for autonomous vehicle technology standards—unlike standards for most other automotive technologies—to specify precise environmental conditions under which compliance must be met and tested, include performance standards and tests under a wide range of environmental conditions, and take into account how diverse populations of drivers might use the technologies.

Keywords: autonomous vehicle technologies, advanced driver-assistance systems, liability, regulation, policy.

EXECUTIVE SUMMARY

Autonomous vehicle technologies and advanced driver-assistance systems have the potential to enormously benefit humankind. Yet, stakeholders have repeatedly voiced substantial concern about tort liability for damages that may result from the use of these technologies. Who will be responsible when the inevitable crash occurs, and to what extent? How should standards and regulations handle these systems? This research is an initial step toward creating policies to address autonomous vehicle technologies.

We define *autonomous vehicle technologies* as technologies and developments that enable a vehicle to assist, make decisions for, and, ultimately, replace a human driver. Such technologies include crash warning systems, adaptive cruise control, lane-keeping systems, and autonomous parking technology (often collectively termed *advanced driver-assistance systems*, or ADASs), and, ultimately, full-scale driverless cars. Collectively, these technologies can improve safety by reducing the number of crashes, reducing traffic congestion, increasing fuel efficiency, reducing the environmental effects of driving, and helping to resolve land-use problems (such as the need for parking facilities adjacent to homes and businesses).

As these technologies increasingly perform complex driving functions, they also shift responsibility for driving from the driver to the vehicle itself. This motivates a new look at liability and regulatory regimes because of the increasing uncertainty about what should happen when the inevitable crash occurs and the implications for the adoption of these technologies. In this work, we identify the controlling legal principles for crashes involving autonomous vehicle technologies, evaluate how the existing liability regime would likely assign responsibility in crashes involving such technologies, and examine the implications for their adoption. We also review the existing regulatory environment for autonomous vehicle technologies, examine where standards and regulations might fall short, and suggest general principles and guidelines for future standard setting and rulemaking.

We find that the existing liability regime does not seem to present unusual liability concerns for owners or drivers of vehicles equipped with autonomous vehicle technologies. On the contrary, the decrease in the number of crashes and the associated lower insurance costs that these technologies are expected to bring about will encourage drivers and automobile-insurance companies to adopt this technology.

In contrast, manufacturers' products liability is expected to increase, and this may lead to inefficient delays in the adoption of this technology. Manufacturers may be held responsible under several theories of liability for systems that aid the driver but leave him or her in total or partial control. Warnings and consumer education will play a crucial role in managing manufacturer liability for these systems, but liability concerns may significantly slow the introduction of technologies that are likely to increase that liability, even if they are socially desirable. One potential approach to this problem is to more fully integrate a cost-benefit analysis into the standard for liability in a way that accounts for the consideration of the benefits associated with this technology. But it is difficult to specify the appropriate sets of costs and benefits that should be considered, and further research on this issue would be helpful.

One approach to reducing manufacturer liability would be for policymakers (probably federal) to issue a uniform set of regulatory standards that would preempt state tort suits. Under the doctrine of preemption, state tort law claims that are inconsistent with the objective of a federal regulation could be preempted by the federal regulation. While such an approach offers the advantage of uniform standards, and probably speedier introduction of these technologies, it also carries significant disadvantages. These include reliance on a single institution to properly mandate the appropriate standards and the elimination of the traditional access to the courts to seek redress for a claimed wrong.

As of today, no regulations exist for autonomous vehicle technologies. Looking forward, we find that there are unique features of autonomous vehicle technologies that future efforts will need to consider. First, standardization of technology performance and system interfaces will be particularly important for the many technologies that interact with and share control with the driver. Drivers are likely to use these technologies in different vehicles created by different manufacturers, and their safe use depends on the driver understanding how to use each technology and its capabilities and limitations. Second, autonomous vehicle technologies will be used by a wide range of drivers and passengers who vary in their expectations of how and when the technologies will work and in their ability to understand each system's warnings and directions. Therefore, standards must be developed that take into account diverse populations. Third, autonomous vehicle technologies sense and make judgments about the vehicle's external environment, which cannot be controlled and can vary tremendously. Therefore, performance standards for these technologies must specify the environmental conditions under which the tests must occur and, ideally, will include testing under a wide range of environmental conditions.

While this report is just a preliminary effort to survey the likely liability and regulatory implications of this technology, we make a few suggestions that policymakers and automakers may wish to consider. First, it will be important to ensure that consumer expectations do not exceed the limits of the available technology. While we anticipate that fully autonomous operation of cars will be possible at some point, the first steps will retain the human driver as an important part of the control of the car. Drivers will be tempted to rely on the technologies in dangerous ways. Avoiding false expectations will be important to ensure safety. Manufacturers will have strong incentives to design systems to prevent this overreliance to reduce liability under legal theories that consider consumer expectations.

Second, it is important that the operation of these technologies be standardized among manufacturers so that the technologies function in materially the same way regardless of car manufacturer. This will reduce the risk of crashes stemming from consumer confusion. Furthermore, significant research has been done on such technologies as lane departure warning, driver-fatigue monitoring, and collision warning, and the benefits are significant. We recommend that the US DOT accelerate rulemaking for these mature technologies.

Third, Congress could consider creating a comprehensive regulatory regime to govern the use of these technologies. If it does so, it should also consider explicitly preempting inconsistent state-court tort remedies. This may minimize the number of inconsistent legal regimes that manufacturers face and simplify and speed the introduction of these technologies. While federal preemption has important disadvantages, it might speed the

development and utilization of these technologies and should be considered, if accompanied by a comprehensive federal regulatory regime.

ABBREVIATIONS

3D	three-dimensional
ACC	adaptive cruise control
ADAS	advanced driver-assistance system
CAMP	Crash Avoidance Metrics Partnership
CWS	collision warning system
DARPA	Defense Advanced Research Projects Agency
EEED	Environment, Energy, and Economic Development Program
EPA	U.S. Environmental Protection Agency
FDA	Food and Drug Administration
FMVSS	Federal Motor Vehicle Safety Standard
GNSS	global navigation satellite system
GPS	Global Positioning System
ICJ	RAND Institute for Civil Justice
IHRA-ITS	International Harmonized Research Activities working group on intelligent transport systems
INS	inertial navigation system
ISE	RAND Infrastructure, Safety, and Environment
ISO	International Organization for Standardization
ITS	intelligent transport system
IVHS	intelligent vehicle highway system
LCDAS	lane-change decision-aid system
m	Meter
mph	miles per hour
NCAP	New Car Assessment Program
NGO	nongovernmental organization
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automobile Engineers
US DOT	U.S. Department of Transportation

1. INTRODUCTION

Autonomous vehicle technologies refers to technologies and developments that enable a vehicle to assist, make decisions for, and, ultimately, replace a human driver. Such technologies include crash warning systems, adaptive cruise control (ACC), lane-keeping systems, autonomous parking technology (often collectively termed *advanced driver-assistance systems*, or ADASs), and, ultimately, full-scale driverless cars.

These technologies potentially offer tremendous social, economic, and environmental benefits. In the United States, more than 40,000 people are killed each year in crashes, and approximately 2.5 million are injured (NHTSA, 2008c). The vast majority of these crashes are the result of human error (Choi et al., 2008; FMCSA, 2006), and, by greatly reducing the opportunity for human error, autonomous vehicle technologies have the potential to greatly reduce the number of crashes. For example, a report by the Federal Highway Administration finds that up to 48 percent of the 18 million annual rear-end, run-off-road, and lane-change crashes could be prevented with the widespread deployment of integrated driver-assistance and warning systems (ITS, undated [a]). Similarly, a study of commercial vehicles found that a bundled system of collision warning, ACC, and advanced braking could prevent 23–28 percent of rear-end crashes (Battelle, 2007). Because the daily toll from crashes is so high, even small improvements could save a significant number of lives.

Autonomous driving can also increase fuel efficiency and reduce the environmental effects of driving. One study found that, “because [ACC] reduces the degree of acceleration relative to manual driving, and because [it] would be used more than [conventional cruise control], deployment of [ACC] systems will result in increased fuel efficiency and decreased emissions” (NHTSA, 1999 [2002], pp. 5–17). Bose and Ioannou (2001) demonstrated in simulation that, if 10 percent of vehicles used ACC, fuel consumption could be reduced by 8.5–30 percent and pollution could be reduced from 1.5 to 60 percent, depending on acceleration characteristics (Bose and Ioannou, 2001). Work is currently being done to use these technologies to improve traffic flow (Kesting et al., 2005; Zhou and Peng, 2005).

Eventually, occupants will also benefit from being able to safely pursue other activities while their vehicles drive themselves. Such full-scale driverless cars can offer mobility and independence to those without it. They may even be used as valets to perform tasks and errands with no driver and no passengers on board. This valet capacity could also help resolve land-use problems that result from the need for most businesses and residences to have parking within a short walk. If a car could be quickly summoned, it could be stored at some distance from where it will be entered or exited.

In some ways, such technologies are not the first “autonomous” aids to driving: Air bags and antilock brakes also intervene automatically and have been around for decades. However, emerging and future autonomous vehicle technologies are unique in the extent to which they contribute to driving. In traditional vehicles, the human driver is responsible for negotiating virtually all elements of driving, including other vehicles on the road, pedestrians, road conditions, and the weather. The driver must analyze the highly complex, highly variable

environment and is responsible for making judgments about when, where, and how to drive. Autonomous vehicle technologies will increasingly perform these challenging functions in addition to, or instead of, the driver. In doing so, such systems increasingly shift responsibility for driving from the driver to the vehicle itself.

This motivates a new look at liability and regulatory regimes because of the increasing uncertainty about what should happen when the inevitable crash occurs. Who will be responsible and to what extent? In the United States, state tort law plays a central role in resolving disputes. Accordingly, tort law doctrine will have enormous implications for the development and implementation (or lack thereof) of these technologies (Hunziker and Jones, 1994). Additionally, the government regulates automobiles substantially. Yet, no regulatory standards exist for autonomous vehicle technologies, despite the fact that some technologies are already on the market. What role should regulation play, and how should it interact with the relevant tort law in this context? What first principles can be established in this emerging field?

Such institutional concerns shape investment in autonomous vehicle technologies and, when unresolved, can pose barriers to their development and adoption (GAO, 1997; Cheon, 2002; Deakin, 2004). This research is an initial step toward creating an integrated collection of policies to understand and address these issues. In this work, we first evaluate how the existing liability regime would likely assign responsibility in crashes involving autonomous vehicle technologies. We identify the controlling legal principles for crashes involving these technologies and examine the implications for their further development and adoption. We conclude that autonomous vehicle technologies are likely to reduce liability for drivers but increase liability for manufacturers as perceived responsibility for crashes shifts from drivers to the vehicle itself. This may impede development and use of these technologies. Second, we examine the existing regulatory environment for autonomous vehicle technologies, examine where standards and regulations might fall short, and suggest general principles and guidelines for future standard setting and rulemaking. We then offer tentative conclusions about the effect of this landscape on the introduction of autonomous vehicle technologies and identify areas of potential further research.

We begin in Section 2 with an introduction to autonomous vehicle technologies and discuss prior work in Section 3. Section 4 presents analysis of the current liability regime and its application to autonomous vehicle technologies. In Section 5, we discuss standards and regulations and their application to autonomous vehicle technologies. We conclude in Section 6 with a summary, policy suggestions, and opportunities for future work in these areas.

2. AUTONOMOUS VEHICLE TECHNOLOGIES

We define *autonomous vehicle technologies* as those technologies that gather information about the environment and autonomously make judgments about driving to inform the driver, take partial control of the vehicle, or drive the car autonomously without any human intervention.¹ We have limited the scope of this research effort to in-vehicle technologies that are not dependent on new infrastructure or the installation of new technology in the road.²

A widely used approach to categorizing these technologies is by the degree to which they intervene in the driving of the vehicle (Carsten and Nilsson, 2001). This approach is particularly useful for examining the implications of liability and regulation as control shifts from the driver to the vehicle. However, while much of the literature uses discrete categories to describe these systems (e.g., Ho, 2006; Schwarz, 2005), we feel that they are more aptly described as points along a spectrum, from complete driver control to complete vehicle control. This notional spectrum is illustrated in Figure 2.1.

¹ Many of the technologies we have dubbed *autonomous vehicle technologies* are often collectively referred to as *advanced driver assistance systems* (ADASs). We use the term *autonomous vehicle technologies* instead of ADAS, however, to precisely refer to technologies that gather information and autonomously make judgments about driving and that, for the purposes of this study, are likely to present a shift in liability. The term *advanced driver assistance systems* is imprecise because (1) the classification of a technology as *advanced* is subjective and changes as new technologies emerge, and (2) there is no consensus about what is and what is not an ADAS. Additionally, the term *ADAS* does not map well to the technologies we examine. For example, ADAS typically includes technologies that only present information to the driver without making judgments, such as navigation aids and night-vision aids, and excludes such technologies as fully autonomous vehicles.

² We focus our analysis on technologies in which the driving “intelligence” resides within the vehicle rather than in the surrounding road infrastructure (i.e., *intelligent highways*) for two reasons. First, as we discuss in our review of prior work in Section 3, infrastructure-based systems were the focus of much of the earlier research and development efforts, and, consequently, many others have already discussed the liability and regulatory regimes for these technologies (e.g., Ayers, 1994; Cheon, 2002; Khasnabis, Ellis, and Baig, 1997; Roberts et al., 1993; Syverud, 1992). Second, and perhaps more important, in-vehicle systems are reaching drivers much more rapidly and widely than infrastructure-intensive systems, which must overcome a wide range of institutional challenges (see Deakin, 2004; Cheon, 2002; Alkadri, Benouar, and Tsao, 1998). In 1997, for example, the U.S. Department of Transportation (US DOT) discussed a shift in the National Automated Highway System Consortium’s focus on driver-assistance systems because of a widespread lack of support among administration and other stakeholders for the high-cost, long-term planning horizon and liability concerns associated with the automated highway system (GAO, 1997). This program was terminated early in 1998. Given the lack of political support for expensive, wholesale changes in the U.S. transportation infrastructure, the liability and regulation of the many in-vehicle systems appearing on the market more immediately affect consumers and manufacturers. This is not to suggest that infrastructure is unnecessary—the Global Positioning System (GPS), for example, is a critical navigation component for many autonomous vehicle technologies. Moreover, much research is under way in both the public and private sectors to develop infrastructure that assists and enables in-vehicle autonomous vehicle technologies, such as communication networks for vehicle-to-vehicle communication (Shulman and Deering, 2005). Similarly, researchers have examined pathways to pilot and then broadly adopt these systems (e.g. Shladover et al., 2001). A new look at liability and regulation of these systems will be warranted as these support systems are deployed and as new public-private partnerships emerge to manage them.

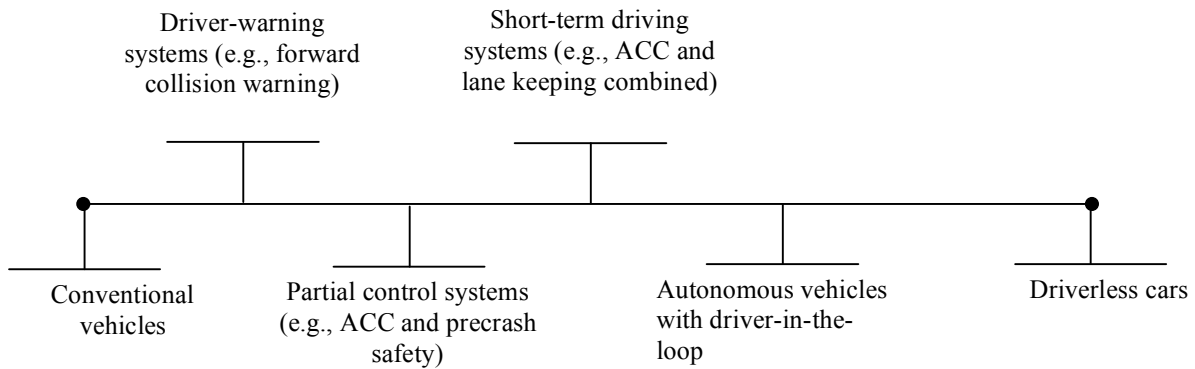


Figure 2.1. Notional Spectrum of Control. It is common to describe and categorize autonomous vehicle technologies according to the degree to which they intervene in the driving of the vehicle. At one end of this spectrum, conventional vehicles are completely in the driver’s control, while, at the other end, driverless cars do not require a human behind the wheel. Note that the distances between systems in this figure are for visual clarity only; they do not reflect “distances” in terms of technical complexity.

Near one end of the spectrum, warning and assistance systems alert the driver to dangerous conditions, such as unintended lane departures and impending forward, rear-end, and lateral collisions, and guide the driver in maneuvers, such as changing lanes and parking. Simple forward collision-avoidance systems, for example, monitor the speed differential with and the distance from the preceding vehicle and alert the driver with an audio cue when there is a risk of a collision. Other technologies aim to protect those outside the vehicle. Pedestrian-detection systems, for example, identify and alert drivers to pedestrians and cyclists, particularly if they are in low-visibility areas toward the rear of the vehicle or in the driver’s blind spot (Chan, 2006). Such technologies affect the driving process indirectly by influencing the driver rather than by acting on the vehicle. In this way, the driver must interpret the suggestions and warnings, take into account other factors that may affect the validity of the information (e.g., the weather, other traffic, road conditions), and, ultimately, drive the vehicle.

Intervention systems take the next step toward vehicle autonomy. They gather information, process it, and take partial control of the driving task in some way. ACC is perhaps the best known of these technologies. Traditional cruise control fixes the velocity of the vehicle without regard to the external environment, while ACC tailors cruise control to the flow of traffic: It reduces speed when preceding vehicles are moving slower than the desired speed and then accelerates again when becomes safe to do so. In this way, ACC is able to reduce forward collisions, particularly when the driver may be distracted and where the flow of traffic is uneven. Lane-keeping systems use vision or laser technologies to track lane markings and keep the vehicle in its current lane. Although these technologies actively control the vehicle in some ways, they must be activated by the driver, with the idea that the driver is responsible for judging when it is appropriate to use them (e.g., when traffic and weather conditions

allow). However, some of these technologies disengage automatically. Many ACC systems, for example, automatically deactivate at low speeds when cruise control may not be appropriate: They warn the driver that intervention is required and then release control of the braking and acceleration with the expectation that the driver will resume control over those functions.

A few technologies exert partial control of the vehicle without being engaged by the driver. To date, such systems are limited to those that intervene when a crash is imminent and no action on the part of the driver can prevent it. For example, precrash safety systems tighten seat belts and apply the brakes prior to impact in an effort to reduce the effects of the crash (e.g., DENSO Corporation, undated). Parallels can be drawn between these technologies and air bags: Both activate without the driver's influence but only when a crash is imminent and with the aim of reducing injury and damage. However, a distinction can be made between air bags and these technologies: Air bags are not controlling the central functions of the car and are triggered by the impact itself.

Next, we can foresee a host of systems that take over driving for short periods of time or in certain circumstances at the discretion of the driver. For example, combining ACC and lane keeping creates a system that is capable of driving itself in highway-like environments: ACC maintains speed, and lane keeping maintains steering.³ Similarly, other technologies may autonomously park the vehicle or change lanes on the highway. As before, the driver will (at least in the near future) have to activate these systems at his or her discretion.

Finally, at the far end of the spectrum are fully autonomous vehicles that are capable of driving from origin to destination entirely on their own. Such vehicles are not yet available, but significant leaps forward have been made in recent years. The Defense Advanced Research Projects Agency (DARPA), for example, recently held a series of high-stakes, high-profile competitions among industry and university research groups to develop fully autonomous vehicles, first for off-road and trail driving in the Grand Challenge and then, in 2007, for urban environments in the Urban Challenge. The vehicles completed a series of driving missions completely autonomously with no human intervention while obeying all traffic rules and operating in the presence of other autonomous and human-driven vehicles (Urmson et al., 2007).

We can envision several roles for fully autonomous passenger vehicles. First, they could enable would-be drivers to perform other tasks, turning morning commutes, for example, into opportunities to catch up on sleep, enjoy breakfast, or prepare for the day's work. In such scenarios, the driver is in the vehicle but is not involved in the driving process in any way. Second, they would provide mobility and independence to those without it, including the elderly, the physically challenged, and even children. The vehicle, for example, could chauffeur the elderly to medical appointments or children to school and soccer practice. Here, passengers are in the vehicle but they are not intended to participate in driving. Finally, vehicles would be able to act as valets with no driver and no passengers on board. The vehicle could pick up dry cleaning and groceries and return books to the library or park itself after dropping the owner off at work. These scenarios demonstrate different levels of human involvement in

³ In 2006, Honda launched its Accord ADAS for sale to the public in Europe with just such capabilities (Miller, 2006).

personal transportation, even when the vehicle is fully autonomous; thus, they may also present different liability concerns. As we discuss later, crashes (and liability) may result if consumers are confused about the capabilities of technology. This has heightened concern for technologies that only partially take control of the automobile and still leave the human (and, therefore, error-prone) driver in the control loop.

2.1 A FRAMEWORK FOR UNDERSTANDING AUTONOMOUS VEHICLE TECHNOLOGIES

In traditional vehicles without autonomous vehicle technologies, the human driver negotiates virtually all of the interaction between the vehicle, the driving objective, and the external environment. The driver determines the long-term navigation task (e.g., arriving at the grocery store in 20 minutes), continuously evaluates the environment surrounding the vehicle (including other vehicles, lane markings, signs, pedestrians, weather, and road conditions), determines the desired vehicle behavior (e.g., to change lanes), decides how to achieve that trajectory (e.g., a smooth arc or a sharp swerve), and exerts control over the vehicle by manipulating lateral movement and speed. The driver is also responsible for providing information to others in the environment—e.g., waving another driver through an intersection, honking at a pedestrian who appears to be walking into the line of traffic, or using signals to indicate a turn. The vehicle’s only “autonomous” response to the environment occurs when the environment has an immediate effect on the vehicle’s performance. For example, the vehicle’s air bags automatically deploy only when its crash sensors measure the actual force of an impact but not in the split second before, when the impact is imminent and perhaps anticipated by the driver but not yet experienced by the vehicle. Similarly, antilock braking systems engage when the wheel speed sensors determine a disparity in rotational speeds between the four wheels that is indicative of a locking wheel but do not sense or respond directly to the driving conditions that may have caused it (e.g., icy roads).

In contrast to technologies in conventional vehicles, autonomous vehicle technologies perform many of these complex functions and respond to the environment directly; this enables them to play ever-larger roles in driving. The robotics research literature roughly categorizes these functions into three categories: sensing, planning, and acting. This framework is an oversimplification and an overgeneralization of the processes unique to each technology and each implementation, but the terms can help us understand how these systems operate. Sensing, planning, and acting are functions that humans perform naturally and seamlessly, usually without conscious thought. For autonomous systems, however, each can be an extremely complex and difficult engineering challenge. We begin by describing these different functions and how they are performed, and then examine different autonomous vehicle technologies.

2.1.1 Sensing

Sensing consists of gathering information about the external environment and the internal system in order to build a model, called a *world model*, that represents and describes the vehicle, its surroundings, and the relationships between them. Depending on the system function, this model may include the external environment, such as road conditions, weather, and traffic; vehicle-performance characteristics, such as velocity, heading, and tire

pressure; and even the behavior of vehicle occupants, such as the driver's eye movements, seat-belt use, and passenger weight distribution. In a fully autonomous vehicle, *all* of this information may need to be incorporated simultaneously into a complete world model.

There are a number of challenges associated with sensing, particularly for systems that perform complex or multiple functions. First, individual sensors are limited in what they can detect or measure and depend on favorable environmental conditions.⁴ Consequently, systems may need to have many different sensors to gather all the required information and to provide redundancy and increased reliability. For example, Tartan Racing, a team in the DARPA Urban Challenge, employed eight different types of sensors on its vehicle and multiple sensors of each type (Urmson et al., 2007). These sensors generate a tremendous amount of data per second. Second, the vehicle must be able to process the data fast enough to avoid a backlog of information. Third, some of the data will be good data (e.g., color information from cameras in the day), and some not (e.g., color information from cameras at night), and the system must be able to recognize the difference. Fourth, data from different sensors or gathered at different times may conflict; algorithms must reconcile contradictions in the data and, in the end, create a complete model that is accurate enough to enable the vehicle to drive safely and efficiently.

2.1.2 Planning

In planning, the system applies an algorithm to analyze the world model and create a set of actions that bring the system closer to its objective. In complex systems, such as fully autonomous vehicles, planning produces a sequence of high-level behaviors similar to those a human would take (e.g., change lanes, then take the next exit and turn right at the end of the ramp) and trajectories to achieve those behaviors (e.g., a sequence of wheel curvatures and speeds). In simpler systems, however, this step may be omitted if features in the world model can be mapped a priori onto desired actions (e.g., in a precrash braking system, the brakes may engage whenever the distance to the preceding vehicle is less than 2 meters [m] and the vehicle speed is more than 10 miles per hour [mph]).

⁴ Vision, radar, and laser are some of the most common sensor types for measuring the external environment. Vision-based systems use cameras to detect color and shape but depend on favorable lighting conditions. Used in stereo pairs, cameras can also determine distances to objects but with less accuracy than most laser and radar systems. Laser and radar emit light and radio signals, respectively, which reflect off of objects in the environment and return to the sensor. By measuring the time of the signal flight, these sensors can determine the distance to and velocity of objects and construct three-dimensional (3D) representations of the environment. Laser systems measure distances to all types of solid objects, but they are best at short range and do not operate on water or in rain. Radar systems, on the other hand, operate at long ranges but are limited to detecting metallic objects; this is ideal for detecting vehicles but not other traffic.

GPS and inertial navigation systems (INSs) are the most common sensors for detecting the vehicle's own position, velocity, and orientation. GPS is a global navigation satellite system (GNSS) that provides accurate absolute positioning, orientation, and velocity by measuring signals from satellites orbiting the earth. As such, GPS requires a clear view of the sky and does not perform well in urban environments or under tree cover. INSs work in all environments: They use gyroscopes and accelerometers to accurately track the vehicle's position, orientation, and velocity relative to a starting reference point and are critical when external sources of position (e.g., GPS) are unavailable. INSs, however, can accrue significant error over time.

One of the challenges in planning is that the system needs to select actions that will occur in the future even when it has accurate information only about the past and the present. Therefore, it needs to extrapolate the future state of the environment, which may contain moving elements that often do not behave as expected. For example, a vehicle's plan may involve it driving at a particular speed and in a particular direction, but this may be based on the assumption that the preceding vehicle will maintain its current speed. If the preceding vehicle suddenly decelerates, the system will have to very rapidly prepare a new plan of action. This is a second challenge in planning: The system needs to compute plans fast enough to always be responsive to the driving task, which can require several planners to be running simultaneously.⁵

2.1.3 Acting

Lastly, *acting* is the actual execution of plans by manipulating the steering, throttle, brakes, and other vehicle components. Vehicles today are increasingly being developed with drive-by-wire technology, which replaces the traditional mechanical and hydraulic control systems with electronic control systems. This allows autonomous vehicle technologies to use computers to control the vehicle components, which is a far easier and more reliable approach than manipulating the components with physical force. Although drive-by-wire tremendously simplifies acting on the vehicle components, there are still challenges associated with producing the desired driving effect. For example, on an icy road, turning the wheel column rapidly may turn the vehicle's wheels but may not turn the vehicle itself because of a loss of traction. A tight sensing, planning, and acting cycle makes it possible to detect and correct unexpected vehicle behaviors and unexpected traffic and environmental events.

2.1.4 Integrating Sensing, Planning, and Acting

In classic robotic control architecture, sensing, planning, and acting are distinct processes that take place in sequence. Similar approaches may work in simple autonomous vehicle technologies—e.g., those that warn the driver when specific conditions are met. In systems like fully autonomous vehicles, however, the difficulty and uncertainty of the driving task requires that these functions be performed continuously and asynchronously and be tightly integrated in multiple control loops. For example, there may be a very fast sense-act control loop between a forward-looking laser and the brakes that slows or stops the vehicle whenever a close obstacle is encountered, regardless of the higher-level transportation goals (e.g., changing lanes). The data from this same laser may simultaneously feed into a larger sense-plan-act control loop to perform other maneuvers. Not surprisingly, these systems can become very complex, and their performance and reliability can be difficult to test and prove.

⁵ Tartan Racing's explanation of its approach to planning describes these challenges in detail (Ferguson et al., 2008).

2.2 THE WORKINGS OF AUTONOMOUS VEHICLE TECHNOLOGIES

Building on this foundation, we now turn to how specific autonomous vehicle technologies work, paying particular attention to those aspects that may have implications for liability and regulation. Driver-warning systems are intended to perform very specific functions: monitor immediate areas around the vehicle and alert the driver when certain risky conditions occur. Collision warning systems (CWSs), for example, continuously sense the distance to the vehicle immediately ahead or behind of the host vehicle, typically with a camera or radar, and determine when that vehicle is within some distance threshold that poses a threat. Lane departure warning systems sense the lane markings of the host vehicle's lane with cameras or lasers and alert the driver when the vehicle appears to be veering from its lane unintentionally. Indications that the lane change is unintentional may include that the driver has not turned on the indicator or that the driver's gaze is not directed at the road as determined by an inward-looking camera that monitors the driver's eye movement.

From a technological perspective, such systems are relatively simple. The world model required for operation is small, consisting of the vehicle, its lane, and vehicles immediately ahead or behind. This means that sensing is limited to one or two sensors that monitor very specific areas of the road and that it is relatively easy to fuse sensor data. These systems are also simple in terms of their decisionmaking: Instead of planning, it suffices to evaluate whether the world model meets some predefined conditions that constitute a scenario that warrants a warning. Further, as warning systems, they also do not act on the vehicle.

Systems that exert some control on the vehicle use technologies and approaches similar to those in warning systems. ACC senses the distance to the preceding car using the same technology as forward collision warning systems and uses the world model to compute the appropriate speed adjustment required to meet the vehicle spacing set by the driver. Drive-by-wire technology makes it possible to compute and execute smooth throttle adjustments. In this way, ACCs use a sense-act model and do not need to do any planning. A lane-keeping system is to a lane departure warning systems what ACC is to a forward collision warning system: it utilizes the same types of sensors and world models to compute desired vehicle headings and to execute smooth changes in heading.

One challenge is to ensure that the driver understands when the system works properly and when it could fail or has failed. These systems may not operate in certain weather or visibility conditions in which sensors are unable to operate or in circumstances that may "confuse" the sensor. For example, lane departure warning systems may not effectively detect lane departures in areas of active construction, where several lane markings may overlap to indicate lane shifts or may be missing entirely. In these circumstances, what is the extent of a manufacturer's responsibility in alerting the driver when the system may not be operating properly, given that the driver is expected to be continuously attentive? What level of system integrity is required?⁶ Additionally, for some systems, the driver is expected to intervene when the system cannot control the vehicle completely. For example, if a very rapid stop is required, ACC may depend on the driver to provide braking beyond its own capabilities. ACC also does not respond

⁶ We use the term *system integrity* to describe a system's ability to recognize that it is performing unreliably (e.g., because its components have malfunctioned or because it is operating in an unsuitable environment) and to notify the user that it should not be used.

to driving hazards, such as debris on the road or potholes—the driver is expected to intervene. Simultaneously, research suggests that drivers using these conveniences often become complacent and slow to intervene when necessary; this behavioral adaptation means drivers are less responsive and responsible than if they were fully in control (Rudin-Brown and Parker, 2004). Does such evidence suggest that manufacturers may be responsible for monitoring driver behavior as well as vehicle behavior? Some manufacturers have already taken a step toward ensuring that the driver assumes responsibility and is attentive, by requiring the driver to periodically depress a button or by monitoring the driver by sensing eye movements and grip on the steering wheel. As discussed later, litigation may occur around the issue of driver monitoring and the danger of the driver relying on the technology for something that it is not designed to accomplish.

The complexity of systems that take full control of the vehicle at the discretion of the driver depends on what functions these systems perform. The underlying “autopilot” system resulting from the combination of ACC and lane keeping may be no more complex than the sum of its individual parts: It may still utilize a sense-act paradigm that uses relatively few and simple sensors to build a basic world model that is governed by straightforward behavioral rules. However, the combination of ACC and lane keeping could cause consumers to overrely on the system in a way that they would not if they were using each system independently. Then, new additional technology may need to be introduced to counteract this reliance (e.g., by monitoring the driver carefully). In this way, the system may become be much more complex than the sum of its parts.

Such systems as autonomous parking and lane changing will be more complex. They will need to look beyond the narrowly defined vehicle environment that has sufficed for other systems. Automatic parallel-parking systems, for example, have to sense the stationary vehicles around the parking space and pedestrians who may be on the sidewalk; monitor the trajectory of cars, bicycles, and other objects coming up from behind and approaching from ahead; and plan complex maneuvers to fit in the space.

Fully autonomous vehicles, such as the entrants into DARPA’s Grand and Urban Challenges, are tremendously more complex. As discussed earlier, they must sense the environment broadly, using a host of sensors that may present conflicting or incomplete pictures of the environment; develop complex current and future world models; rapidly plan and replan given uncertainties and constantly changing circumstances; and maintain total control over the vehicle. The challenges of these technologies, however, go beyond system and algorithmic complexity. While it is possible to design autonomous vehicles that obey all traffic rules, they, like human drivers, must share the road with other drivers who do not do so. Additionally, there are many unique human aspects to driving: Human drivers watch the body language and eye contact of pedestrians to anticipate whether they will attempt to cut into traffic, drivers signal to each other with eye contact and body language, and local driving etiquette can preempt actual traffic rules.⁷ How can technology be designed to accommodate these customs? What

⁷ In Pittsburgh, Pennsylvania, for example, the “Pittsburgh left” is a regional custom in which the first driver stopped at a traffic light will sometimes wait for a moment after the light turns green to yield to the first driver in the oncoming traffic who wishes to make a left turn. In most other places, of course, drivers wishing to make a left turn across traffic yield to the oncoming traffic.

happens when others expect customary behaviors from drivers that are not implemented in driverless cars? Furthermore, in many driving situations, the correct procedures are often unclear. If a vehicle breaks down in one lane of a two-way street, drivers coming in either direction will usually take turns to pass and keep the traffic flowing. Negotiating such situations involves taking some risks and making some assumptions. Can autonomous vehicles be designed to behave safely and appropriately in such situations? Experiences from the Urban Challenge suggest that it is possible: During the competition, some vehicles were able to take appropriate mitigating actions when others were not operating correctly. But, what risks and assumptions can autonomous vehicles make, and will we and should we allow it? Who will be responsible under these circumstances?

3. PRIOR WORK

Before beginning our own analysis, we briefly discuss prior work that addresses the implications of liability and regulation on the adoption of autonomous vehicle technologies and closely related systems.

Intelligent vehicle highway systems (IVHSs) received significant attention in the scientific research community in the 1990s, and a complementary body of work addresses the liability issues that arise from their deployment. Much of the technical research emphasized infrastructure-intensive intelligent and automated highways. Given the government's major role in implementing such systems, the liability research focuses on government liability and *sovereign immunity*, a doctrine that protects federal, state, and local governments from being held liable.

Roberts et al. (1993) thoroughly cataloged the status at the time in the 50 states of the doctrine of sovereign immunity, a doctrine that sometimes immunizes governmental agents from tort liability, and list (but do not analyze) several options that could be used to create an environment that encourages IVHS development without compromising safety. Khasnabis, Ellis, and Baig (1997) provide an initial look at how sovereign immunity applies to different aspects of government involvement in automated highway systems (e.g., planning, design, development) and pose the question, "How can the government balance the interest of citizens at large against protecting its agencies, employees, and contractors from lawsuits?" Balancing safety and innovation is still a key issue for the introduction of autonomous vehicle technologies and motivates our own work; however, this earlier body of work does not address the host of new technologies that focus on driver assistance and autonomy within individual vehicles. This move to decentralized networks of autonomous vehicles makes issues of sovereign immunity less relevant because the requirement for government action is greatly lessened.

Some of the early research also addresses the then-emerging driver-assistance systems, particularly collision warning and ACC. In a series of three articles, Bagby and Gittings discuss general tools for highway liability risk management (1999a); explain principles of tort reform, products liability reform, and privacy law (1999b); and apply these principles to advanced highway systems and electronic toll collection (2000). The third article additionally identifies key litigation risks for collision warning and intervention systems (e.g., sensor malfunctions that cause abrupt and unnecessary stopping; system failure to warn drivers of potential collisions; driver overreliance on systems) and for ACC (e.g., outright malfunction, such as a failure to disengage; driver's inability to control the system or intervene when necessary).

Ayers (1994) surveyed a range of emerging autonomous vehicle technologies and automated highways, evaluated the likelihood of a shift in liability occurring, discussed the appropriateness of government intervention, and highlighted the most-promising interventions for different technologies. Ayers found that collision warning and collision-avoidance systems "are likely to generate a host of negligence suits against auto manufacturers" and that liability disclaimers and federal regulations may be the most effective methods of dealing with the liability concerns (p. 21). The report was written before many of these technologies appeared on the market, and Ayers further

speculated that “the liability for almost all accidents in cars equipped with collision-avoidance systems would conceivably fall on the manufacturer” (p. 22), which could “delay or even prevent the deployment of collision warning systems that are cost-effective in terms of accident reduction” (p. 25).

Syverud (1992) examines the legal cases stemming from the introduction of air bags, antilock brakes, cruise control, and cellular telephones to provide some general lessons for the liability concerns for autonomous vehicle technologies. In another report, Syverud (1993) examines the legal barriers to a wide range of IVHSs and finds that liability poses a significant barrier particularly to autonomous vehicle technologies that take control of the vehicle. In this work, Syverud’s interviews with manufacturers reveal that liability concerns had already adversely affected research and development in these technologies in several companies. One interviewee is quoted as saying that “IVHS will essentially remain ‘information technology and a few pie-in-the sky pork barrel control technology demonstrations, at least in this country, until you lawyers do something about products liability law’” (1993, p. 25). Syverud sums up that, “[a]bsent a substantial shift of responsibility for automobile accidents or significant legislative reform, tort liability is likely to deter significant private investment in [advanced vehicle-control systems] in the United States” (1993, p. 51).

Collectively, this body of work frames the general concerns about liability and autonomous vehicle technologies, identifies specific types of litigation that could be expected in the then-emerging technologies, and suggests initial strategies for addressing the risks. This work provides a foundation for the analysis in this report, but it is now more than a decade old. Written at a time when autonomous vehicle technologies were just beginning to be developed, this work is necessarily speculative and does not consider recent advances in or actual implementations of autonomous vehicle technologies or recent developments in tort law.

Some recent work has been done on the legal implications of ADASs, though most of this work is from Europe and relates specifically to European law. The RESPONSE 1, RESPONSE 2, and RESPONSE 3 projects are sponsored by the European Commission and the European auto industry to develop a code of practice for accelerating the market introduction of ADASs. Part of this work is to examine the liability risk of these technologies, but the work to date is very general and does not yet include the legal analysis that is necessary (Schwarz, 2005; RESPONSE 2, 2004).⁸ Van Wees and colleagues have published a number of articles (van der Heijden and van Wees, 2001; van Wees, 2000, 2004; van Wees and Brookhuis, 2005) mapping out the likely liability consequences of some categories of ADAS-related crashes under European law. Like others, van Wees and Brookhuis note, “One of the most prominent questions in this context is to what extent the use of ADAS may shift liability for road crashes from drivers to car manufacturers and system developers and whether current liability regimes are suited to accommodate the introduction of ADAS” (p. 358). Their findings, based on the European Products liability Directive, include that manufacturers must take care to educate consumers about technology

⁸ For example, Schwarz (2005, p. 3) observes that “[t]here is a possibility that the information provided by the system may be incorrect or inaccurate. If this is the case, manufacturer or distributor liability should also be taken into consideration.”

limitations, to consider the behavior of a range of users when defining “reasonable use” of the technology, and to test technologies in a wide range of circumstances. While these guidelines will be generally relevant to manufacturers in the United States, the legal analysis cannot be directly transferred from Europe. Van der Heijden and van Wees (2001, p. 321) note that, “Due to [several] differences [in] the legal situation in the field of products liability law in Europe and the USA, although in terms of the underlying principle [they are] the same, in practice [they are] not comparable.” When comparing the European and U.S. regimes, van Wees (2000, p. 7) found that “products liability in the US will indeed be a greater threat for the deployment of electronic driver support systems” than in Europe and attributed this to broad legal differences, such as high damage awards, the use of technical expert testimony, and the system of jury trials in the United States, rather than fundamental differences in products liability laws.

Recent research and development efforts undertaken in the United States do recognize the need for resolving liability, regulation, and other nontechnical concerns. For example, the US DOT’s IntelliDriveSM program aims to enable vehicles to identify roadway threats and communicate these threats to other vehicles over a wireless network; its work plan includes the development of wireless-communication standards and studies of liability and regulation (see ITS, undated[b]). Similarly, participants at the 2004 workshop of the US DOT’s Cooperative Intersection Collision Avoidance Systems program have expressed concerns about the distribution of liability among the many stakeholders (see ITS, 2005).

Nevertheless, recent work on these issues seems to only broadly and theoretically survey the liability concerns associated with autonomous vehicles and fails to offer a concrete analysis. Cheon’s (2002) examination of the institutional barriers to automated highway systems highlights general liability issues that also apply to in-vehicle autonomous vehicle technologies. The observations include that liability concerns may lead to highly conservative regulation and practice, that tort reform may be necessary, and that consumer education and the development of standards may reduce liability. While this work frames many of the concerns, it does not provide a specific analysis of the liability regime. Ho (2006) explores the policy implications of driver-warning systems and pays particular attention to standards and regulations, in part as a way to address liability concerns. Like Cheon’s, however, this work does not include a legal analysis. Nevertheless, Ho (2006, p. 100) finds that the benefits of safety standards outweigh the costs and that “safety standards must be designed and set as soon as possible in order to ensure that future warning systems meet a minimum level of safety before they are introduced more widely into the market.”

In sum, the literature substantiates the importance of rational, well-developed regulatory, safety, and liability regimes for autonomous vehicle technologies and offers some building blocks to this end. However, it simultaneously highlights that an analysis of the liability and regulatory implications of autonomous vehicle technologies has not been conducted.

4. THE CURRENT LIABILITY REGIME AND ITS APPLICATION TO AUTONOMOUS VEHICLE TECHNOLOGIES

In this section, we explain the principles of motor vehicle crash and products liability law and how they are likely to apply to autonomous vehicle technologies. While a full discussion of the goals of tort law lie well beyond this work, in general, we view the role of a liability regime as providing appropriate incentives to encourage efficient precautions against crashes, compensating victims, and promoting corrective justice.⁹ This, of course, includes the efficient development of technology that can reduce crashes.

We do not anticipate liability of drivers (and their insurers) for auto crashes to delay the introduction of autonomous vehicle technologies. Indeed, we anticipate that the reduction in crashes caused by human error may encourage adoption of these technologies. Manufacturers, in contrast, may face increased liability under principles of products liability law and changed social expectations about the cause of automobile crashes. This may lead to inefficient delays in the integration of this technology into automobiles.

4.1 LIABILITY FOR DRIVERS AND INSURERS

The liability implications of autonomous vehicle technologies are largely defined by the body of law that governs motor vehicle crashes and products liability law. The law governing crashes is a mixture of state tort law and the state's financial responsibility law that mandates insurance for drivers. As a result, the mandatory-insurance regime substantially affects litigation that occurs after crashes. We begin by discussing driver liability and then apply these theories of liability to autonomous vehicle technologies.

4.1.1 Theories of Driver Liability

There are three basic theories of tort liability that affect drivers—traditional negligence, no-fault liability, and strict liability—and we discuss each in turn.¹⁰

Under traditional negligence principles, a person is civilly liable for harms that the person causes if the harm is a tort. The wrongdoer (*tortfeasor*) must compensate the victim for the harms suffered.¹¹ The traditional elements of a negligent tort are the existence of a duty, the breach of that duty, causation, and injury. In the case of

⁹ By *efficient*, we generally mean that the social benefits of the technology outweigh the social costs. One commonly understood (but not uncontroversial) function of tort law is to encourage the undertaking of safety precautions to efficiently minimize risk. A sizable literature exists explicating this function of tort law. See, e.g., Calabresi (1970).

¹⁰ *Tort* is a general term for wrong and is also a term that refers to the general legal field of torts. A *negligent tort* is a particular category of tort. Other categories include *intentional tort* (the wrongdoer deliberately harms the victim) and *strict-liability torts* (the wrongdoer is liable for harms regardless of whether he or she took reasonable care to prevent them).

¹¹ In some cases, the tortfeasor must pay punitive damages in addition to those necessary to compensate the victim (*compensatory damages*).

automobiles, drivers have a duty to take reasonable care in operation. Drivers are liable for injuries that they cause in violation of this duty of reasonable care.

The central idea of liability for negligence is that a party should be held liable for harms caused by it *unreasonably* failing to prevent the risk. For example, suppose that Marty drives a car with defective brakes because he is too lazy to get the brakes repaired. As a result of his defective brakes, he injures a pedestrian. In this hypothetical, Marty will probably be found negligent. It was not *reasonable* for Marty to fail to repair his brakes.

For good and bad, *reasonableness* is a fairly vague concept. Judge Learned Hand attempted to provide more guidance by defining negligence with a mathematical formula: $B < PL$ (*United States v. Carroll Towing*, 159 F.2d 173, 1947). In Hand's formulation, B , the proper burden of care, was defined by the probability of harm, P , multiplied by the cost of the loss that would result, L . If a measure to prevent the harm cost *more* than the cost of the harm multiplied by the probability of the harm, it would not have been efficient for the defendant to have taken and the defendant should not be considered negligent. If, on the other hand, the accident-reducing measure cost *less* than the probability of harm multiplied by the cost of the harm, it would have been efficient to undertake the precaution and the defendant should be found negligent for failing to do so. In this way, Judge Hand attempted to provide an economic metric and conceptual rigor to the analysis of the accident-prevention methods—the duty of care—required. In Marty's case, let us assume that the cost of the pedestrian's injury was \$10,000 and that Marty's chance of injuring the pedestrian was 50 percent if he did not repair the brakes: $0.5 \times \$10,000 = \$5,000$. If the cost of repairing the brakes was less than \$5,000, Marty should be found liable, using Judge Hand's calculus.¹²

In the day-to-day resolution of automobile crash claims, the operation of the traditional system of liability for negligence has been influenced by the mandatory-insurance system. Insurance adjusters have adopted informal rules to effectively allocate fault (e.g., drivers who rear-end other vehicles are presumed to be at fault). These have minimized more-general analyses of reasonableness and causation in most automobile crash cases, which are resolved without formal litigation. So rather than undertaking a generalized analysis of whether a driver is negligent and therefore liable for a crash—a potentially difficult and open-ended inquiry—an insurance adjuster is likely to refer to a simpler set of rules to determine who owes what to whom (Hensler et al., 1991; Ross, 1980, p. 237: “The law of negligence was made to lean heavily upon the much simpler traffic law”).

Twelve states currently use an alternative system, called *no-fault*, for automobile-crash litigation and insurance. In these states, automobile crash victims are not permitted to sue other drivers in the tort system unless their injuries reach a certain degree of severity, called a *threshold*.¹³ Instead, victims recover their losses through

¹² Applying Judge Hand's formula in practice raises a host of issues. Which costs and benefits should we include in the calculus? See Anderson (2007, arguing that economic analysis of tort law is indeterminate without a theory of which variables should be in the cost-benefit calculus).

¹³ States have adopted either a monetary or verbal threshold. A *monetary threshold* is a certain dollar amount that the victim's injuries have to exceed to recover in tort (\$5,000 in many states). A *verbal threshold* is a description of a certain degree of seriousness. In Pennsylvania, for example, a plaintiff who elects the limitation on tort when purchasing automobile insurance must show that his or her injury is “serious” in order to recover in tort

their own insurance, which directly compensates them for their losses. Proponents of this system argued that it would eliminate the difficult determination of who, if anyone, was at fault for a particular crash, ensure that compensation would be available to victims regardless of whether anyone was legally at fault, and generally reduce litigation and lawsuits.¹⁴

A rare theory of liability that might also affect operators of autonomous vehicle technologies is strict liability for abnormally dangerous or ultrahazardous activities. The rationale for this type of liability is that actors involved in highly unusual activities are more knowledgeable about the risks that such activity entails and should consequently bear the associated costs regardless of whether they are legally at fault for the crash.¹⁵ This theory of liability may be particularly relevant to liability of drivers of early autonomous vehicles. Victims of autonomous vehicle–related crashes may sue the owners or drivers of the vehicles and argue that the operation of autonomous vehicle technologies constituted an ultrahazardous activity and the operators should therefore be strictly liable (regardless of whether they were negligent) for any crashes that occur.

4.1.2 Autonomous Vehicle Technologies and Liability of Drivers

How will autonomous vehicle technologies affect driver liability for automobile crashes? First, these technologies will likely reduce the number and overall cost of crashes. Human error causes the vast majority of crashes today, and, by reducing the risk of human error, autonomous vehicle technologies can reduce the incidence of crashes. This will, in turn, reduce automobile-insurance costs.¹⁶ To encourage adoption, insurers may offer discounts for operators who purchase automobiles with the appropriate systems. Historically, insurance companies have been important intermediaries in recognizing the safety benefits of technologies that reduce risk and

(75 Pa. C.S. §1705). “Serious” is defined as “a personal injury resulting in death, serious impairment of body function or permanent serious disfigurement” (75 Pa. C.S. §1702).

¹⁴ It has proven somewhat disappointing in practice, with costs remaining higher than expected. See Anderson, Heaton, and Carroll (in process).

¹⁵ This theory of liability is set forth in §§519–524A of the Restatement (Second) of Torts (1977): “One who carries on an abnormally dangerous activity is subject to liability for harm to the person, land or chattels of another resulting from the activity, although he has exercised the utmost care to prevent the harm.” Section 520 sets forth the following factors to be considered in determining whether an activity is abnormally dangerous or ultrahazardous:

- (a) existence of a high degree of risk of some harm to the person, land or chattels of others;
- (b) likelihood that the harm that results from it will be great; (c) inability to eliminate the risk by the exercise of reasonable care; (d) extent to which the activity is not a matter of common usage;
- (e) inappropriateness of the activity to the place where it is carried on; and (f) extent to which its value to the community is outweighed by its dangerous attributes.

¹⁶ If these technologies reduce crashes sufficiently, it is possible that the very need for specialized automobile insurance may disappear entirely. Injuries that result from automobile crashes might be covered by health insurance and homeowner’s liability insurance, in the way that bicycle crashes or other crashes are now covered. It is not clear how much crashes would have to be reduced in order to make specialized automobile-accident insurance undesirable. In theory, automobile-accident costs could today be covered under other policies, though this would require a substantial revision of state law and insurance markets.

encouraging their policyholders to invest in them. In Europe, for example, insurers have offered a 20-percent discount on automobile insurance for policyholders who purchase a car with a lane-keeping function and ACC.¹⁷

Second, and more radically, autonomous vehicle technologies may undermine the degree to which a driver must necessarily be at fault for a crash. Currently, the driver is generally considered exclusively responsible for control of the vehicle. Hence, we commonly speak of crashes as being caused by one or more at-fault drivers. In the vast majority of crashes, we ascribe blame to one or more drivers rather than to design features of the car.¹⁸ Autonomous vehicle technologies will likely dilute the sense that drivers are directly and solely responsible for their automobiles. By shifting responsibility for the automobile from the human driver to the car or its manufacturer, these systems are likely to undermine the conventional social attribution of blame for automobile crashes.¹⁹

This reduction in fault may be roughly proportional to the extent to which the particular technology apparently controls the car. As explained in Section 2, the technology operates on a continuum between complete driver control and complete automobile control. If the technology simply provides additional information to the driver (e.g., lane-departure warning), it is less likely to undermine the sense to which the driver retains ultimate responsibility for the vehicle. In contrast, suppose a car with an autopilot feature engaged crashes into a car in front of it. If the driver's use of the autopilot was proper, it seems odd to argue that the driver was necessarily at fault.²⁰ In crashes that involve drivers reasonably relying on a car's ability to control itself, there may not be an at-fault driver for the victim to sue.

While the victims in these circumstances could presumably sue the vehicle manufacturer, products liability lawsuits are more expensive to bring and take more time to resolve than run-of-the-mill automobile-crash litigation. This shift in responsibility from the driver to the manufacturer may make no-fault automobile-insurance regimes more attractive. They are designed to provide compensation to victims relatively quickly, and they do not depend upon the identification of an "at-fault" party.²¹

Third, this technology may also change the distribution of harms caused by crashes. Presently, the vast majority of crashes result in relatively minor harm, and these minor crashes vastly outnumber the major ones.

¹⁷ It is unclear whether the discount is partially subsidized by the automobile manufacturer (see Loh, 2008).

¹⁸ In theory, injuries suffered in crashes could be said to be caused by the manufacturer's design decision to allow automobiles to exceed 20 mph instead of blaming crashes on (inevitable) driver error. The attribution of responsibility or causation for a crash (or any event) is a complex process and that there are a variety of plausible candidates. Choosing one has policy implications. See Calabresi (1975, p. 73).

¹⁹ Automobile manufacturers resisted air-bag technology for exactly this reason: concern that legal responsibility for crashes would shift from the driver to manufacturers (Wetmore, 2004, p. 391).

²⁰ As tort scholars have long recognized, the assignment of legal responsibility (and liability) does not, in theory, need to match our sense of moral responsibility (see Calabresi and Hirschoff, 1972, arguing that liability could be placed on the cheapest-cost avoider—the party that is in the position to avoid the costs most cheaply). For example, one could hold automobile operators strictly liable for crashes that resulted from the operation of their automobiles, regardless of fault (defined either morally or economically). More recently, corrective-justice and civil-recourse tort theorists have questioned whether disconnecting legal responsibility from the sense of wrong is consistent with many features of tort law. See, e.g., Coleman (1992).

²¹ If one of the proposed forms of universal or near-universal health coverage is enacted, the need for speedy compensation may become less important.

Suppose that autonomous vehicle technologies are remarkably effective at virtually eliminating minor crashes caused by human error. But it may be that the comparatively few crashes that do occur usually result in very serious injuries or fatalities (e.g., because autonomous vehicles are operating at much higher speeds or densities). This change in the distribution of crashes may affect the economics of insuring against them. Actuarially, it is much easier for an insurance company to calculate the expected costs of somewhat common small crashes than of rarer, much larger events. This may limit the downward trend in automobile-insurance costs that we would otherwise expect.

Similarly, new categories of crashes might arise and these might pose interesting questions of how the liability system sets incentives to coordinate care among parties. Suppose that most cars brake automatically when they sense a pedestrian in their path. As more cars with this feature come to be on the road, pedestrians may expect that cars will stop, in the same way that people stick their limbs in elevator doors confident that the door will automatically reopen. The general level of pedestrian care may decline as people become accustomed to this common safety feature. But if there were a few models of cars that did not stop in the same way, a new category of crashes could emerge. In this case, should pedestrians who wrongly assume that a car would automatically stop and are then injured be able to recover? To allow recovery in this instance would seem to undermine incentives for pedestrians to take efficient care. On the other hand, allowing the injured pedestrian to recover may encourage the universal adoption of this safety feature. Since negligence is defined by unreasonableness, the evolving set of shared assumptions about the operation of the roadways—what counts as “reasonable”—will determine liability.

Fourth, we think that it is not likely that operators of partially or fully autonomous vehicles will be found strictly liable with driving such vehicles as an ultrahazardous activity. As explained earlier, these technologies will be introduced incrementally and will initially serve merely to aid the driver rather than take full control of the vehicle. This will give the public and courts time to become familiar with the capabilities and limits of the technology. As a result, it seems unlikely that courts will consider its gradual introduction and use to be ultrahazardous. On the other hand, this would not be true if a person attempted to operate a car fully autonomously before the technology adequately matured. Suppose, for example, that a home hobbyist put together his own autonomous vehicle and attempted to operate it on public roads. Victims of any crashes that resulted may well be successful in convincing a court to find the operator strictly liable on the grounds that such activity was ultrahazardous.

Overall, we do not anticipate that liability for individual drivers will be a problematic obstacle to the use of autonomous vehicle technologies. On the contrary, the decrease in the expected probability of a crash and associated lower insurance costs that autonomous vehicle technologies will bring about will encourage adoption of these technologies by drivers and automobile-insurance companies. As responsibility for crashes shifts away from the driver, no-fault systems may become more attractive.

On the other hand, these technologies pose challenges for manufacturers and may increase their liability risk in ways that discourage the efficient introduction of these technologies.

4.2 LIABILITY OF MANUFACTURERS

We anticipate that current liability laws may lead to inefficient delays in manufacturers introducing autonomous vehicle technologies. The gradual shift in responsibility for automobile operation from the driver to the vehicle will lead to a similar shift in liability for crashes from the driver to the manufacturer. Recognizing this effect, manufacturers may be reluctant to introduce technology that will increase their liability.

Liability of automobile manufacturers is governed by product-liability law, which is a hybrid of tort and contract law concerned with the liability of manufacturers for their products. Substantial variations exist among states, but many states have adopted portions of the Restatement (Second) of Torts (ALI, 1977) and the Restatement (Third) of Products Liability (ALI, 1998). These restatements, produced by the American Law Institute, are efforts to systematize the law. While not automatically binding on any court, many state supreme courts adopt portions of the restatements to govern particular areas of the law.

Product-liability law can be divided into theories of *liability* and kinds of *defect*. Theories of liability include negligence, misrepresentation, warranty, and strict liability.²² Types of defect include manufacturing defects, design defects, and warning defects. A product-liability lawsuit will involve one or more theories of manufacturer liability attached to a specific allegation of a type of defect. In practice, the legal tests for the theories of liability often overlap and, depending on the jurisdiction, may be identical. In the next sections, we discuss these theories of liability, the types of defect, and the way in which each may apply to the categories of autonomous vehicle technologies.

4.2.1 Theories of Liability

Negligence. Negligence is the most common theory of liability and is the legal standard most often used in tort law. As explained earlier, the central idea of liability for negligence is that a party should be held liable for harms it caused by its *unreasonably* failure to prevent the risk. We explained earlier Judge Hand’s economic definition of negligence and “reasonableness.” While equating negligence with cost-benefit analysis has been criticized by many theorists as reductive and eliminating the subtleties of negligence (see, e.g., Vandall, 1986), some form of cost-benefit analysis remains influential in product-liability cases. Recently, courts and the restatement reporters have been reintroducing the core concept of negligence—reasonableness (and, in some cases, cost-benefit analysis)—into other theories of products liability.

While it is difficult to generalize, automobile (and subsystem) manufacturers may fare well under a negligence standard that uses a cost-benefit analysis that includes crashes avoided from the use of autonomous vehicle technologies. Automakers can argue that the overall benefits from the use of a particular technology outweigh the risks. The number of crashes avoided by the use of these technologies is probably large.

²² We use *theory* here to mean a legal theory that allows a jury to award damages by connecting a particular set of facts with legal consequences.

In contrast, plaintiffs will likely seek to exclude any global cost-benefit analysis that considers the benefits of avoided crashes and try to focus the reasonableness analysis on the specific facts around the crash (e.g., was the automobile manufacturer reasonable in failing to include a warning about sleeping while the ACC and lane-keeping functions were engaged? What were the costs and benefits of that particular decision?). The plaintiff would likely argue that evidence about the numerous crashes prevented by this technology was irrelevant. By focusing on the specific circumstances of the particular crash, plaintiffs will attempt to focus the reasonableness and cost-benefit analysis away from the long-term safety benefits of these technologies.

Unfortunately, the socially optimal liability rule is unclear. Permitting the defendant to include the long-run benefits in the cost-benefit analysis may encourage the adoption of technology that can indeed save many lives. On the other hand, it may shield the manufacturer from liability for shorter-run decisions that were inefficiently dangerous. Suppose, for example, that a crash-prevention system operates successfully 70 percent of the time but that, with additional time and work, it could have been designed to operate successfully 90 percent of the time. Then suppose that a victim is injured in a crash that would have been prevented had the system worked 90 percent of the time. Assume that the adoption of the 70-percent technology is socially desirable but the adoption of the 90-percent technology would be even more socially desirable. How should the cost-benefit analysis be conducted? Is the manufacturer permitted to cite the 70 percent of crashes that were prevented in arguing for the benefits of the technology? Or should the cost-benefit analysis focus on the manufacturer's failure to design the product to function at 90-percent effectiveness? If the latter, the manufacturer might not employ the technology, thereby leading to many preventable crashes. In calculating the marginal cost of the 90-percent technology, should the manufacturer be able to count the lives lost in the delay in implementation as compared to possible release of the 70-percent technology? A host of important definitional issues as to what can be counted as cost and benefit must first be resolved. These issues make the integration of cost-benefit analysis into tort law complex.

Tortious Misrepresentation. Tortious misrepresentation arises when a party—intentionally or unintentionally—misleads the plaintiff. There are three types: fraudulent, negligent, and strict liability. *Fraudulent misrepresentation* requires that the plaintiff show *scienter*—actual knowledge on the part of the defendant that the representation is false. *Negligent misrepresentation* requires the plaintiff to show that the defendant negligently asserted some statement as true (see, e.g., *Boos v. Claude*, 69 S.D. 254, 1943: used-car retailer advertised car as being in perfect working order despite defective brakes). In many jurisdictions, this theory of liability has largely been superseded by the advent of strict liability for misrepresentation.²³ *Strict liability for misrepresentation* does

²³ Section 402B of the Restatement (Second) of Torts, “Misrepresentation by Seller of Chattels to Consumer,” states,

One engaged in the business of selling chattels who, by advertising, labels, or otherwise, makes to the public a misrepresentation of a material fact concerning the character or quality of a chattel sold by him is subject to liability for physical harm to a consumer of the chattel caused by justifiable reliance upon the misrepresentation even though (a) it is not made fraudulently or negligently and (b) the consumer has not bought the chattel from or entered into any contractual relation with the seller.

not require the plaintiff to prove either fraud or negligence. A false statement of material fact made by the manufacturer that was justifiably relied on by the consumer can give rise to liability under this theory.²⁴ However, a manufacturer will not be found liable for mere “puffery”—vague positive statements made in advertising about the product. The line between a material misstatement and mere puffery is not always clear (see, e.g., *Berkebile v. Brantly Helicopter Corp.*, 462 Pa. 83, 1975: advertising brochures for helicopter manufacturer did not create liability where brochures stated that helicopter was “safe, dependable helicopter” and was “easy to fly” for beginners, because these were “puffs.”).

Tortious misrepresentation may play a role in litigation involving crashes that result from autonomous vehicle technologies. If advertising overpromises the benefits of these technologies, consumers may misuse them. Consider the following hypothetical scenario. Suppose that an automaker touts the “autopilot-like” features of its ACC and lane-keeping function. In fact, the technologies are intended to be used by an alert driver supervising their operation. After activating the ACC and lane-keeping function, a consumer assumes that the car is in control and falls asleep. Due to road resurfacing, the lane-keeping function fails, and the automobile leaves the roadway and crashes into a tree. The consumer then sues the automaker for tortious misrepresentation based on the advertising that suggested that the car was able to control itself.

To minimize crashes like this one and to protect themselves from such liability, automakers must be cautious in promoting autonomous vehicle technologies. This is probably more of a danger as this technology is initially employed and developed. If a car is, in fact, fully autonomous, this concern disappears because, presumably, the driver really can rely on the vehicle. But as automakers market technologies that substantially aid a driver but still require important action on the part of the driver, communicating what the technology can and cannot do is very important to minimize crashes caused by drivers misunderstanding the capacities of a technology. Tortious misrepresentation may be a theory used to prevent advertising that leads to these dangerous misunderstandings.

Warranty. Warranty is a third theory of products liability relevant to autonomous vehicle technologies. Warranty claims may be divided into express warranties, the implied warranty of merchantability, and implied warranty of merchantability for a particular purpose.

When a seller *expressly warrants* some good and the good does not conform to general rules of merchantability, the buyer may recover. If a consumer buys a toaster, and the toaster shoots flames, the consumer can recover against the manufacturer. These claims are governed by the Uniform Commercial Code, adopted by

The Restatement (Third) of Products Liability (§9, comment b) adopts the Restatement (Second) formulation of misrepresentation: “The rules governing liability for innocent product misrepresentation are stated in the Restatement, Second, of Torts § 402B.”

²⁴ See, e.g., *Hauter v. Zogarts*, 14 Cal. 3d 104, 1975 (manufacturer is strictly liable for injuries that result from golf simulator where instruction manual states “Completely Safe Ball Will Not Hit Player”); compare *General Motors v. Howard*, 244 So. 2d 726, 728, Miss., 1971 (car manufacturer not strictly liable for injuries after steering wheel advertised as telescopic in a crash did not fully telescope in crash). There have been relatively few reported cases that cite this section of the Restatement (Owen, Montgomery, and Davis, 2007, p. 90).

most states.²⁵ Victims of automobile-related crashes have recovered under these theories (see, e.g., *McCarty v. E. J. Korvette*, 28 Md. App. 421, 1975: tire guaranteed against blowouts). In *Caboni v. General Motors Corp.* (398 F.3d 357, 2005), for example, an air bag failed to deploy after a crash. The court explained that the relevant legal question was whether product performance “matched that described by the language of the warranty provided with the vehicle, rather than whether the airbag performed as it was designed to perform.” The scope of the relevant warranty can be conveyed by text or by illustrations (see, e.g., *Sylvestri v. Warner & Swasey Co.*, 398 F.2d 598, 1968: illustrations showing backhoe used in particular way created express warranty: “essential idea conveyed by the advertising representations which is relevant”). Originally, plaintiffs had to prove that they detrimentally relied on the specific warranty. More recently, however, the courts have moved away from requiring reliance (*Lutz Farms v. Asgrow Seed Co.*, 948 F.2d 645, 1991, citing cases). Some courts have noted the similarity between a theory of liability based on warranty and §402B strict liability (e.g., *Klages v. General Ordnance Equipment Corp.*, 240 Pa. Super. 356, 1976).

The *implied warranty of merchantability* suggests that the good sold is generally free from defects and reasonably fit for the ordinary uses of the good. This is governed by §2-314 of the Uniform Commercial Code.²⁶ While a good does not have to be suitable for all possible uses, it has to be safe for the anticipated uses (see, e.g., *Maybank v. S. S. Kresge*, 46 N.C. App. 687, 1980: photographic flashbulb that explodes, injuring user’s eye, is not merchantable). It is closely related to strict tort liability, and most courts equate *unmerchantable* with defectiveness under strict-liability standards.

²⁵ Section 2-313 of the Uniform Commercial Code, “Express Warranties by Affirmation, Promise, Description, Sample,” states,

(1) Express warranties by the seller are created as follows: (a) Any affirmation of fact or promise made by the seller to the buyer which relates to the goods and becomes part of the basis of the bargain creates an express warranty that the goods shall conform to the affirmation or promise. (b) Any description of the goods which is made part of the basis of the bargain creates an express warranty that the goods shall conform to the description. (c) Any sample or model which is made part of the basis of the bargain creates an express warranty that the whole of the goods shall conform to the sample or model. (2) It is not necessary to the creation of an express warranty that the seller use formal words such as “warrant” or “guarantee” or that he have a specific intention to make a warranty, but an affirmation merely of the value of the goods or a statement purporting to be merely the seller’s opinion or commendation of the goods does not create a warranty.

²⁶ Section 2-314, “Implied Warranty: Merchantability; Usage of Trade,” states,

(1) Unless excluded or modified (Section 2-316), a warranty that the goods shall be merchantable is implied in a contract for their sale if the seller is a merchant with respect to goods of that kind. Under this section the serving for value of food or drink to be consumed either on the premises or elsewhere is a sale. (2) Goods to be merchantable must be at least such as: (a) pass without objection in the trade under the contract description; (b) in the case of fungible goods, are of fair average quality within the description; (c) are fit for the ordinary purposes for which goods of that description are used; (d) run, within the variations permitted by the agreement, of even kind, quality and quantity within each unit and among all units involved; (e) are adequately contained, packaged, and labeled as the agreement may require; and (f) conform to the promise or affirmations of fact made on the container or label if any. (2) Unless excluded or modified (Section 2-316) other implied warranties may arise from course of dealing or usage of trade.

The last warranty theory of liability is *implied warranty for a particular purpose*, governed by §2-315 of the Uniform Commercial Code.²⁷ This provision is applicable when the seller is specifically apprised of the buyer's intended use of the good and the buyer relies on the seller's statements. This theory is less likely to be applicable in the autonomous vehicle technology context for suits by consumers against manufacturers. It is sometimes used, however, by manufacturers against part suppliers and might arise in that context (e.g., *Gellenbeck v. Sears, Roebuck & Co.*, 59 Mich. App. 339, 1975: supplier of chains for use in swing sets was liable to assembler for sale of chains that did not resist twisting forces).

In general, sellers can disclaim (disavow) or limit warranties pursuant to contract law. Some states have limited merchants' ability to disclaim warranties.

The warranty theory of liability is unlikely to be particularly important to the development of autonomous vehicles for two reasons. First, because warranties (except for the implied warranty of merchantability) can generally be disclaimed, manufacturers are likely to substantially limit warranties. Second, the implied warranty of merchantability has merged into strict liability in most jurisdictions, and most of the legal analysis is focused on the strict-liability theory, which we discuss in the next section.

Strict Products liability. Strict products liability is a fourth theory of liability available to victims in lieu of having to prove negligence, misrepresentation, or violation of a warranty on the part of the defendant. Strict liability is conventionally contrasted with negligence because, in theory, it does not require any showing of negligence, unreasonableness, or any kind of fault on the part of the defendant. In its most extreme interpretation, strict products liability means that manufacturers insure users against all harms that come from their product, regardless of fault. Proponents of this loss-spreading rationale argued that strict liability can and should serve this compensation function and that manufacturers could easily pass on the additional costs of tort judgments to consumers by raising the prices of their products (see Priest and Owen, 1985). Manufacturers would also have the appropriate incentives to reduce the dangerousness of their products. While this expansive version of strict liability has not been adopted, the rationale of broad liability in order to spread costs underlies strict tort liability as it actually functions today.²⁸

In most states, strict tort liability is governed by the Restatement (Second) of Torts §402A (ALI, 1977).²⁹ Under §402A, the seller of a product is liable for harm caused by such product when it is sold in a "defective

²⁷ Section 2-315, "Implied Warranty: Fitness for Particular Purpose," states, Where the seller at the time of contracting has reason to know any particular purpose for which the goods are required and that the buyer is relying on the seller's skill or judgment to select or furnish suitable goods, there is unless excluded or modified under the next section an implied warranty that the goods shall be fit for such purpose.

²⁸ Every state except Delaware, Massachusetts, Michigan, North Carolina, and Virginia has adopted strict liability in tort of some form. The states that have rejected strict liability in tort achieve similar ends through interpretation of warranty law (Owen, 2008, §5.3).

²⁹Section 402A, "Special Liability of Seller of Product for Physical Harm to User or Consumer," states, One who sells any product in a defective condition unreasonably dangerous to the user or consumer or to his property is subject to liability for physical harm thereby caused to the ultimate user or

condition unreasonably dangerous to the user.” A product is deemed defective if it “left the supplier’s control lacking any element necessary to make it safe for its intended use or possessing any feature that renders it unsafe for the intended use” (§402A). Under §402A, the imposition of strict liability for a product defect is not affected by the fact that the manufacturer or other supplier has exercised all possible care. However, litigation about whether a product is *unreasonably* dangerous often introduces an analysis of the reasonableness of the manufacturers’ actions—an analysis that usually resembles the analysis of reasonableness that occurs in negligence cases and often includes one that can include the same cost-benefit analysis issues that were discussed earlier.

Some states have adopted §2 of Restatement (Third) of Torts. Published in 1998, approximately 30 years after §402A first appeared, it incorporates some of the relevant jurisprudence that has developed as courts have interpreted §402A. It retains the traditional strict-liability theory of recovery for claims of manufacturing defect but, with respect to claims of design defect and inadequate warnings, incorporates an explicit balancing exercise that is more akin to a negligence analysis.³⁰

Section 2 adopts a reasonableness-based, risk-utility balancing test as the standard for adjudging the defectiveness of product designs and warnings. Section 2 also makes clear that even a dangerous product is not defective unless there is proof of a reasonable alternative design (see ALI, 1998, §2, comment d). Comments to §2 also specify that the risk-benefit balancing done to judge product design must be done in light of knowledge attainable at the time the product was distributed. The comments also suggest that industry practice and the state of the art are relevant to the balancing analysis. With regard to warnings, §2 states that a seller is not liable for failing to warn of known risks and risk-avoidance measures that should be obvious.

consumer, or to his property, if (a) the seller is engaged in the business of selling such a product, and (b) it is expected to and does reach the user or consumer without substantial change in the condition in which it is sold. (2) The rule stated in Subsection (1) applies although (a) the seller has exercised all possible care in the preparation and sale of his product, and (b) the user or consumer has not bought the product from or entered into any contractual relation with the seller. Caveat: The Institute expresses no opinion as to whether the rules stated in this Section may not apply (1) to harm to persons other than users or consumers; (2) to the seller of a product expected to be processed or otherwise substantially changed before it reaches the user or consumer; or (3) to the seller of a component part of a product to be assembled.

³⁰ Section 2 of Restatement (Third) of Products Liability states,

A product is defective when, at the time of sale or distribution, it contains a manufacturing defect, is defective in design, or is defective because of inadequate instructions or warnings. A product: (1) contains a manufacturing defect when the product departs from its intended design even though all possible care was exercised in the preparation and marketing of the product; (2) is defective in design when the foreseeable risks of harm posed by the product could have been reduced or avoided by the adoption of a reasonable alternative design by the seller or other distributor, or a predecessor in the commercial chain of distribution, and the omission of the alternative design renders the product not reasonably safe; (3) is defective because of inadequate instructions or warnings when the foreseeable risks of harm posed by the product could have been reduced or avoided by the provision of reasonable instructions or warnings by the seller or other distributor, or a predecessor in the commercial chain of distribution, and the omission of the instructions or warnings renders the product not reasonably safe.

Strict liability under §402A is probably the theory most often used by plaintiffs in suits involving the design of automobiles. As such, it will play a central role in litigation over the responsibility for crashes associated with autonomous vehicle technologies. In the wake of a crash involving an automobile with autonomous vehicle technologies, victims may argue that the car's technology was defective in some way. How these principles are applied will depend, however, on the type of product defect alleged.

4.2.2 Types of Defectiveness

Originally, product-liability case law and doctrine did not distinguish among kinds of defect. Over time, however, three categories of defect emerged: manufacturing defect, design defect, and failure to warn.

Manufacturing Defects. A product is said to have a manufacturing defect, according to §2(a) of the Restatement (Third) of Products Liability, if it “departs from its intended design even though all possible care was exercised in the preparation and marketing of the product.” Manufacturing defects can be divided into two types. First, the manufacturer can construct the product using flawed raw materials (e.g., unduly brittle steel used in a wheel) (see, e.g., *Magnuson v. Kelsey-Hayes*, 844 S.W.2d 448, 1992). Second, the manufacturer could assemble the raw materials in an erroneous way—for example, by accidentally severing an important electrical cable during the manufacturing process. In either case, the product does not meet the manufacturer's own design specification.³¹

If a plaintiff can prove a manufacturing defect by showing that a particular product does not meet the manufacturer's own specifications, the manufacturer has very few defenses and is usually found liable. But as “lean” production techniques and quality process improvement continues to spread within the automobile industry, the number of conventional manufacturing defects in automobiles is likely to continue to decrease (Dassbach, 1994).

Unless a particular autonomous vehicle technology relies on a particular part that is prone to defectiveness (e.g., a sensor with a high rate of defect), we do not anticipate significant litigation around manufacturing defects. In cases in which manufacturing defects do occur and lead to crashes, of course, plaintiffs will generally recover. Instead, more litigation is likely to arise with respect to design defects.

Design Defects. An allegation of a design defect submits that the design of the product itself is defective. Courts have used two principal tests for defectiveness of design: consumer expectations and cost-benefit. The consumer-expectation test was explained by one court as follows:

A product is defective in design or formulation when it is more dangerous than an ordinary consumer would expect when used in an intended or reasonably foreseeable manner. Moreover, the question of what an ordinary consumer expects in terms of the risks posed by the product is generally one for the trier of fact. (*Donegal Mutual Insurance v. White Consolidated Industries*, 166 Ohio App. 3d 569, 2006)

³¹ In cases in which the plaintiff cannot allege any particular deviation from the manufacturer's specifications, the plaintiff can still ask the jury to infer that an unspecified manufacturing error was responsible for the accident. For example, in *Ducko v. Chrysler Motors Corp.* (433 Pa. Super. 47, 1994), the court found that a jury could infer that the car was defective at the time of sale from the fact that it crashed without other explanation, even absent any specific evidence of defect.

Comment i to §402A of the Restatement (Second) of Torts defines *unreasonably dangerous* as, in part, an issue of consumer expectations:

i. Unreasonably Dangerous. The rule stated in this Section applies only where the defective condition of the product makes it unreasonably dangerous to the user or consumer. Many products cannot possibly be made entirely safe for all consumption, and any food or drug necessarily involves some risk of harm, if only from over-consumption. Ordinary sugar is a deadly poison to diabetics, and castor oil found use under Mussolini as an instrument of torture. That is not what is meant by “unreasonably dangerous” in this section. The article sold must be dangerous to an extent beyond that which would be contemplated by the ordinary consumer who purchases it, with the ordinary knowledge common to the community as to its characteristics.

While the consumer-expectation test is still used by some jurisdictions, many have abandoned it as unworkable.

The consumer-expectation test might result in substantial liability for the manufacturers of autonomous vehicle technologies simply because consumers may have unrealistic expectations about the capabilities of these technologies (compare with *Hisrich v. Volvo Cars of North America*, 226 F.3d 445, 2000: in product-liability suit following air-bag deployment leading to fatality, an instruction was warranted on the consumer-expectation test under Ohio law). Technologies that are engineered to assist the driver may be overly relied on to replace the need for independent vigilance on the part of the vehicle operator. A definition of *design defect* that relies primarily on consumer expectations may result in finding many design defects and lead to substantial manufacturer liability. As noted earlier (in discussing tortious misrepresentation), managing consumer expectations to prevent reliance that exceeds the capacities of these technologies will be important to minimize the number of crashes and reduce liability.

The cost-benefit (sometimes also called *risk-utility*) test is used by many courts to determine whether a design is defective. It attempts to weigh the benefits, or utility, provided by the particular design against the costs, or risks, associated with it. In this respect, it is similar to the Learned Hand test for negligence explained earlier.

Many courts have adopted the following factors in conducting the cost-benefit analysis (Wade, 1973):

- the usefulness and desirability of the product: its utility to the user and to the public as a whole
- the safety aspects of the product: the likelihood that it will cause injury and the probable seriousness of the injury
- the availability of a substitute product that would meet the same need and not be as unsafe
- the manufacturer’s ability to eliminate the unsafe character of the product without impairing its usefulness or making it too expensive to maintain its utility
- the user’s ability to avoid danger by the exercise of care in the use of the product
- the user’s anticipated awareness of the dangers inherent in the product and their avoidability because of general public knowledge of the obvious condition of the product or because of the existence of suitable warnings or instructions

- the feasibility of spreading the loss by the manufacturer setting the price of the product or carrying liability insurance.

The precise factors that courts use in conducting a cost-benefit analysis to determine whether a design is defective vary by jurisdiction.

Some jurisdictions combine the consumer-expectation and risk-utility tests and allow a plaintiff to prove design defect by proving either theory (see, e.g., *Barker v. Lull Engineering Co.*, 20 Cal. 3d 413, 1978). Others have somewhat confusingly defined consumer expectations in part by a cost-benefit analysis (*Potter v. Chicago Pneumatic Tool Co.*, 241 Conn. 199, 1997). Consistent with §2(b) of the Restatement (Third) of Products Liability, many courts require a plaintiff to show that an alternative design was feasible that would have presented the harm.

Current liability law on design defects may hinder the efficient adoption of autonomous vehicle technologies. Suppose that a particular type of “autobrake” crash-avoidance technology works to prevent crashes 80 percent of the time. The other 20 percent of the time, however, the technology does not work and the crash occurs as it would have in the absence of the technology. Victims in those crashes may sue the manufacturer and argue that the product was defective because it failed to operate properly in their crashes. Under existing liability doctrine, they have a colorable argument: The product did not work as designed (manufacturing defect), as advertised (tortious misrepresentation), and as warranted (breach of the implied warrant of merchantability). A manufacturer facing a decision as to whether to employ such a technology in its vehicles might very well decide not to, purely on the basis of expected liability costs.

Yet, the social benefits of this technology are vast (see Parchomovsky and Stein, 2008, arguing that current tort law inefficiently deters innovation and suggesting reforms). An 80-percent decline (or even a 10-percent decline) in even a subcategory of crashes could save many lives and billions of dollars. The existing liability regime does a poor job of aligning private incentives with the public good in this kind of situation.

One approach to this problem is to integrate a cost-benefit analysis into the standard for liability as discussed earlier; this integration has the potential to reduce manufacturer liability because it allows the consideration of the benefits in reduced crash costs that are associated with this technology. If the cost-benefit analysis is permitted to include these benefits, tort liability for crashes that result from autonomous vehicle technologies is unlikely because it seems highly likely that the adoption of these technologies is far more likely to reduce human error and traffic crashes than cause them. In the long run, this may be the socially optimal solution.

But while this may be appropriate calculation of the long-run socially optimal solution, it may also undermine incentives for safer product design in the short run. Suppose that an auto manufacturer has a choice between two autonomous vehicle technologies, one of which is much safer but only slightly more expensive. If the courts adopt a cost-benefit analysis that includes the benefits of the crashes eliminated by an autonomous vehicle technology, it may be that the manufacturer will not be found liable regardless of whether it chooses the safer or more dangerous technology. By focusing on the long-run costs and benefits to society of the adoption of autonomous vehicle technologies, the courts may undermine shorter-run opportunities for efficient safety. In this

way, conducting the liability cost-benefit analysis by including more costs and benefits may undermine other incentives for safety in the shorter run.³²

To maximize the social benefits of this technology, policymakers need to structure the liability regime to encourage the development of this technology without undermining marginal incentives for safety. Further research is necessary to determine which costs and benefits should be included in the cost-benefit analysis.

We also anticipate litigation around the optimal way to monitor and integrate the driver for those transitional technologies that are designed to function with a supervisory driver. This issue poses particular difficulties because alertly supervising the driving function without actively participating may be very difficult for humans, who are prone to lose attention when not directly engaged. Finding an appropriate way to allow these technologies to minimize human error without provoking dangerous overreliance on them may prove difficult and prompt post-crash litigation.³³ It will probably be in automakers' interest to continue to focus attention on the need for a responsible driver to monitor the autonomous vehicle technologies, even after the technologies mature sufficiently to allow truly autonomous operation. To the extent possible, automakers will want to preserve the social norm that crashes are primarily the moral and legal responsibility of the driver, both to minimize their own liability and to ensure safety.

Finally, it is also possible that auto manufacturers will be sued for *failing* to incorporate autonomous vehicle technologies in their vehicles. While absence of available safety technology is a common basis for design-defect lawsuits (e.g., *Camacho v. Honda Motor Co.*, 741 P.2d 1240, 1987, overturning summary dismissal of suit alleging that Honda could easily have added crash bars to its motorcycles, which would have prevented the plaintiff's leg injuries), this theory has met with little success in the automotive field because manufacturers have successfully argued that state tort remedies were preempted by federal regulation (*Geier v. American Honda Motor Co.*, 529 U.S. 861, 2000, finding that the plaintiff's claim that the manufacturer was negligent for failing to include air bags was implicitly preempted by the National Traffic and Motor Vehicle Safety Act). We discuss preemption and the relationship between regulation and tort in Section 4.3.

Warning Defects. Products can also be found defective for their failure to include appropriate warnings. If there is a hidden danger in the product, the manufacturer has an obligation to warn of the danger. If it fails to do so, the product can be found defective as a result of its failure to warn. Section 2(c) Restatement (Third) of Products Liability defines a defect for failure to warn as follows:

A product . . . is defective because of inadequate instructions or warnings when the foreseeable risks of harm posed by the product could have been reduced or avoided by the provision of reasonable

³² See Anderson (2007) for a fuller discussion of the way in which the tort system attempts to balance optimization in the short and long runs.

³³ Use of multiple driver-assistance systems at the same time also increases this risk. So, for example, relying on lane-keeping function and ACC together may pose risks of overreliance that would not be raised if only one of these technologies was used at a time.

instructions or warnings . . . and the omission of the instructions or warnings renders the product not reasonably safe.

There is, however, no clear consensus on an appropriate determination of the conditions in which warnings are required. Nor is there a clear test as to when existing warnings are adequate. Courts and commentators have expressed the concern that, after a crash, the cost of an additional warning addressing the circumstances of the accident will seem infinitesimal to a jury compared with the realized costs of the accident and the injuries suffered by the plaintiff. As one court explained,

Failure to warn cases have the curious property that, when the episode is examined in hindsight, it appears as though addition of warnings keyed to a particular accident would be virtually cost free. . . . The primary cost is, in fact, the increase in time and effort required for the user to grasp the message. The inclusion of each extra item dilutes the punch of every other item. (*Cotton v. Buckeye Gas Products Co.*, 840 F.2d 937–939, 1988)

According to this view, courts should be concerned about juries being too quick to find liability for a failure to warn.

There is likely to be substantial litigation over the extent to which warnings are appropriate with autonomous vehicles. Should a manufacturer warn a consumer that she should not use a laptop computer while using ACC and the lane-keeping function? The plaintiff in such a case could argue that the cost of such a warning would be trivial and might save numerous lives. The defendant could argue that it is impossible to anticipate every situation that could require a warning and that the instruction manual that accompanied the car clearly set out the limits of the automobile’s autonomous vehicle systems.³⁴

4.3 EFFECT OF REGULATION AND PREEMPTION

Relevant regulations, engineering standards, and industry custom are usually admissible but not dispositive as to whether a defendant either met or failed to meet the appropriate standard of care (Owen, Montgomery, and Davis, 2007, p. 290).³⁵ So, in most state tort cases, the plaintiff or defendant can introduce the existence of a state or federal regulation, standard, or evidence of industry custom in arguing his or her case. The jury is free to consider this evidence in determining whether the defendant satisfied the appropriate standard of care. Contrary to this general rule, the Restatement (Third) of Products Liability §4 (1998) indicates that, in product-liability cases, a manufacturer’s *failure* to adhere to a relevant rule should give rise to liability in a design-defect or failure-to-warn case but that the manufacturer’s adherence to the relevant rule does not preclude liability.³⁶

³⁴ Inquiry into the proper role of warnings also raises the issue of preemption, discussed in the next section. Pharmaceutical manufacturers have been successful in convincing the Food and Drug Administration (FDA) and the U.S. Supreme Court that the FDA’s warning requirements should preempt state tort-law remedies for failure to warn. They argue that federal preemption protects carefully crafted regulatory compromises made by expert agencies and prevents the chaos of 51 separate tort regimes that might find that different and contradictory sets of warnings are required to avoid liability. We discuss preemption in more detail in the next section, while noting here its particular salience to warnings.

³⁵ As explained in the next section, Society of Automobile Engineers (SAE) standards governing autonomous vehicle technologies are beginning to emerge, but there are few federal regulations at this point.

³⁶ Section 4, “Noncompliance and Compliance with Product Safety Statutes or Regulations, states, In connection with liability for defective design or inadequate instructions or warnings: (a) a product’s noncompliance with an applicable product safety statute or administrative regulation

In the case of federal preemption, however, compliance with federal regulations can completely absolve a defendant of liability in state courts. This doctrine is based on the Supremacy Clause of the United States Constitution.³⁷ Preemption occurs when a court finds that Congress intended to preempt state laws that are inconsistent with the regulations enacted by the designated agency. This can occur when a federal statute either explicitly preempts inconsistent state law (*express preemption*) or implicitly does so by the creation of a regulation that is inconsistent with state tort law. So, for example, product manufacturers argue that federal safety regulations preempt inconsistent state tort law and preclude lawsuits by injured plaintiffs.

Preemption is a controversial subject. Proponents of the doctrine argue that an expert federal agency is better suited to weighing the appropriate advantages and disadvantages of a product design or warning than a lay jury and that it is unfair to subject product manufacturers to potentially 51 different and sometimes conflicting sets of requirements, depending on the particular holdings of juries in 51 jurisdictions.

Opponents of preemption argue that extinguishing state tort law rights is a violation of states' rights. They quote Justice Louis D. Brandeis, who famously sought to leave open the possibility that "a single courageous State may, if its citizens choose, serve as a laboratory; and try novel social and economic experiments without risk to the rest of the country" (*New State Ice Co. v. Liebman*, 285 U.S. 311, 1932, Justice Brandeis, dissenting). Opponents of federal preemption argue that not only does federal preemption stifle this "laboratory" and regulatory innovation but it permits powerful industries to snuff out traditional rights of action and hobble the states' concurrent regulatory aegis.

Another, more fundamental argument against preemption of state tort law remedies stems from the function of the tort law system itself. If state tort law exists only to serve as an efficient means to regulate risk, preemption may make sense if the federal government can do a better job at doing so. In recent years, Jules Coleman and several other tort theorists have argued that an important function of tort law is to provide corrective justice—to provide a procedure to right wrongs (Coleman, 1992; Zipursky, 2003). Federal preemption eliminates the state remedy without replacing it with any equivalent procedure. Accordingly, if one believes that an important function of tort law is corrective justice or civil recourse, one might be skeptical of federal preemption of state tort law remedies.³⁸

renders the product defective with respect to the risks sought to be reduced by the statute or regulation; and (b) a product's compliance with an applicable product safety statute or administrative regulation is properly considered in determining whether the product is defective with respect to the risks sought to be reduced by the statute or regulation, but such compliance does not preclude as a matter of law a finding of product defect.

³⁷ The Supremacy Clause states,

This Constitution, and the Laws of the United States which shall be made in Pursuance thereof; and all Treaties made, or which shall be made, under the authority of the United States, shall be the supreme Law of the land; and the Judges in every State shall be bound thereby, any Thing in the Constitution or Laws of any State to the Contrary notwithstanding. (U.S. Constitution, Art. VI, cl. 2)

³⁸ A counterargument in favor of pre-emption could be made as follows: Pre-emption does not destroy the state process for righting a wrong. Instead, it simply moves the definition of the wrong to a body (the federal regulatory agency) that is better suited to making the determination of whether a wrong that needs righting has

Preemption has arisen in the automotive context in litigation over a manufacturer's failure to install air bags. In *Geier v. American Honda Motor Co.* (2000), the U.S. Supreme Court found that state tort litigation over a manufacturer's failure to install air bags was preempted by the National Traffic and Motor Vehicle Safety Act (Pub. L. No. 89-563). More specifically, the Court found that the Federal Motor Vehicle Safety Standard (FMVSS) 208, promulgated by the US DOT, required manufacturers to equip some but not all of their 1987 vehicle-year vehicles with passive restraints. Because the plaintiffs' theory that the defendants were negligent under state tort law for failing to include air bags was inconsistent with the objectives of this regulation (FMVSS 208), the Court held that the state lawsuits were preempted.

Presently, there has been very little regulation promulgated by the US DOT with respect to autonomous vehicle technologies. Should the US DOT promulgate such regulation, it is likely that state tort law claims that were found to be inconsistent with the objective of the regulation would be held to be preempted under the analysis used in *Geier*. Substantial litigation might be expected as to whether particular state-law claims are, in fact, inconsistent with the objectives of the regulation. Resolution of those claims will depend on the specific state tort law claims, the specific regulation, and the court's analysis of whether they are "inconsistent."

4.4 CONCLUSIONS AND RECURRING THEMES

We have examined how the U.S. tort system applies to autonomous vehicle technologies and whether it creates potential liability problems for either drivers or manufacturers that would prevent the efficient adoption of these technologies. The existing liability regime does not seem to present unusual liability concerns for owners or drivers of vehicles equipped with autonomous vehicle technologies. On the contrary, the decrease in the number of crashes and the associated lower insurance costs that these technologies are expected to bring about will encourage the adoption of this technology by drivers and automobile-insurance companies.

In contrast, manufacturer liability is expected to increase, and this may lead to inefficient delays in the adoption of these technologies. Manufacturers may be held responsible under several theories of liability for systems that aid the driver but leave him or her in total or partial control, under the claim that drivers were misinformed about the true capabilities of the system. Warnings and consumer education will play a crucial role in managing manufacturer liability for these systems. Manufacturers are likely to understate system capabilities during advertising, educate owners when purchasing vehicles with these capabilities, and require drivers to acknowledge that they understand the limitations in some way before the technologies can be activated. Some manufacturers have taken further steps to ensure that drivers understand and maintain their responsibility for driving by monitoring driver behavior when these technologies are activated and warning the driver or deactivating the technology if the driver appears to be inattentive. While there may be litigation in this area, these claims are not expected to

occurred. On this view, federal preemption does not infringe on the ability of the state process to vindicate corrective justice when a wrong actually occurs.

significantly hinder the introduction of most of these technologies (as evidenced by those already on the market) because of the options available to the manufacturer and because, ultimately, the driver is behind the wheel.³⁹

However, manufacturers' well-founded liability concerns may slow the introduction of even socially beneficial technologies. This delay may be perfectly appropriate for technologies that are extremely complex, such as fully autonomous vehicles, for which it is enormously difficult to prove complete reliability, given the range of conditions in which the vehicle will need to operate. On the other hand, this may be problematic for some technologies that provide benefits some of the time and do no additional harm otherwise. One approach to this problem is to integrate a cost-benefit analysis into the standard for liability: It has the potential to reduce manufacturer liability because it allows the consideration of the benefits in reduced crash costs that are associated with this technology. But it is difficult to specify the appropriate sets of costs and benefits that should be considered.⁴⁰

Another possible approach is regulatory preemption—requiring manufacturers to incorporate the most-promising forms of this technology by regulatory fiat but simultaneously exempting the manufacturers from state court liability. Mandatory driver first-party health insurance might be an additional variation on this approach to minimize the risk of uncompensated victims. A full analysis of the advantages and disadvantages to such an approach is beyond this exploratory paper and requires further research.

Uncertainty itself over the magnitude of the liability risks may also deter and delay introduction of these technologies. This can create a catch-22 because the court system can resolve this uncertainty only when claims are actually brought and litigated, which, of course, requires that the technology be introduced. Nonetheless, we anticipate that, as this technology is gradually introduced into the marketplace, the legal standards will be clarified.⁴¹

³⁹ The shift from a focus on the driver as being primarily responsible for crashes to the vehicle manufacturer will be complete if and when driverless cars are introduced. In such a case, there is obviously no conventional “driver” to hold responsible.

⁴⁰ Another possible solution is for a regulatory agency to require the use of certain safety technologies but to simultaneously exempt, through preemption, manufacturers from liability associated with that technology. This may be appropriate for safety technologies whose overall benefits are very clear, but the disadvantages of preemption are discussed in the text in this section.

⁴¹ Our analysis necessarily raises a more general question: Why should we be concerned about liability issues raised by a new technology? The answer is the same as for why we care about tort law at all: that a tort regime must balance economic incentives, victim compensation, and corrective justice. Any new technology has the potential to change the sets of risks, benefits, and expectations that tort law must reconcile.

5. STANDARDS AND REGULATIONS AND THEIR APPLICATION TO AUTONOMOUS VEHICLE TECHNOLOGIES

In this section, we provide an introduction to motor-vehicle regulations and standards and describe the existing regulations and standards for autonomous vehicle technologies. We then provide a general discussion of how and under what circumstances standards and regulations may need to be developed in the future, drawing on the experiences of air-bag rulemaking in particular.

Government regulations and engineering standards are policy instruments used to address safety, health, environment, and other public concerns. Although the terms *standards* and *regulations* are often used interchangeably because the tools are often coupled and complementary, they have distinct meanings. *Regulations* are mandatory requirements developed by policymakers that are specified by law and are enforceable by the government. *Standards*, in contrast, are engineering criteria developed by the technology community that specify how a product should be designed or how it should perform. Yet, standards alone have no authority; an industry or group voluntarily adopts them for consistency, interoperability, and safety. In some scenarios and for some industries, demonstrating that products meet well-accepted industry standards may also provide some liability protection for manufacturers. The SAE, for example, has developed standards for the comfort, fit, and convenience of seat belts in trucks and buses (SAE, 2007); these particular standards are voluntarily met by manufacturers and are not enforced by government regulations. Standards become enforceable law, however, when they are included as part of a regulation. The FMVSSs, for example, specify performance standards for a wide range of safety components that must be met by law, including, for example, that vehicles must meet specific crash test–survivability requirements.

5.1 OVERVIEW OF REGULATIONS FOR AUTOMOBILES

From its beginnings in the early 20th century into the 1950s, the automobile industry was generally viewed as a valuable national resource and as the source of much of the country’s industrial success. However, in about the mid-1950s, the public started to see and become deeply concerned about the negative safety and environmental effects of driving and began to demand changes. Consumers were anxious to curb pollution, fuel consumption, and rates of injury and death caused by crashes, and government regulations were put in place both to control existing technologies and to create incentives for developing better technologies. The complex political and social forces at play (detailed in Lorang and Linden, 1977, and Heywood et al., 1977) resulted in the beginnings of standard-based automobile regulation.

Today, the government substantially regulates automobiles with the aim of increasing safety, reducing pollution, and reducing gas consumption. The US DOT maintains the FMVSSs, which prescribe a wide range of safety standards and test procedures, from crash-avoidance components, such as brakes and indicators, to crashworthiness features, such as seat belts and air bags, to post-crash factors, such as the integrity of the fuel

system. The U.S. Environmental Protection Agency (EPA) oversees fuel economy and emission tests and standards, which make up the other major segment of federal automobile standards and regulations.

5.2 AIR BAG REGULATION

Like many autonomous vehicle technologies, the automatic intervention of air bags in crashes shifts safety responsibilities (such as using active restraints) from the drivers and other vehicle occupants to the vehicle and its manufacturer. In doing so, it also reflects a shift in liability from the driver to the automobile manufacturer. Thus, experiences with air-bag regulation are particularly relevant to autonomous vehicle technologies and serve to illustrate many facets of regulation. Here, we provide a brief history of air bags as a case study of rulemaking for emerging technologies. Later, we discuss their implications for autonomous vehicle technology standards and regulation.

Air bags were initially introduced in the early 1970s in higher-end models, such as the Oldsmobile Toronado. At that time, air bags were marketed as alternatives to seat belts rather than as supplements. Jameson M. Wetmore (2004, p. 390) notes the perspective of policymakers and industry experts at the time:

They argued that a system of inflatable pillows could be automatically deployed inside a vehicle in the event of a collision that would hold occupants in place even if they were not wearing seat belts. They contended that such a system would replace both seatbelts and the need to rely on automobile occupants to engage a restraint device.

In this era, voluntary seat-belt usage was quite low. Using the logic that air bags would make seat belts unnecessary, in the 1970s, the National Highway Traffic Safety Administration (NHTSA) initiated efforts to pass regulations requiring air bags in all U.S. automobiles. Such regulations met with significant resistance from automobile manufacturers, which did not want either the responsibility or the liability for the losses resulting from crashes and did not believe that these safety features would sell. This tension produced “a standoff between airbag proponents and the automakers that resulted in contentious debates, several court cases, and very few airbags” (Wetmore, 2004, p. 391).

In 1984, the US DOT passed a ruling requiring vehicles manufactured after 1990 to be equipped with some type of passive restraint system (e.g., air bags or automatic seat belts) (Wetmore, 2004); in 1991, this regulation was amended to require air bags in particular in all automobiles by 1999 (Pub. L. No. 102-240). The mandatory performance standards in the FMVSS further required air bags to protect an unbelted adult male passenger in a head-on, 30 mph crash. Additionally, by 1990, the situation had changed dramatically, and air bags were being installed in millions of cars. Wetmore attributes this development to three factors: First, technology had advanced to enable air-bag deployment with high reliability; second, public attitude shifted, and safety features became important factors for consumers; and, third, air bags were no longer being promoted as replacements but as *supplements* to seat belts, which resulted in a sharing of responsibility between manufacturers and passengers and lessened manufacturers’ potential liability (Wetmore, 2004).

While air bags have certainly saved many lives, they have not lived up to original expectations: In 1977, NHTSA estimated that air bags would save on the order of 9,000 lives per year and based its regulations on these

expectations (Thompson, Segui-Gomez, and Graham, 2002). Today, by contrast, NHTSA calculates that air bags saved 8,369 lives in the 14 years between 1987 and 2001 (Glassbrenner, undated). Simultaneously, however, it has become evident that air bags pose a risk to many passengers, particularly smaller passengers, such as women of small stature, the elderly, and children. NHTSA (2008a) determined that 291 deaths were caused by air bags between 1990 and July 2008, primarily due to the extreme force that is necessary to meet the performance standard of protecting the unbelted adult male passenger. Houston and Richardson (2000) describe the strong reaction to these losses and a backlash against air bags, despite their benefits.

The unintended consequences of air bags have led to technology developments and changes to standards and regulations. Between 1997 and 2000, NHTSA developed a number of interim solutions designed to reduce the risks of air bags, including on-off switches and deployment with less force (Ho, 2006). Simultaneously, safer air bags, called *advanced air bags*, were developed that deploy with a force tailored to the occupant by taking into account the seat position, belt usage, occupant weight, and other factors. In 2000, NHTSA mandated that the introduction of these advanced air bags begin in 2003 and that, by 2006, every new passenger vehicle would include these safety measures (NHTSA, 2000).

What lessons does this experience offer for regulation of autonomous vehicle technologies? We suggest that modesty and flexibility are necessary. The early air-bag regulators envisioned air bags as being a substitute for seat belts because the rates of seat-belt usage were so low and appeared intractable. Few anticipated that seat-belt usage would rise as much over time as it has and that air bags would eventually be used primarily as a supplement rather than a substitute for seat belts. Similarly unexpected developments are likely to arise in the context of autonomous vehicle technologies.

5.3 CURRENT STANDARDS AND REGULATIONS FOR AUTONOMOUS VEHICLE TECHNOLOGIES

The need for both standards and regulations for some of these technologies has been recognized. In 2001, the National Transportation Safety Board (NTSB) issued a report analyzing ACC and CWSs and emphasizing the importance of both performance standards and regulations. The NTSB recommended that the US DOT complete rulemaking on performance standards for ACC and CWSs for both commercial and passenger vehicles and that it require the installation of CWSs in all commercial vehicles. Without standards for system operation and driver interaction, the NTSB felt that the use of a variety of systems would lead to driver confusion and incorrect interventions and responses to system behavior (NTSB, 2001).

To our knowledge, however, there are currently no federal regulations related specifically to autonomous vehicle technologies: None of these technologies is, to date, required in any type of vehicle, and there are no mandatory standards related to their specific design or performance. As suggested by the experiences of air-bag regulation, there are likely to be several closely related reasons for this. First, regulatory promulgation is fundamentally an iterative and slow process, given the cycles of proposals, requests for comments, reviews, and lobbying that precede rulemaking. Second, with autonomous vehicle technologies in particular, their newness and

rapid evolution create uncertainty in both effects of rulemaking and of the technology itself (GAO and U.S. Senate Committee on Commerce, Science, and Transportation, 2008). Moreover, with rapid technology changes, it can be challenging to prescribe rules that will remain relevant and appropriate through the development process (van Wees, 2004). Third, given the many stakeholders (manufacturers, government, nongovernmental organizations [NGOs], and private citizens), reaching a consensus is difficult. For example, NHTSA's New Car Assessment Program (NCAP) will, in 2011, include a rating system indicating whether advanced safety technologies, such as forward collision warning, are available in a particular car model (NHTSA, 2008b). However, this rating system does not evaluate or differentiate among technologies, in part because of significant differences and disagreement among manufacturers and consumer groups as to whether and how these technologies ought to be evaluated (NHTSA, 2008b). Fourth, industry is generally resistant to regulation, often citing price increases that the market may not necessarily bear, undesirable constraints on design and development, and superior alternatives to government regulation, such as industry-developed standards and rules.

Although regulatory promulgation has yet to occur, there are numerous national and international government and industry efforts to develop principles, guidelines, and standards for autonomous vehicle technologies. The Crash Avoidance Metrics Partnership (CAMP) brings together auto manufacturers on projects that "accelerate the implementation of crash avoidance countermeasures to improve traffic safety by defining and developing necessary pre-competitive enabling elements of future systems" (Shulman and Deering, 2005, p. 3). It includes, for example, the Forward Collision Warning Requirements Project, which addresses alert function and interface requirements through real and simulated tests with human drivers. Several organizations address intelligent transport systems (ITSs) more broadly. The International Harmonized Research Activities working group on ITSs (IHRA-ITS) was put together to lead research and encourage collaboration on ITS safety issues; one of its objectives is to conduct research that provides a strong grounding for internationally harmonized regulations (Burns, 2005; IHRA-ITS, 2008). The International Organization for Standardization (ISO) has set up an international working group (ISO/TC204/WG14) under its ITS technical committee to evaluate design guidelines and recommend standards for any technologies that aid in "avoiding crashes; increasing roadway efficiency; adding to driver convenience; reducing driver workload; improving the level of travellers' safety, security, and assistance . . . ; warn of impending danger; advise of corrective actions; partially or fully automate driving tasks; report travellers' distress; and request needed emergency services" (APEC, 2006). The SAE similarly has an ITS division that addresses these technologies.

Such organizational and research efforts have been fruitful. The US DOT has published a set of voluntary operational requirements for CWSs and ACC (Houser, Pierowicz, and McClellan, 2005), but it does not serve as a standard, specification, or regulation. The ISO and SAE have published several standards related to autonomous vehicle technologies. These include but are not limited to the following:

- SAE standard J2399, *Adaptive Cruise Control (ACC) Operating Characteristics and User Interface* (SAE, 2003b)

- SAE standard J2400, *Human Factors in Forward Collision Warning Systems: Operating Characteristics and User Interface Requirements* (SAE, 2003a)
- ISO standard 15622, *Transport Information and Control Systems: Adaptive Cruise Control Systems: Performance Requirements and Test Procedures* (ISO, 2007b)
- ISO standard 15623, *Transport Information and Control Systems: Forward Vehicle Collision Warning Systems: Performance Requirements and Test Procedures* (ISO, 2008a)
- ISO standard 17361, *Intelligent Transport Systems: Lane Departure Warning System: Performance Requirements and Test Procedures* (ISO, 2007a)
- ISO standard 17387, *Intelligent Transport Systems: Lane Change Decision Aid Systems (LCDAS): Performance Requirements and Test Procedures* (ISO, 2008b).

Other related standards are discussed by the IHRA-ITS (2008).

Upon examination, it is clear that these standards are just beginning to be articulated, no doubt in part because these technologies are themselves under development. First, the standards are not yet precisely defined. For example, the ISO standard for lane departure warning states, “An easily perceivable haptic and/or audible warning shall be provided” (ISO, 2007a). But, what does “easily perceivable” mean and for what population of drivers? Similarly, the SAE standard for ACC includes specifications for sensors, stating that “ACC systems shall be capable of responding to all licensable motorized road vehicles, including motorcycles, intended for use on public roads” (SAE, 2003b). Yet, this does not specify the environmental conditions under which this is to hold true. Additionally, although these standards include many specifications and some basic test procedures, essentially none has been written with the primary objective of defining conformance requirements (i.e., test methods and procedures). Such conformance requirements are necessary in order to determine whether a technology or system is actually in compliance with the specifications (APEC, 2006). Moreover, where test procedures are described, the environmental conditions are either ideal or unspecified.

5.4 FUTURE IMPLICATIONS FOR STANDARDS AND REGULATIONS FOR AUTONOMOUS VEHICLE TECHNOLOGIES

Let us now look forward and outline some of the issues that policymakers will have to address for standards and regulations for autonomous vehicle technologies. These observations are necessarily somewhat speculative, given the scope and intentions of this work as a first step into the role of liability and regulation.

Autonomous vehicle technologies, like air bags, will be used by a wide range of drivers and passengers. Recall that standards for air bags were set for only a limited section of the driver and passenger population—namely, average male adults. It became apparent only after widespread implementation that they put smaller passengers at risk of injury or death. Autonomous vehicle technologies, too, will affect different people differently. In the case of driver-warning systems, for example, users’ expectations of how and when the technology will work and their ability to understand the system’s directions and warnings will affect the effectiveness of the technology. Therefore, standards must be developed that take into account diverse populations. Simultaneously, drivers are also likely to

use autonomous vehicle technologies in vehicles developed by different manufacturers—the NTSB’s case of professional drivers operating a range of different vehicles is a good example of this (NTSB, 2001). As we have discussed, driver interaction and involvement is critical to many autonomous vehicle technologies (e.g., warning systems that operate specifically by influencing the driver, and other technologies, such as ACC, that must be activated by the driver and require the driver to intervene at critical moments). As the NTSB suggests, standardizing these technologies will be particularly important to achieving safety goals.

Regulations may also help coordinate expectations. Suppose that pedestrians become accustomed to cars automatically braking in their presence. Regulation of these functions will help minimize hazards that may arise if pedestrian expectations and cars’ capacities are not aligned.

Additionally, the significant difference between traditional automotive technologies and autonomous vehicle technologies is that autonomous vehicle technologies sense and make judgments about the vehicle’s external environment, which cannot be controlled and can vary tremendously in terms of other vehicular traffic on the road, pedestrians and other road users, static objects, the quality of road itself and road elements (e.g., lane markings and signs), and weather and lighting conditions. Therefore, the performance requirements of sensors and sensor-fusion systems that build the vehicle’s world model are extremely important. As discussed, a variety of sensors can be employed for each type of autonomous vehicle technology, many sensors are likely to be employed in concert, and each type of sensor has different operating specifications and may not operate effectively in some environments. Given this, it seems clear that performance standards for autonomous vehicle technologies must specify the environmental conditions under which the tests must occur and, ideally, will include testing under a wide range of environmental conditions.

For technologies at one end of our spectrum that leave the driver in at least some control of the vehicle at all times (e.g., driver-warning systems and ACC), conformance requirements that specify a smaller set of environmental conditions may be acceptable as the driver is ultimately still responsible for interpreting the environment and determining whether these technologies ought to be used. However, as we move toward fully autonomous vehicles and driverless cars, the standards and testing need to span the *entire* range of conditions in which the vehicle might be expected to operate. Anticipating and testing operation under all possible scenarios is extremely challenging and is likely to be a significant barrier to deploying fully autonomous vehicles absent additional operational experience with these technologies. Given these obstacles, it is also possible that future policies and technologies will try to control the environment of autonomous vehicles (for example, by segregating lanes strictly for autonomous vehicles or limiting their operation to certain areas or conditions).⁴² Finally, there are general guidelines that are applicable to regulating any advanced technology, particularly those that deal with safety. Mandating the inclusion of autonomous vehicle technologies may not meet with success or be appropriate until at least the following circumstances are met. First, the technology must be mature enough that manufacturers are

⁴² Existing dedicated busways may prove to be relatively controlled environments in which to pilot these efforts.

confident in their operation or are confident that they will not be held liable if they do not operate perfectly (e.g., because of modifications to the liability regime to encourage adoption). In the 1970s, when air-bag regulations were initially being developed, manufacturers were not confident in the sensing capabilities of air bag–deployment sensors and, partly for this reason, strongly resisted the mandate to include air bags. Despite the fact that even partially effective air bags could save many lives, they feared liability for the cases in which the air bags did not properly deploy. A similar policy standoff could occur between lawmakers and manufacturers if regulatory requirements for autonomous vehicle technologies appear to place an extraordinary liability burden on manufacturers. Second, the safety effects ought to be well understood. Certainly, this includes understanding the performance of different technologies in different conditions and with different users. Beyond this, the costs and benefits ought to have been accurately assessed. We now know that the benefits of air bags were significantly overestimated at the time of rulemaking and that the actual benefits, while substantial, were fewer, resulting in criticism of air bags overall as a safety measure. Similarly, many expect ADAS technology to dramatically improve safety and reduce the incidence and effects of crashes. While initial evidence supports the benefits of these technologies, accurate estimates of costs and benefits are critical for policymakers to develop appropriate rules and for manufacturers, insurance companies, consumers, and other stakeholders to make appropriate decisions.

6. SUMMARY, POLICY SUGGESTIONS, AND FUTURE WORK

Autonomous vehicle technologies have the potential to enormously benefit humankind. Yet, manufacturers of these technologies have repeatedly voiced substantial concern about tort liability for damages that may result from the use of this technology. Who will be responsible when the inevitable crash occurs, and to what extent? How should standards and regulations handle these systems? This research is an initial step toward creating policies to address autonomous vehicle technologies.

6.1 SUMMARY

In holding tortfeasors liable for the harms they cause, the U.S. tort system aims, in part, to punish wrongdoers, to compensate those who have been wronged, to efficiently encourage investments in safety, and to discourage the introduction of products and services that are unsafe. The transition from fully human-driven vehicles to human-driven vehicles equipped with autonomous vehicle technologies to fully autonomous vehicles holds the promise of improving safety but is likely to shift the focus of liability for automobile crashes from drivers to the vehicle manufacturers. How will the liability regime govern this transition?

Our work suggests that, while the existing liability regime does not present unusual liability concerns for owners and drivers, the liability of manufacturers is expected to increase and, in certain circumstances, be problematic. For technologies that share vehicle control (and, thus, responsibility) with the driver, a manufacturer may be held liable under the claim that a driver was misinformed about the true capabilities of the system. Warnings, consumer education, and driver monitoring will play a crucial role in managing manufacturer liability for these systems, and these claims are not expected to create unusual barriers to adoption.

On the other hand, the liability may significantly slow the introduction of technologies that increase manufacturer liability. This may be appropriate for technologies that are highly complex (e.g., fully autonomous vehicles) and for which it is extremely difficult to prove safety and reliability. It may be problematic, however, for those technologies that provide benefits some of the time and do no additional harm otherwise (e.g., precrash braking). One approach to this problem may be to further integrate a cost-benefit analysis into the standard for liability—though, as we discuss, further research is required to specify the scope of costs and benefits that go into such an analysis and to ensure that the approach balances long-term and short-term safety goals.

Government regulations are likely to play an important role in autonomous vehicle technologies by setting standards for how they perform and by requiring them to be included in future vehicles. As of today, however, no regulations exist for autonomous vehicle technologies. Nevertheless, there are numerous national and international government and industry efforts to develop principles, guidelines, and standards for these technologies. The ISO and

SAE in particular have published several standards, but these standards are only just beginning to address the requirements for autonomous vehicle technologies.

Looking forward, we find that there are unique features of autonomous vehicle technologies that future efforts will need to consider. First, standardization of technology performance and system interfaces will be particularly important for the many technologies that interact with and share control with the driver. Drivers are likely to use these technologies in different vehicles created by different manufacturers, and their safe use depends on the driver understanding how to use the technology and the technology's capabilities and limitations.

Second, autonomous vehicle technologies will be used by a wide range of drivers and passengers. How they interact with the vehicle occupants varies, not just by the passengers' physical characteristics, but also by their expectations of how and when the technology will work and by their ability to understand the system's warnings and directions. Therefore, standards must be developed that take into account diverse populations.

Lastly, the significant difference between traditional automotive technologies and autonomous vehicle technologies is that autonomous vehicle technologies sense and make judgments about a vehicle's external environment, which cannot be controlled and can vary tremendously. Therefore, performance standards for autonomous vehicle technologies must specify the environmental conditions under which the tests must occur and, ideally, will include testing under a wide range of environmental conditions. For technologies that leave the driver in at least some control, conformance requirements that specify a smaller set of environmental conditions may be acceptable, as the driver is ultimately still responsible. However, as we move toward fully autonomous vehicles and driverless cars, the standards and testing should span the *entire* range of conditions in which the vehicle might be expected to operate.

6.2 POLICY SUGGESTIONS

While this report is just a preliminary effort to plumb the likely liability and regulatory implications of this technology, we make few suggestions that policymakers and automakers may wish to consider.

Consumer Education. While autonomous vehicle technologies offer enormous potential, it will be important to ensure that consumer expectations do not exceed the limits of the available technology. We anticipate that fully autonomous operation of cars will be possible at some point, but the first steps will retain the human driver as an important part of the control of the car. Drivers will be tempted to rely on the technology in dangerous ways. Avoiding these false expectations will be important both to ensure safety and to reduce liability for automakers under theories of liability that consider consumer expectations. Additionally, more research may be needed to determine the best strategies for consumer education. What are the different mental models among consumers of how these technologies work? What communication medium is most effective—manuals, videos, simulation training, in-person training, or other techniques? Is this education sufficient once, intermittently, or every time the driver engages the technology?

Regulation and Standardization. It is important that the operation of these technologies be standardized across manufacturers so that the technology functions in materially the same way regardless of car manufacturer.

This will reduce the risk of crashes stemming from consumer confusion. Furthermore, significant research has been done on such technologies as lane departure warning, driver-fatigue monitoring, and collision warning, and the benefits are significant. Like the NTSB, we recommend that the US DOT accelerate rulemaking for these mature technologies.

Warnings and Preemption. Congress could consider creating a comprehensive regulatory regime to govern the use of these technologies. If it does so, it should also consider preempting inconsistent state-court tort remedies. This may minimize the number of inconsistent legal regimes that manufacturers face and simplify and speed the introduction of this technology. While federal preemption has important disadvantages, it might speed the development and utilization of this technology and should be considered, if accompanied by a comprehensive federal regulatory regime.

6.3 FUTURE RESEARCH IN LIABILITY AND REGULATION OF AUTONOMOUS VEHICLE TECHNOLOGIES

In the course of this work, we have identified several opportunities for future research that can help in realizing the efficient adoption of autonomous vehicle technologies.

Opportunities for Appropriate Cost-Benefit Analyses. As we have discussed, integrating a cost-benefit analysis into the standard for liability has the potential to reduce manufacturer liability because it allows the consideration of the benefits in reduced crash costs that are associated with these technologies. If the cost-benefit analysis is permitted to include these benefits, tort liability for crashes that result from autonomous vehicle technologies is unlikely because the adoption of these technologies seems far more likely to reduce human error and traffic crashes than cause them. But while this may be appropriate calculation of the long-run socially optimal solution, it may also undermine incentives for safer product design in the short run. To maximize the social benefits of these technologies, policymakers need to structure the liability regime to encourage the development of this technology without undermining marginal incentives for safety. Further research is necessary to determine which costs and benefits should be included in the analysis.

Further Empirical Research. Determining the optimal liability regime and forecasting technology development and adoption will require empirical research in addition to academic research into the ways in which liability rules affect the behaviors of manufacturers, consumers, and insurance providers in this context. What is the pace of manufacturers' research and development for autonomous vehicle technologies, and how do their strategies reflect concerns about liability, cost, and investment opportunity costs? Are there technological advances that have not been brought to the market because of particular liability concerns? Are insurance companies already offering or considering offering incentives for consumers to purchase vehicles with autonomous vehicle technologies? Are these incentives having an effect on consumer choices? Such evidence would also be of value in developing a road map and a timeline for the resolution of liability issues and the emergence of more-advanced autonomous vehicle technologies.

In-Depth Analyses of Technologies and Deployment Scenarios. While we have looked at liability and regulatory concerns generally, it is important to examine these issues as they relate to different technologies and deployment scenarios specifically. Liability issues are likely to play out differently for forward and rear collision-avoidance systems than for cooperative intersection collision-avoidance systems, in which multiple vehicles may be working together. Further analyses will also be required as different types of support infrastructure emerge, such as vehicle-to-vehicle communication networks. The types of public-private partnerships that are employed for these systems will play a particularly significant role: A vehicle-to-vehicle communication system operated entirely by a commercial provider will have different liability and regulatory implications from those of a system shared between industry and government. Such in-depth analyses are likely to have valuable insights for technology research and development efforts currently under way.

International Comparisons of Liability and Regulatory Regimes. Most automobile manufacturers sell their products in many jurisdictions, and there is evidence that manufacturers have launched certain autonomous vehicle technologies in other countries but not in the United States. In 2006, for example, Honda introduced its Accord model in the UK with a combined lane-keeping and ACC system that allows the vehicle to drive itself under the driver's watch; this combination of features has yet to be introduced in the United States (Miller, 2006). Ho (2006, p. 27) observes a general trend that "the U.S. market trails Europe, and the European market trails Japan by 2 to 3 years." What is the extent of these differences? What aspects of the liability and regulatory rules in those countries have enabled accelerated deployment? What other factors are at play (e.g., differences in consumers' sensitivity to price)? What is the effect on safety and on consumer behavior? Do consumers in different countries have different demands for these technologies? If so, how might that affect implementation strategies? Are there opportunities to modify the U.S. regimes to capture the benefits that have been experienced elsewhere?

Comparison with Other Transportation Contexts. Some of these same issues concerning the effect of liability on the introduction of technology arise in other transportation contexts—e.g., operating railroads, air traffic, or marine transport. An analysis of how liability affected the introduction of new technology in these contexts may shed further light on policy lessons for the autonomous vehicle technology context.

Guidelines for Conformance Standards That Consider Environmental Variation. As we have mentioned before, performance standards for autonomous vehicle technologies must specify the environmental conditions under which the tests must occur and, ideally, will include testing under a wide range of environmental conditions. Yet, there is an incredibly large range of weather, lighting, traffic, and road conditions and an essentially infinite set of combinations, and physically testing all of them is certainly impossible. What set of environmental testing conditions will suffice for standards for different types of technologies? The value of testing in a particular environmental condition will vary depending on the specific sensors and components used. Can a single set of test conditions be developed to effectively evaluate all systems? How much of this testing can occur in simulation and at what fidelity? The military has also recognized the need for broad testing for its autonomous vehicles (CAUGVT, 2002); can partnerships be made between defense and industry to leverage different capabilities and resources to this end?

Such efforts as these will provide both a broader and deeper understanding of the liability and regulatory concerns associated with autonomous vehicle technologies. Understanding these and other nontechnical issues, in turn, will help to educate stakeholders about possible benefits and risks and to drive the policymaking that is necessary to realize the tremendous potential of these technologies.

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