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AUTONOMY AT SCALE

Intelligent Machines Advancing Technology to Improve our Future

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USE CASE: SURFACE TRANSPORTATION

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Our nation's roadway systems were planned, developed, and adapted in preceding centuries for use by vehicles under human control. We will examine the potential benefits and challenges in transforming the surface transportation ecosystem from one in which vehicles are largely human driven to one in which *automated vehicles* are the rule rather than the exception.

We will use the term *automated vehicles* to conform with current surface transportation community practice. Automation implies both autonomous (independent) movement and connectivity or signaling within the transportation ecosystem. An automated vehicle (AV) specifically refers to a machine moving passengers or goods on a roadway system with both autonomous movement and wireless connectivity.

Background

The concept of AV technology is not new. An oft-quoted AV milestone was the General Motors Futurama exhibit presented at the 1939 World's Fair in New York[1] featuring driverless vehicles navigating high-speed interconnected roadways. While early 20th century technology was too crude to realize the promise of the Futurama exhibit, the notion of an AV has remained a popular and compelling vision. Underlying the durability of this vision is the fact that human driving is widely understood in intimate detail. Further, the idea of transferring routine control to the vehicle itself has become an increasingly common and widely accepted practice. In fact, one could characterize the last 80 years as a steady succession of new technologies and market acceptance testing towards something not unlike the AV vision depicted in the Futurama exhibit.

First on this path were a raft of "automatic" innovations where sub-elements of vehicle control could be assigned to the vehicle itself. For example, (non-adaptive) cruise control became a popular mass market option on many vehicles in the 1970s. Cruise control relieves the driver of the tedium of maintaining uniform speed on long interstate trips, with the added benefit of improved fuel economy (when properly applied). Note that with cruise

Figure 1: Surface and near-surface autonomy at scale.

control, only one aspect of the driving task was allocated to the vehicle in this case (speed control) and the driver remained responsible for overall vigilance to avoid collisions and remain within legal speed limits. The advent of cruise control generated accounts (some apocryphal) of human drivers engaging the speed control system and turning their attention elsewhere (e.g., to adjudicate a backseat dispute among children) under the mistaken belief that cruise control was in fact, comprehensive autonomy. Real or invented, these accounts had the effect of normalizing driver expectations regarding the limitations of this automated feature. One can view recent forms of vehicle automation (e.g., Autopilot[2] and Super Cruise[3]) as modern extensions of the original cruise control concept that include steering and braking.

Both economic viability and driver behavior are critical factors in understanding the current state of AVs and the potential for automation at scale.

A more recent, related set of innovations have the driver relinquishing complete or near-complete control of the driving task to the vehicle under defined scenarios. One example is automated parallel parking. Here, the vehicle uses sensor inputs and computer control of steering, throttle, and braking to complete a reliable, low-speed maneuver that some human drivers find frustrating to execute. While such systems are widely available in current passenger vehicles, the popularity and use of automated parallel parking is not yet at the same level of ubiquity as cruise control. This can be partially attributed to this being a relatively new innovation, but also because the amount of time spent in free-flow interstate travel dwarfs the time spent parallel parking for nearly all drivers. Therefore, the exposure to the specific automated driving scenario is infrequent, so detailed driver understanding of this automation scenario is less often reinforced.

Consistency in describing partial and full vehicle automation is an important aspect of coordinating and organizing a move to mass automation. Broadly, AVs assign some aspect of a safety-critical control function (e.g., steering, throttle, or braking) to occur without direct driver input.[4] The level of automation will determine the extent of control or monitoring role that a human operator needs to play based on the Society of Automotive Engineers (SAE) six-part formal classification system for AVs (Levels 0 to 5)[5]. AVs may be isolated (i.e., lack ability to communicate with nearby vehicles or infrastructure, but connected to manufacturer's back office) or may be connected (i.e., use communications systems such as connected vehicle technology, in which vehicles can communicate with nearby vehicles and roadside infrastructure wirelessly). Connectivity will be required to realize the full potential benefits and broad-scale implementation of AVs. The United States Department of Transportation (USDOT) is currently considering a parallel classification system for vehicle connectivity that complements the SAE vehicle automation classification.

Innovations like cruise control and automated parallel parking are examples of the steps on the path to automated vehicles; however, two things must occur for driving automation technologies to be so widely utilized that millions of automated vehicles would be interacting with the roadway system (and each other) every day. First, the innovation must be technologically viable in mass production vehicles at relatively low cost. Second, there must be time for the consumer to understand, trust, and integrate the technology into their driving behavior. Both economic viability and driver behavior are critical factors in understanding the current state of AVs and the potential for automation at scale.

The State of Underlying Fundamental Technologies

Complex driving automation is increasingly viable for mass-market implementation. As with all applications of autonomy, this is related to four key enabling factors linked to fundamental technologies:

- **Sensors Systems** — In the 2017 model year, each vehicle had an average of 60 to 100 sensors. The number of sensors is projected to reach as many as 200 per car—adding up to approximately 22 billion sensors used in the automotive industry per year by 2020[6]. These figures underscore two observations. First, the modern passenger vehicle is a rolling multi-sensor platform, though not all sensors directly support the (automated) driving task. Second, the sheer size of the market for these sensors have made them cost effective for mass deployment. Most automotive sensors have already passed the tipping point where low cost and mass scale can combine in a virtuous cycle of increasing capability available every year at a lower cost from the previous year.
- **Position, Navigation and Timing** — Global positioning systems (GPS), like sensors, are commodity technologies for modern passenger vehicles. Current GPS technology alone, however, does not provide highly precise or even lane-level accuracy everywhere, particularly in challenging environments like high-density urban centers. Local vehicle positioning must be augmented with local sensors that are tracking lane striping, signage, and other cues. Often overlooked is the value of ubiquitous timing, which is critical for realizing practical autonomy at scale.
- **Sensor Fusion and Machine Learning** — The least developed of the fundamental autonomy technologies relates to how sensor inputs are integrated and utilized by a computer system to issue vehicle control messages to the sub-systems that control vehicle motion (e.g., throttle, brake and steering). The most promising approaches rely on machine learning techniques that, much like human drivers, become more capable through repeated exposure. The limitation is that the driving task (human or otherwise), while relatively simple in execution for isolated highways or deserted parking lots in clear weather, is extremely complicated in dense urban streets (e.g., Manhattan) or in low-visibility conditions. Many repetitions and exposure to these conditions are required for a machine learning algorithm to approximate the ability of the human driver. Complex situations may be infrequent, and in situations where no past exposure is relevant, machine learning can be unpredictable.
- **Connectivity** — While recent advances in individual vehicle automation has attracted public attention, an equally critical element in achieving automation at scale relates to the ability of AVs to communicate with each other. Three USDOT pilot deployments of connected vehicle technologies are currently underway[7], wherein (non-AV) vehicles broadcast

messages describing current location, speed, and other data 10 times per second. These messages allow neighboring vehicles to avoid collisions and coordinate motion paths—a fundamental requirement for the realization of autonomy at scale; however, connected vehicle technologies and messaging protocols are still in development, even to support the human driver. The type and frequency of messages needed to enable mass automated driving is an area of active research.

Potential Benefits and Impacts

Before diving into the potential benefits from the deployment of AVs at scale, it is useful to recall that just as our current system is populated with human drivers, the only 100% collision-free AV environment is an environment with no moving vehicles. All mobility requires the acceptance of risk of crashes—either collisions with other vehicles or obstacles (either in the roadway or off the roadway in the case of road departure). Our societal tolerance for some rare collisions to enable broader mobility and productivity from the system falls along a spectrum and is subject to change over time.

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Improved Safety —
The high potential for improved safety through increased automation is often used to justify vehicle automation. This would appear to be a slam-dunk for automation as, one might assume that machines should be able to sense threats and react far faster than humans; however, at this point, it is not clear that current technology is always a clear improvement over human drivers (see call-out box). AVs will doubtlessly improve and eventually exceed human drivers in reaction time and other measures of performance. Some caution is in order, however, regarding how quickly AVs can reliably manage the full complexity of urban driving.

In November 2018 track testing, Uber AVs had to drive 20% slower than the human drivers to match the reaction time of a human driver at 25 mph. – New York Times (12/6/18)[8]

In addition, AVs will be utilized and directed by humans. These directions may not always maximize safety, though, because humans themselves do not reliably manage risk. For example, in roughly half of traffic fatalities, passengers chose not to wear seat belts[9]. Humans who direct automation may do so in ways that circumvent improved safety. Automation on its own may have muted safety impact if humans can override safety-related functions. Even if safety systems are not circumvented, AVs lack the ability to perceive or understand an unfamiliar driving scenario. Therefore, high-risk conditions can result from machines encountering situations where past learning is useless or counter-productive.

Management of collision risk in this case implies slower speed and more cautious maneuvering. Seen from this perspective, humans and machines are always operating on a risk tradeoff continuum between safety and productivity. Machines may or may not have the final say with respect to this tradeoff.

Enhanced Mobility — Automation has high potential for improving the ability of non-driving populations (e.g., elderly, children, persons with disabilities, and persons who choose not to become licensed drivers) to make efficient trips. Possible improvements also extend to those who choose not to own vehicles, however, this depends on availability of shared-use autonomous vehicles and local competition to lessen trip costs. Near-term, AVs will have the greatest impact where it is economical to have many machines available on-demand for shared service. This is particularly relevant for the early state of automation where AVs are the exception rather than the rule.

Higher System Productivity — It is not yet clear that the surface transportation system itself will be more productive when AVs are the rule rather than the exception. Arguments for and against higher bottleneck throughput have been debated in academic papers. Study results are nearly always linked to underlying assumptions about how AVs manage the safety/productivity tradeoff. When a study assumes highly cautious AVs, the result is lower productivity than a system populated with human drivers. When a study assumes a scenario in which vehicles maneuver far more closely to one another than human drivers, the result is more productivity accompanied by speculative safety consequences.

At a strategic level, AVs have the potential to transform commuting and other typical use cases for the transportation system. Relieved of the task of driving, commuters may choose to travel from distant destinations to work centers, using this time to do other tasks, or simply sleep.

Changes in Travel Demand — At a strategic level, AVs have the potential to transform commuting and other typical use cases for the transportation system. Relieved of the task of driving, commuters may choose to travel from distant destinations to work centers, using this time to do other tasks, or simply sleep. AVs, if shared, may reduce the need for and cost of parking, as AVs can simply drive away. At some point, however, a large fleet of AVs may be circling in urban centers, so pricing of vehicles in motion versus remaining stationary may be required.

ORCHESTRATED AUTONOMY: THE NOBLIS PIECES OF EIGHT (PO8) CONCEPT

Isolated autonomous machines must rely on individual machine sensors with limited range and isolated situational awareness—forcing them to act conservatively and myopically. In practice, this means cautious, low-speed maneuvering. The Noblis Pieces of Eight (Po8) system enables nearby connected machines to share situational awareness regarding obstacles and threats projected over time, and collectively plan motion paths and other actions that avoid collision or other conflicts. The Po8 System enables a collective, post-hoc accountability process to assess the reliability of each individual machine to act faithfully in accordance with collectively optimized motion paths and actions. An individual machine establishes a track record within the Po8 System, secured using a blockchain. This record of machine past performance may be factored into collective obstacle mapping and optimized motion/action paths.

In February 2019, The Po8 project was recognized with two international awards (one for Most Creative and one for Highest Potential Impact) in the Mobility Open Blockchain Initiative (MOBI) Grand Challenge, Phase 1, which focused on the use of blockchain to enable orchestrated autonomy.

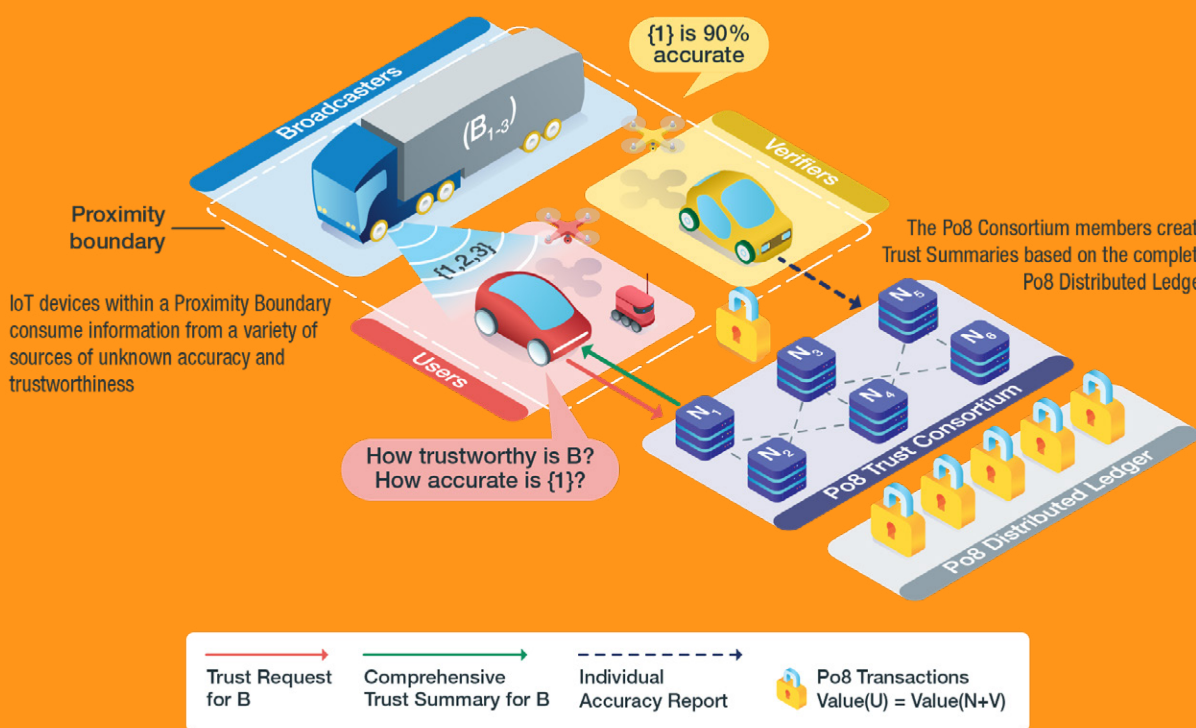

Figure 2. The Pieces of Eight (Po8) Orchestrated Autonomy Concept

Interacting machines in an Internet of Things (IoT) ecosystem consume information of unknown accuracy from other machines nearby. A consortium of distributed leger (or blockchain) technologies track individual machine trustworthiness over time and provide trust reports that account for the prior reputation of individual machines. The result is that increased trust can allow for increasingly high-speed, close following machine movement without risk of collision.

Challenges

Moving AVs from individual marvels to deployment at scale faces some salient challenges.

Difficult or Rare Driving Conditions — The most critical near-term restraint on individual vehicle autonomy relates to improving machine learning algorithms so that they are more reliable in general driving conditions and scenarios. Building from early successes in specific, low-speed automation like automated parallel parking, major investments are underway in the private sector to build up trillions of miles of machine learning experience that can provide the basis for a generalized autonomous driving capability. AVs will become more capable scenario by scenario, for example, moving from adaptive cruise control in isolated highway driving to low-speed congested "creep control" systems. Scenarios beyond barrier-separated facilities (like freeways), good lane marking, or dense pedestrian interaction, will follow later. Most difficult of all will be preparing machine learning for rare events for the simple reason that they do not occur often enough for rapid and safe adaptation by an experienced machine learning system.

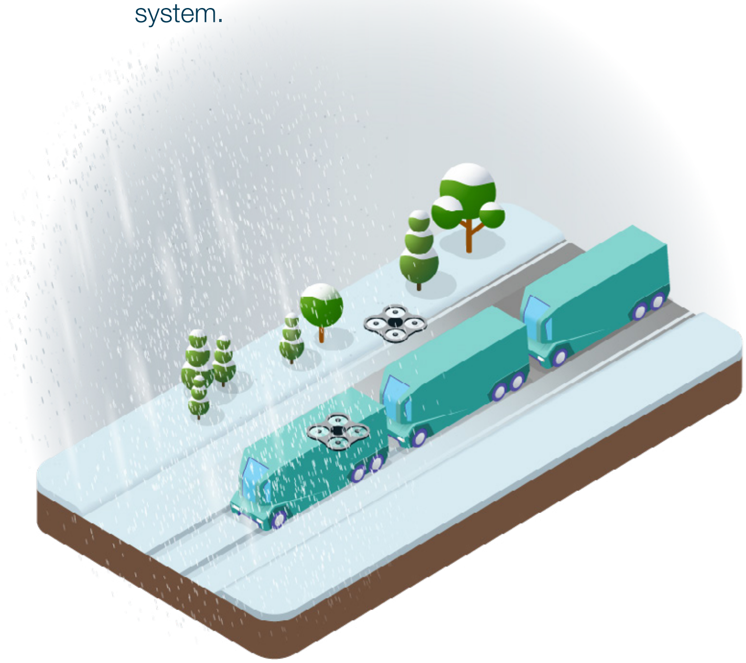

Figure 3: Rare (but critical) event: Drone-supported automated truck platoon encountering winter weather.

Figure 4: Heterogenous, autonomous machines operating in close proximity.

Mixed Human and Autonomous Traffic — AVs are unlikely to enter the roadway ecosystem in one large surge. They are more likely to incrementally stream into specific areas that align with human needs and where there is the ability to create a market for automated driving. The result will be a patchwork of varying AV density and adoption and, for an extended period, AVs that function in full automated mode for some parts (but not all) of a trip. Much like cruise control, drivers may choose to engage complete or near-complete autonomy selectively. For AVs at scale, how and in what form driving automation takes root will significantly influence the rules of engagement established for AV and human driving interaction. As a baseline, the rules humans use will form the template for these interactions. To realize the mobility and productivity benefits associated with AVs at scale, at some point these rules will have be adapted to allow for the close maneuvering and other changes that underpin more transformational mobility benefits.

Heterogeneous Autonomy — Even in systems where AVs are the rule rather than the exception, the capability of individual AVs will vary significantly. First, just as today, the roadway system will be populated with machines that range from large and heavy, with corresponding maneuver performance limitations, to relatively small and light AVs designed for individuals or small loads. The rules of engagement among AVs, as well as the messages they exchange, must accommodate the impact this variation has on stopping distance, acceleration, turning radius, and other vehicle performance characteristics when large numbers of AVs interact in proximity. Second, the system will be populated with AVs that represent different sequential waves of technological maturity, from first generation AVs to the most recent. In this case, newer AVs may be able to sense obstacles and plan motion paths in ways that older AVs may not be able. Again, the rules of mass AV engagement must accommodate these differences. Depending on the messaging, AVs can share a collective situational awareness among cooperating AVs so that each machine is aware of all obstacles seen by all connected AVs—not just the obstacles seen by the individual machine.

Figure 5: Merging automated vehicles with varying capability to brake and accelerate.

Conclusion

Autonomy at scale (in some form) in the surface transportation ecosystem is inevitable. We have been on a path of incremental driving sub-task automation and scenario-based driving automation since the early days of automobile production. The key unknowns regarding AVs at scale relate to where, why, and how quickly—and under what terms. If we, collectively, don't get it right, then we may have a very safe system but with less overall capacity than in the human driver case. Or we may gravitate to what is familiar, a system of AVs that merely mimic human drivers and therefore leave us with essentially the same system-level safety and productivity as we currently experience. Getting driving automation right at scale likely means a journey of corrective behavior straddling the tradeoff of collision risk management. Our most powerful way to influence this process is to establish flexible rules of engagement that permit human-driven and automated machines to operate together. This may mean managing system access and vehicle maneuvers while accommodating AVs of varying capability and human-driven vehicles at the same time. Most critically, our collective encounter with AVs at scale will be a complex, but one-shot experiment. Where we land from a series of incremental compromises will not be easily undone.

Getting driving automation right at scale likely means a journey of corrective behavior straddling the tradeoff of collision risk management. Our most powerful way to influence this process is to establish flexible rules of engagement that permit human-driven and automated machines to operate together.

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