Portland Area Mainline Needs Assessment

DRAFT

Autonomous Vehicles: Working Paper #1

A Summary of Current Conditions and their Implications for Transportation Planning

HNTB Corporation

April 2018

Table of Contents

1. Overview

Each day brings fresh news regarding the advent of Autonomous Vehicles (AV's). Automobile manufacturers are teaming with Artificial Intelligence (AI) firms to hasten production of AV's. Newcomers to the auto industry such as Google and Apple are rapidly developing self-driving technology. Transport service providers such as Uber are testing AV deployments even as they reevaluate their business models for the future. And transportation planners are beginning to consider how their future networks may be impacted by an influx of vehicles that no longer need drivers.

The purpose of this white paper is to provide the Maine Turnpike Authority and others with professional insight regarding the implications of AV's on the transportation planning process. The paper will proceed in the following manner:

- Section 2 will provide an overview of AV's and their current place in today's transportation system.
- Section 3 will discuss the potential impact of AV's on roadway capacity.
- Section 4 will address the likely impact of AV's on vehicle-miles traveled on the transportation network.
- Section 5 will briefly summarize the "State of the Practice" with respect to long-range planning for AV's.
- Section 6 will survey the literature to lay out some potential timeframes for AV deployment.
- Finally, Section 7 will draw conclusions from the analysis with specific application to the Maine Turnpike Authority's planning processes.

2. Automated Vehicles: A Present-Day Snapshot

Although the term "Autonomous Vehicle" is used very broadly, the National Highway Traffic Safety Administration (NHTSA) has actually defined five distinct levels of vehicle automation. These levels attempt to quantify automation along a continuum. They are widely referenced in the AV literature and are pertinent to understanding the likely progression of AV technology as it is rolled out to the public.

The five levels defined by NHTSA are as follows:

- **Level 0 – No Automation**. At this level, the driver is in sole and complete control of all primary vehicle functions (steering, brakes, and acceleration).
- **Level 1 – Function-Specific Automation**. Level 1 automation incorporates one or more control functions that operate independently of each other. This would include functions such as pre-charged brakes that are designed to apply full-braking power when (a) the driver touches the brakes, however lightly, and (b) the vehicle senses a collision is likely to occur.
- **Level 2 – Combined-Function Automation**. This level involves automation of two or more primary control functions that work together to relieve the driver of specific responsibilities. An example would be adaptive cruise control coupled with lane centering, whose functions automate the tasks of both acceleration/deceleration and steering.

- **Level 3 – Limited Self-Driving Automation**. This level of automation enables the driver to relinquish virtually all driving functions under certain traffic or environmental conditions. The vehicle continuously monitors conditions and will alert the driver if the vehicle needs to transition back to human control. Humans are expected to be present and ready to take control (with sufficient transition time) if alerted by the vehicle.
- **Level 4 – Full Self-Driving Automation**. Level 4 automation cedes all driving functions to the vehicle, which monitors roadway conditions and maintains control for the entire trip. This would include both occupied and unoccupied travel. Human input is limited to providing destination input; drivers are not expected to be available to assume control at any point of the trip.

The Society of Automotive Engineers (SAE) goes on to add a distinction between Level 4 and Level 5 automation. According to SAE, Level 4 automation would provide the capability for the vehicle to cede control to a human driver in certain conditions. However, the vehicle would have the backup capability to exit the roadway and safely stop if the human was unable to respond in a timely manner. Under the SAE's "Level 5 automation" definition, the vehicle would be completely responsible for all operations under all roadway and environmental conditions.

It is helpful to think of the levels of automation in terms of responsibility for monitoring the driving environment. For levels 0 through 2, the human driver is responsible, supplemented (to increasing degrees) by the automobile. For level 3 and beyond, the AV system is responsible for monitoring the driving environment, with various levels of backup responsibility delegated to on-board passengers.

The most advanced level of automation in use today is Level 3. The Uber self-driving taxi tests in Tempe (Arizona) and Pittsburgh, as well as the Google self-driving car project (now referred to as "Waymo"), are examples of Level 3 automation. All AV testing on public roads in the United States involves having a driver present in the vehicle. As of February 2018, no states have authorized unoccupied vehicles to be operated on public roads.

Autonomous vehicles were envisioned as far back as 1939, when GM presented an exhibit at the World's Fair (entitled *Futurama*) predicting a future automated highway system.[1] Up until the late 90's, the prevailing concept of an automated highway rested on intelligent infrastructure guiding AV's. A successful test of "driverless vehicles" in 1997 on I-15 in San Diego relied on magnets embedded in the roadway that were read by vehicular sensors connected to an on-board computer. This concept was predicated on the assumptions that additional protective measures would be taken to protect the roads from sudden incursions (e.g. animals unexpectedly dashing in front of a vehicle).

However, the past 20 years have seen a move toward automation that is driven more by vehicle-mounted sensors that do **not** require communication with roadside infrastructure. Rather, the sensors feed the onboard computer which autonomously makes decisions regarding speed and direction. Numerous auto manufacturers are aggressively moving forward with AV development on this model. Some examples of ongoing and planned AV deployments include the following:

- In 2017, Tesla rolled out an "Enhanced Autopilot" option on all its vehicles. This option provides adaptive cruise control, forward collision warning, auto-steer, and self-parking (in certain conditions). Additional features (e.g. automatic lane changing and connecting between freeways)

[1] Anderson, James et al. *Autonomous Vehicle Technology: A Guide for Policymakers.* Rand Corporation (2016), pg. 29.

will be rolled out over time via software updates.[2] This existing system is considered to operate somewhere between Level 2 and Level 3 automation.

- General Motors has filed a Safety Petition with the U. S. Department of Transportation for its self-driving "Cruise AV," a vehicle purported to be "the first production-ready vehicle built from the start to operate safely on its own, with no driver, steering wheel, pedals or manual controls." GM has asked permission to start safely deploying the vehicle in 2019.[3]
- Bloomberg and the Wall Street Journal have both reported that Apple is seeking to roll out a self-driving electric car by 2020, although Apple has not confirmed these reports. Apple CEO Tim Cook has stated only that Apple is "focusing on autonomous systems."[4]
- Ford Motor Company has partnered with Argo AI to develop a virtual driver system for Ford's first fully autonomous vehicle, scheduled to roll out in 2021.[5]
- Reuters reports that Uber has established a non-binding deal with Volvo to purchase up to 24,000 self-driving cars.[6] The self-driving system to be deployed in the Volvo vehicles is under development by Uber's Advanced Technology Group. The system has been tested extensively during self-driving experiments in Tempe and Pittsburgh.

Self-driving technology has also made advances in the realm of trucks. For example:

- In October 2016, in a test run performed in the state of Colorado, a self-driving truck delivered 2,000 cases of Budweiser from Fort Collins to Colorado Springs—a journey of about 130 miles.[7] The interstate portion of the journey conducted with no assistance from the driver. However, a car drove ahead of the truck to ensure the travel lane was free, and the truck was surrounded by the Colorado State Patrol.
- In the state of Nevada, Daimler's *Freightliner Inspiration Truck* has been approved for autonomous driving on public highways. However, as a safety precaution, a driver still needs to be behind the wheel.

These developments make it clear that autonomous driving is at the forefront of a great deal of research, development, and testing. Moreover, these developments involve more than just the traditional automakers, but also involve experts in the realms of computer software and artificial intelligence. Nevertheless, no unoccupied vehicles are operating on the road today. Level 3 autonomy represents the most advanced stage of development on America's highways at present.

3. Impact of AV's on Roadway Capacity

The expectation for AV's is that they have the potential to enhance roadway capacity. In other words, AV technology is widely expected to enable more vehicles to use the road during peak periods. The capacity improvements are the results of the following potential changes:

---

[2] http://www.businessinsider.com/tesla-enhanced-autopilot-system-self-driving-features-2017-6/
[3] http://www.gm.com/mol/m-2018-jan-0112-cruise-av.html
[4] https://www.macworld.co.uk/news/apple/apple-car-release-date-rumours-3425394/
[5] https://medium.com/self-driven/why-we-created-argo-ai-aa3f43ebefb6
[6] https://www.reuters.com/article/us-volvocars-uber/volvo-cars-to-supply-uber-with-up-to-24000-self-driving-cars-idUSKBN1DK1NH
[7] https://www.technologyreview.com/s/603493/10-breakthrough-technologies-2017-self-driving-trucks/

- **Platooning on highways.** AV's could potentially increase freeway capacity by traveling closer together at higher speeds. The State Smart Transportation Institute cites studies suggesting that roadway capacity could double as AV's come to dominate the vehicle fleet.[8]
- **Denser and more responsive flow through intersections.** AV technology deployed at signalized intersections could move vehicles through traffic signals with greater density and with less response time. This would potentially increase traffic signal throughput and reduce delays.
- **Fewer accidents.** The Federal Highway Administration (FHWA) estimates that fully 25% of roadway congestion is related to non-recurring traffic incidents ranging from a flat tire to a multi-car collision.[9] Further, studies suggest that approximately 90% of motor vehicle incidents are caused, at least in part, by human error.[10] If AV technology were to virtually eliminate "human error," then the number of accidents could be reduced by up to 90% and roadway congestion would subsequently be reduced by over 20%.
- **Narrower lanes.** Lane-centering technology has the potential to more precisely locate vehicles within designated lanes. Consequently, travel lanes in the future could potentially be narrower. The ability to provide more lanes within a given width of pavement also represents added capacity.

Clearly, AV technology holds great promise for improving the ability of the existing transportation network to serve rush-hour traffic. However, these predictions for benefits to roadway capacity should be viewed with a measure of caution for the following reasons:

- **Market penetration**. For the highway capacity improvements to be realized, the market penetration of AV's will need to be sufficiently high (likely 50% or greater) to justify the designation of dedicated AV lanes. For the intersection improvements to be realized, AV's will likely need to comprise 95% or more of the vehicle fleet.[11] Such levels of market penetration are likely decades away.[12]
- **Required infrastructure.** As noted above, the improvements in highway capacity will depend on the designation of "AV Only" lanes. The improvements in intersection capacity will likely require vehicle-to-infrastructure communication with the traffic signal controllers. Such infrastructure modifications will require substantial planning, analysis, and investment. Moreover, these improvement to highways and traffic signals will be of limited value unless the local roadway network is sufficient to handle the surge in peak-period throughput.
- **Safety offsets.** While AV technology has the potential to reduce or eliminate the contribution of "human error" to traffic accidents, there are other ways in which AV technology could *compromise* safety. These so-called "safety offsets" include the following:
  - The potential for hardware and software failures;
  - The potential for malicious hacking into AV systems;
  - The likelihood that improvements in safety will ultimately yield increased risk-taking by drivers, sometimes referred to as "offsetting behavior" or "risk compensation"; and

[8] https://www.ssti.us/2016/12/automated-vehicles-will-bring-big-highway-capacity-increases/
[9] https://ops.fhwa.dot.gov/program_areas/reduce-non-cong.htm
[10] Multiple traffic safety studies identified via hyperlink at the following site: http://cyberlaw.stanford.edu/blog/2013/12/human-error-cause-vehicle-crashes
[11] Eno Center for Transportation. *Preparing a Nation for Autonomous Vehicles*. October 2013. Available on-line at https://www.enotrans.org/.
[12] A survey of possible timelines for deployment will be presented in Section 6.

- The potential for increased hazards in situations in which human-driven vehicles are mixed in with autonomous vehicles driving in high-speed platoons.

The bottom line with respect to AV's and roadway capacity is: Don't expect too much, too soon. The improvements are contingent on (a) achieving a high market share of fully-autonomous vehicles (recognizing the current market share is 0.0%), and (b) providing some measure of infrastructure to prioritize AV traffic flow. This will require considerable time and planning. The benefits are likely to be very small during the initial stages as the nation adapts to a mix of AV's and human-driven vehicles.

4. Impact of AV's on Vehicle-Miles Traveled (VMT)

The advent of autonomous vehicles promises to dramatically change the way in which people use the roadway network. Some of these changes will tend to diminish the mileage that one drives, while others will have the opposite effect. This section will summarize the various ways in which AVs are likely to impact VMT and will attempt to draw some preliminary conclusions regarding the extent to which VMT is likely to change.

4.1 Factors tending to reduce VMT

The primary characteristic of AV's that is likely to reduce VMT is *reduced vehicle ownership*. Based on the assumption that possession of fewer vehicles will lead families to undertake driving less frequently, there are two ways in which the advent of AV's is likely to reduce vehicle ownership:

- **Costs**. Particularly in the early stages of deployment, AV's will be extremely expensive. Estimates of the exact cost vary wildly since the technology is still in a developmental phase. A single sensor component being employed by Waymo[13] is stated to cost approximately $7,500.[14] When this cost is added to hardware, software, and research and development costs, it is very possible that the self-driving capability *alone* will initially add $25,000 to the cost of a vehicle.[15] It is likely that some families will choose to have fewer vehicles to mitigate the price increase.
- **Ridesharing capability**. Self-driving capability means that one vehicle could serve multiple people throughout the day. For example, depending on family schedules, one AV could conceivably transport both parents to work and still get the kids to school. Or a family that doesn't need its AV during the daytime hours could share it with a neighbor who has a need for mid-day mobility. Research noted by the Eno Center for Transportation found that "a single shared AV could replace between nine and thirteen privately owned or household-owned vehicles, without compromising current travel patterns."[16] Depending on the extent to which drivers are willing to share rides, AV's could clearly support a lifestyle with lower vehicle ownership.

Additionally, VMT in urban settings may be reduced slightly due to more efficient travel. Trips that today may involve extensive cruising in search of a parking space could be replaced by a shorter trip in which an AV delivers its occupant to the destination, followed by a trip to a designated AV parking area.[17] However,

---

[13] Waymo is a sister company of Google, both of which fall under the holding group *Alphabet*. In December 2016, Waymo assumed control of the effort that began as Google's driverless car project.

[14] http://www.businessinsider.com/googles-waymo-reduces-lidar-cost-90-in-effort-to-scale-self-driving-cars-2017-1

[15] A court filing in Waymo's lawsuit against Uber revealed that Google alone has spent $1.1 billion in the development of software and hardware for AV's. Such massive outlays will need to be recovered by the eventual purchase price of AV's when they come to market.

[16] Eno, pg. 7.

[17] Litman, Todd. *Autonomous Vehicle Implementation Predictions*. Victoria Transport Policy Institute, December 2017, pg. 13.

such VMT reductions are likely to be minor, and are certainly speculative at this early stage in the transportation planning process.

4.2 Factors tending to increase VMT

In contrast to the small number of AV-related factors that will tend to drive VMT downward, there are many factors associated with self-driving vehicles that will apply upward pressure to VMT. Some of the more prominent factors are discussed below.

- **Serving the underserved**. AV's will provide new mobility options for people that are underserved today—namely, underage drivers and the elderly. Pent-up demand from these groups that are largely unable to drive themselves will tend to generate more VMT. Analysis performed by KPMG suggests that this factor alone could boost VMT by more than 15%.[18]
- **Empty trips**. Although ridesharing may tend to reduce vehicle ownership, it will also create a new phenomenon—empty trips. Vehicles that serve multiple people throughout the day will necessarily spend some portion of the day traveling empty, during intervals between dropping off one occupant and picking up a new occupant. Modeling performed by the Eno Center for Transportation suggests that 10-13% of all travel with an AV fleet will be empty.[19] This will tend to increase VMT.
- **Potential transit changes**. If AV taxis tend to replace conventional mass transit on a broad scale, the result will be greater VMT.
- **Lower "productivity cost**." One deterrent against driving today is the cost in productivity of being behind the wheel—a cost that escalates when stuck in traffic. AV's help to diminish this "productivity cost" by enabling drivers to work during their trip. By reducing part of the cost of driving, AV's could encourage *more* driving and thus push VMT upward.
- **Suburban growth**. In the long term, a reduction in the productivity cost of driving could end up encouraging greater development in suburbs and exurbs. A more dispersed land use pattern would tend to increase VMT.

Most experts seem to suggest that AV's will have a net effect of *increasing* VMT. The VMT-suppressing effects of reduced vehicle ownership will likely be more than offset by the addition of empty trips as well as the addition of trips serving underage drivers and the elderly. And unless proactive measures such as road pricing and land use management are implemented, the sudden bump in in-vehicle productivity will likely encourage more driving and more dispersed settlement.

At this juncture, there is no consensus on whether the AV-related improvements to capacity will be sufficient to offset the anticipated growth in VMT. As the Rand report notes, "…the overall effect of AV technology on congestion is uncertain."[20]

---

[18] KPMG estimated that providing mobility to the underage and the elderly would boost overall VMT by 500 billion. The analysis used 2014 as a baseline, in which nationwide VMT was 3.0 trillion. See KPMG's document entitled *The Clockspeed Dilemma* (November 2015), available on-line at https://assets.kpmg.com/content/dam/kpmg/pdf/2016/04/auto-clockspeed-dilemma.pdf

[19] Eno, pg. 18.

[20] Anderson, pg. 15.

5. AV's and the State of the Practice of Transportation Planning

The development of autonomous vehicle technology is fast-moving, and many of the implications of the technology are still uncertain. Some of the questions that currently cloud the transportation planning process include:

- Will AV technology ultimately increase congestion? Or will it reduce congestion?
- How readily will people adopt vehicle sharing and ridesharing?
- How long will it take for the technology to become affordable?
- How long will it take for AV's to be fully authorized for travel throughout the United States?

While there is general acceptance that widespread deployment of AV's is forthcoming, uncertainty remains concerning the timing and the implications of that deployment. As a result, AV planning efforts have lagged AV technology development. Generally speaking, transportation planning is advancing on three fronts: the public sector, the private sector, and transportation consultants. Some examples of activities occurring on each of these three fronts are summarized in the subsections that follow.

5.1 Transportation Planning & the Public Sector

The uncertainty noted above has meant that public sector agencies and officials are moving forward slowly. Some examples of public sector action include:

- The Colorado Department of Transportation (CDOT) recently announced their intent to add capacity to C-470 south of I-70, on the west side of Denver. The new capacity would initially be in the form of express lanes that would be available for drivers willing to pay a toll. However, the CDOT project manager, Ben Davis, noted that one of the express lanes could be designated as an AV lane at some point in the future. Davis further noted that this was the first time that automated vehicles had been explicitly mentioned in any of CDOT's formal planning documents.[21]
- Randy Iwalski, Executive Director of the Contra Costa County Transportation Authority, stated in a presentation that his agency was now using 3,200 vehicles per hour per lane (vphpl) as a rule of thumb for freeway planning in the future. This represents an increase of 60% over the more traditional figure of 2,000 vphpl, accounting for his agency's estimate of the capacity-related improvements that may be associated with AV technology.[22]
- Currently, about 21 states have passed legislation related to autonomous vehicles.[23] In some instances, the legislation was simply a matter defining terms such as "fully autonomous vehicle" and "automated driving system." In other instances, states provided more far-reaching support for the testing of autonomous vehicles, subject to certain safety standards (e.g. requiring a driver behind the wheel during testing on public roads). States like Arizona, Nevada, and Pennsylvania have been at the forefront in facilitating testing by tech giants such as Uber and Waymo.[24] At the other end of the spectrum, approximately 20 states, have taken no legislative action whatsoever regarding AV's.[25]

---

[21] http://www.govtech.com/fs/infrastructure/AV-Lanes-Could-Play-into-Colorados-Traffic-Reduction-Plans.html
[22] https://www.ssti.us/2016/12/automated-vehicles-will-bring-big-highway-capacity-increases/
[23] http://www.ncsl.org/research/transportation/autonomous-vehicles-self-driving-vehicles-enacted-legislation.aspx
[24] Waymo was formerly known as 'the Google self-driving car project'.
[25] https://www.autoinsurance.org/which-states-allow-automated-vehicles-to-drive-on-the-road/, accessed 1/30/18.

Involvement at the public sector level has primarily been involved with establishing a legal framework for deploying and testing autonomous vehicles. Beyond that, agencies are opting to take limited preliminary steps in integrating AV's into the planning process.

5.2 Transportation Planning & the Private Sector

While public sector action has been measured and cautious, private sector input to the transportation planning process has been far more aggressive. A brief industry survey found that, in some cases, entities with a financial stake in the advancement of AV technology were acting as strong advocates for proactive planning in support of AV deployment. For example:

- The Madrona Venture Group, a venture capital firm with headquarters in Seattle, recently released a "vision paper" recommending an aggressively-phased conversion of I-5 to "all autonomous." The paper recommended that transportation planners in the Seattle-Vancouver region implement the following steps on the I-5 corridor between the two cities:
    - Immediately allow vehicles with Level 3 autonomy (or higher) to use the existing HOV lanes;
    - By 2025 (or earlier if a tipping point has been reached), allocate a dedicated lane for autonomous vehicles;
    - By 2030, limit non-autonomous vehicles to a single lane; and
    - By 2040, restrict usage by non-autonomous vehicles to certain time periods—typically during weekends and overnight periods.
- In Wisconsin, officials with Foxconn Technology Group have been strongly advocating the planned deployment of AV-related infrastructure in the vicinity of its planned 500-acre facility in Mount Pleasant, Wisconsin. Foxconn has advocated the provision of a dedicated AV lane on I-94 running between Milwaukee's Mitchell International Airport and the factory (a distance of roughly 20 miles) to facilitate the movement of cargo. The company has also revealed plans for employees to park in lots on the west side of I-94, with AV's ferrying employees from these lots to one of the two planned campuses. The Wisconsin Department of Transportation (WisDOT) has stated that it is "strongly committed" to supporting upgrades that would facilitate the movement of autonomous vehicles in the region.[26]

These two instances suggest that AV planning will be driven, in part, by powerful private sector entities with a financial stake in the successful deployment of AV technology. Large corporations like Foxconn that provide jobs for literally tens of thousands of residents can have enormous influence in the planning process.

5.3 Transportation Planning & Consultants

Much of the AV-related literature stems from consultants and "think tanks" such as the Rand Corporation, the Victoria Transport Policy Institute, the Eno Center for Transportation, the Reason Foundation, and various academic institutions. These entities can be expected to scan industry developments and advise public sector agencies regarding how to be both prudent and proactive in guiding the deployment of AV technology.

[26] https://www.jsonline.com/story/news/politics/2017/12/08/foxconn-wants-use-driverless-vehicles-move-thousands-employees-racine-county/931773001/, accessed January 2018.

Some of the common themes cited in a survey of literature from various consultant groups are cited below.

Planning should be sequential and gradual. The Victoria Transport Policy Institute (VTPI) has laid out a template for AV planning whose broad strokes are shared by many others. The template suggests that AV planning should follow this general progression:[27]

1. Clear the legal barriers to support initial AV deployments.
2. Develop a framework for testing AV performance.
3. Evaluate the costs and benefits of AV technology under actual operating conditions.
4. Study and, if appropriate, support specific AV applications requiring minimal modification to infrastructure (e.g. demand response services).
5. Make progressive changes if AV's prove to be both effective and common. A progressive series of changes could include:
    - Dedicating highway lanes to AV use;
    - Making modifications to roadway design criteria; and
    - Imposing restrictions on human driving.

In short, the sequence laid out by VTPI proposes to deploy and test AV technology, verify the benefits, and make changes as necessary to take advantage of the benefits. The key takeaway is that public sector agencies should be hesitant to make substantial changes before the technology has proven to be beneficial through both *observed behavior* and *widespread acceptance*.

Broad deployment of AV technology could take a while. Many consultants warn that it will take some time for the vehicle fleet to reflect a high share of AV's. For example, VTPI asserts that two conditions would need to be met in order for AV's for comprise a majority of the vehicle fleet by 2035:

- Most new vehicle purchases after 2025 would need to be autonomous; and
- New vehicle purchase rates would need to triple. This means that many low- and middle-income people that currently purchase used vehicles would instead need to choose to spend significantly more to purchase a new vehicle.[28]

In other words, for AV's to make up a majority of vehicles by 2035, they would need to be affordable to most people within the next seven years, and they would need to be so attractive that they would generate new vehicle purchases at unprecedented rates. Even if both conditions were met—a situation viewed by VTPI as very unlikely[29]—nearly half the fleet in 2035 would still be human-driven. So even though it is important for agencies to think through the implications of AV deployment, there is time to respond to the new technology with thoughtful deliberation.

Think about land use and road pricing. With the productivity cost of driving going down, it is virtually inevitable that, all else being equal, people will choose to drive more. This could create a near-term boost in travel and long-term population shifts away from densely settled population centers. If suburban sprawl

[27] Litman, pg. 24.
[28] Litman, pg. 20.
[29] VTPI projects that the vehicle fleet will be approximately 20% autonomous in 2035 (Litman, pg. 20).

is a concern, then some combination of road pricing and land use policies will eventually be required to curtail the unintended consequences of "productive driving."

Some planning challenges are coming into focus. While the exact nature of the changes to be wrought by AV's is still fuzzy, some upcoming tasks are becoming clear. Engineers and planners will need to consider the following in the years to come:

- *Exclusive lane designation*. Engineers will need to begin identifying the point at which it makes sense to dedicate lanes to AV's. This will require making decisions regarding the level of service that should be maintained for non-AV's. Who should be given priority when allocating infrastructure, AV's or non-AV's? This is the sort of question that transportation professionals will likely need to grapple with in years ahead.
- *Regional model updates*. The nature of trip-making will change when AV's become a more prevalent portion of the vehicle fleet. The advent of empty trips (e.g. cruising between one drop-off and a subsequent pick-up), the addition of new trips (primarily related to underserved populations such as underage drivers and the elderly), and changes in parking patterns will combine to alter prevailing transportation patterns. As a result, planners will need to continually monitor evolving trends in order to keep regional models current and relevant.
- *Consistency in signing*. The Rand report provided the following short-term recommendation for State DOT's: "Require stricter conformance to road signing requirements, particularly those that involve construction or some alteration to the roadway. This would both aid human drivers and ease some of the perception requirements for AV's."[30] Testing has consistently revealed that AV's have had some of their most challenging passages through traffic incidents and work zones. The more uniform the implementation of traffic control measures in such instances, the greater the likelihood of successful AV navigation.

The imminent growth of AV's portends changes in infrastructure. However, as VTPI notes, "To be prudent, such infrastructure changes should only occur after autonomous vehicle benefits, affordability and public acceptance are fully demonstrated." Planners should be vigilant but not hasty.

All signs point to caution. At this point, the only certainty with respect to autonomous vehicles is that the technology is advancing rapidly in the wake of billions of dollars spent in research and development. The pace with which the technology will roll out and be embraced by the traveling public, as well as the ramifications of this technology for the world of transportation, are still clouded in uncertainty.

Therefore, most advisors are suggesting cautious moves for public sector agencies. As the Rand report notes, "at this point, aggressive policymaker intervention is premature and would probably do more harm than good."[31]

6. Possible Timeframe for AV Deployment

A review of the literature suggests that the timeframe during which AV's will penetrate America's vehicle fleet will be better measured in *decades* than *years*. The subsections that follow present four key factors that will combine to prolong the deployment of autonomous vehicles.

[30] Anderson, pg. 21.
[31] Anderson, pg. 24.

Factor #1 – More Technological Progress Is Needed

The Victoria Transport Policy Institute report cites several authorities that warn against an overly-ambitious view of the rapid deployment of fully autonomous vehicles.[32] According to this report:

- Artificial intelligence expert Yoshua Bengio has stated, "I think people underestimate how much basic science still needs to be done before these cars or such systems will be able to anticipate the kinds of unusual, dangerous situations that can happen on the road."
- Raquel Urtasun, director of Uber's self-driving vehicle lab, said, "Having self-driving cars at a smaller scale, on a small set of roads, we are fairly close. To see at an Uber scale we are far…Nobody has a solution to self-driving cars that is reliable and safe enough to work everywhere."
- Gill Pratt, CEO of the Toyota Research Institute, has stated that autonomous driving "is a wonderful goal, but none of us in the automobile or IT industries are close to achieving true Level 5 autonomy."
- Huei Peng, director of the Michigan Mobility Transformation Center, said that "it may be decades before a vehicle can drive itself safely at any speed on any road in any weather."

In short, AV technology is still years away from being able to handle "exceptional" conditions that, while rare, are nevertheless an integral part of achieving true Level 5 autonomy.

Factor #2 – Lessons from History

History suggests that major automotive innovations can take decades to become commonplace. For example:

- *Automatic transmissions.* The first automatic transmission was introduced in 1940 model year vehicles. However, they were not both consistently reliable and affordable in North America until the 1980's.
- *Air bags.* Ford and General Motors began to offer cars equipped with air bags in the early 1970's. However, air bags did not become commonplace in American cars until the 1990's.
- *In-vehicle navigation*. The first in-vehicle navigation systems rolled out in the early 1980's. However, their growth was initially very slow. Two events (spaced years apart) helped to open in-vehicle navigation to the traveling public. First, in 2000, President Clinton signed a bill ordering the military to cease the scrambling of GPS signals used by civilians. This provided for the *availability* of highly-reliable positioning data. Second, the smartphone revolution that began in 2007 with the first release of the iPhone provided a means of delivering the now-available GPS data to the masses. Today, it is likely that over 80% of drivers have in-vehicle navigation at their fingertips via the smartphone.
- *Hybrids.* Hybrids are an example of technology that showed initial promise yet grew slowly. In fact, hybrids today appear to be in decline. The first commercially-available hybrids were available in 1997. Their market share reached a peak of 3.3% in 2012, when fuel prices were flirting with all-time highs. However, the combined effects of declining fuel prices and growth in electric vehicles have caused hybrids to decline to a market share of about 2%.[33]

---

[32] Litman, pg. 17.

[33] Litman (pp. 18-19) discusses various technologies and deployment timeframes.

As the examples above illustrate, even the fastest-moving advances have taken 20 years or more to become commonplace. Factors that contribute to a longer timeframe are *expense* and *proven benefits*. Hybrid technology, which was relatively expensive and provided modest benefits (in the context of declining fuel prices), was slow to become mainstream. By contrast, in-vehicle navigation—a very helpful technology that became virtually free as smartphones became ubiquitous—burst onto the scene relatively quickly. AV technology will likely be slow to become mainstream until its costs are reasonable and its benefits are clear.

Factor #3 – Non-Technological Barriers to Deployment

The barriers to deployment of AV technology are not purely technological. Numerous parties have a stake in the ultimate deployment of autonomous vehicles, including policymakers, regulators, insurance providers, the environmental lobby, and consumer advocates. Navigating the social, legal, and regulatory challenges of AV's could be more daunting than the technological hurdles. Ajay Chopra of Fortune magazine summed up the coming conflicts when he recently wrote, "AV technology is improving rapidly. Soon technological capability won't be the greatest impediment to adoption; societal friction will be. This friction will delay full autonomy for at least a decade…"[34]

Factor #4 – The Fleet Replacement Process

Replacement of the vehicle fleet is a gradual process, especially given the improvement in quality and durability of vehicles in recent decades. It takes an estimated 15 years for the existing vehicle fleet to be replaced. This means that once fully autonomous vehicles are available, it will still take approximately 15 years before they dominate the marketplace. And that figure would only hold true if all new vehicles being purchased were autonomous. Given that (a) non-autonomous vehicles will almost certainly continue to be manufactured and sold, even after fully autonomous vehicles are deployed; and (b) autonomous vehicles will be considerably more expensive than conventional automobiles, it is plausible that the fleet replacement cycle could extend for 20 to 25 years or beyond.

Given these considerations, it is difficult to pinpoint the likely time at which AV's will rule the road. The Reason Foundation asserts that full fleet replacement is at least 30 years away—10 years to work through the technological, legal, and regulatory barriers, and 20 years to permeate the vehicle fleet.[35] Todd Litman of the VTPI provides a longer-term estimate, asserting it will take 30-50 years for AV's to reach 90% market share.[36] Both Reason and the VTPI agree that AV's won't reach 50% market share for at least 20 years. This suggests that transportation planning can move forward with reasonable confidence that the vehicle fleet will be majority human-driven through approximately 2038.

---

[34] http://fortune.com/2017/07/22/driverless-cars-autonomous-vehicles-self-driving-uber-google-tesla/

[35] Poole, Robert. What Do Autonomous Vehicles Mean for the Future of U.S. Highways? Reason Foundation Commentary posted on January 6, 2016. Available on-line at https://reason.org/commentary/what-do-autonomous-vehicles-mean-fo/

[36] Litman, pp. 19-20.

7. Summary

Considerable technological advancement has been made in the development of autonomous vehicles. Entities such as Waymo, Uber, and Tesla routinely make headlines, pushing the envelope with respect to self-driving vehicles. Nearly every major automobile manufacturer has established a projected release date for delivery of autonomous vehicles. Clearly, the race is on.

Nevertheless, the consensus is that we are still about 10 years away from the point at which fully autonomous vehicles are legally driving on America's public highways. Both technological and institutional barriers remain that will slow the march to full autonomy.

It is generally believed that the advent of AV's will ultimately increase the number of vehicle-miles driven nationally. This is primarily due to the convergence of three factors: (1) the diminished "productivity cost" of driving will tend to induce more travel; (2) population groups that are currently underserved (e.g. underage drivers and the elderly) will have new mobility options; and (3) movements made by empty vehicles will add perhaps 10-13% to the "occupied" VMT total.

Whether the additional VMT will cause more congestion, or whether the additional VMT will be offset by AV-related capacity improvements, is a matter of debate.

In the future, engineers and planners will need to grapple with issues such as dedicated AV lanes, roadway redesign, road pricing, and land use policies. But before these issues come to the fore, it will be necessary to establish a legal and regulatory framework that will enable the testing of AV's in actual conditions. Further design and implementation of AV-related infrastructure should only proceed if the tests are successful, provide clear benefits, and are broadly accepted by the public.

The research did not uncover anything to suggest that traditional planning processes should be put on hold pending greater clarity with AV development. There is no reason to believe that fully autonomous vehicles alone will bring congestion relief within the next 20 years. In fact, it's possible that AV's will create more congestion.

The Maine Turnpike Authority should move forward with its long-range planning, being mindful that AV development is ongoing and should be monitored.

8. References

Anderson, James et al. *Autonomous Vehicle Technology: A Guide for Policymakers*. Rand Corporation, 2016.

Eno Center for Transportation. *Preparing a Nation for Autonomous Vehicles*: *Opportunities, Barriers, and Policy Recommendations*. October 2013.

KPMG. *The Clockspeed Dilemma*. November 2015. Internet document accessed at: https://assets.kpmg.com/content/dam/kpmg/pdf/2016/04/auto-clockspeed-dilemma.pdf

Litman, Todd. *Autonomous Vehicle Implementation Predictions*. Victoria Transport Policy Institute, December 2017.

Lutin, Kornhauser, & Lam. *The Revolutionary Development of Self-Driving Vehicles and Implications for the Transportation Engineering Profession*. April 2013. Document accessed at: http://orfe.princeton.edu/~alaink/SmartDrivingCars/Papers/ITE_Journal_The%20Revolutionary%20Development%20of%20Self-Driving%20Vehicles%20and%20Implications%20for%20the%20Transportation%20Engineering%20Profession.pdf

Madrona Venture Group. *Convert I-5 into an Autonomous Vehicle Corridor*. White paper presented at the 2017 Cascadia Corridor Innovation Conference. Accessed on-line at: http://www.madrona.com/wp-content/uploads/2017/09/MVG-I5-Proposal-Digital.pdf

Poole, Robert. *What Do Autonomous Vehicles Mean for the Future of U.S. Highways?* Reason Foundation Commentary posted January 6, 2016.