

# Autonomous Vehicle Implementation Predictions *Implications for Transport Planning*

26 November 2018

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*Waymo's self-driving taxis are a well-publicized example of autonomous vehicles.*

## Abstract

This report explores autonomous (also called *self-driving*, *driverless* or *robotic*) vehicle benefits and costs, and impacts on transportation planning issues. It investigates how quickly self-driving vehicles are likely to be developed and deployed based on experience with previous vehicle technologies, their benefits and costs, and how they are likely to affect travel demands and planning decisions such as optimal road, parking and public transit supply. This analysis indicates that some benefits, such as more independent mobility for affluent non-drivers, may begin in the 2020s or 2030s, but most impacts, including reduced traffic and parking congestion (and therefore infrastructure savings), independent mobility for low-income people (and therefore reduced need for public transit), increased safety, energy conservation and pollution reductions, will only be significant when autonomous vehicles become common and affordable, probably in the 2040s to 2050s, and some benefits may require prohibiting human-driven vehicles on certain roadways, which could take even longer.

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## Introduction

The future is ultimately unknowable, but planning requires predictions of impending conditions and needs (Shaheen, Totte and Stocker 2018). Many decision-makers and practitioners (planners, engineers and analysts) wonder how autonomous (also called *self-driving* or *robotic*) vehicles will affect future travel, and planning for roads, parking and public transit systems, and whether public policies should encourage or restrict their use (APA 2016; Grush and Niles 2018; Guerra 2015; Kockelman, et al. 2016; Levinson 2015; Milakis, van Arem and van Wee 2017).

There is considerable uncertainty about these issues. Optimists predict that by 2030, autonomous vehicles will be sufficiently reliable and affordable to replace most human driving, providing independent mobility to non-drivers, reducing driver stress and tedium, and be a panacea for congestion, accident and pollution problems (Johnston and Walker 2017; Keeney 2017; Kok, et al. 2017). However, there are good reasons to be skeptical of such claims.

Most optimistic predictions are made by people with financial interests in the industry, based on experience with electronic innovations such as digital cameras, smart phones and the Internet. Their analysis often overlooks significant obstacles and costs. Although vehicles can now operate autonomously under certain conditions, many technical problems must be solved before they can operate autonomously in all conditions, and those vehicles must be tested, approved for general commercial sale, affordable to most travellers, and attractive to consumers. Motor vehicles last much longer and cost much more than personal computers, cameras or telephones, so new technologies generally require many years to penetrate vehicle fleets. A failure by a camera, telephone or the Internet can be frustrating but are seldom fatal; system failures by motor vehicles can be frustrating *and* deadly to occupants and other road users. Autonomous driving can induce additional vehicle travel which can increase traffic problems. As a result, autonomous vehicles are likely take longer to saturate their markets and will provide smaller net benefits than optimists predict.

These factors have significant transport policy and planning implications (Papa and Ferreira 2018; Speck 2017). Vehicles rely on public infrastructure and impose external costs, and so require more public planning and investment than most other technologies. For example, autonomous vehicles can be programmed based on user preferences (maximizing traffic speeds and occupant safety) or community goals (limiting speeds and protecting other road users), and many predicted autonomous vehicle benefits, including congestion and pollution reductions, require dedicated lanes to allow *platooning* (numerous vehicles driving close together at relatively high speeds). Policy makers must decide how to regulate and price autonomous driving, and when potential benefits justify dedicating traffic lanes to their exclusive use.

This report explores these issues. It investigates, based on experience with previous vehicle technologies, how quickly self-driving vehicles are likely to be developed and deployed, critically evaluates their likely benefits and costs, and discusses their likely travel impacts and their implications for planning decisions such as optimal road, parking and public transit supply.

## Autonomous Vehicle Operational Models

The Society of Automobile Engineers (SAE) defined five levels of autonomous driving, as summarized in Exhibit 1. Levels 1-3 require a licensed driver, but levels 4 and 5 allow driverless operation, which is necessary for many predicted benefits.

**Exhibit 1 Automated Driving Levels (SAE J3016 2014)**

	Human Driver	Automated Systems	Steering and Acceleration/Deceleration	Monitoring of Driving Environment	Fallback When Automation Fails	Automated System is in Control	BASt level	NHTSA level
Human Driver Monitors the Driving Environment	0	NO AUTOMATION				n/a	Driver Only	0
	1	DRIVER ASSISTANCE				Some Driving Modes	Assisted	1
	2	PARTIAL AUTOMATION				Some Driving Modes	Partially Automated	2
Automated Driving System Monitors the Driving Environment	3	CONDITIONAL AUTOMATION				Some Driving Modes	Highly Automated	3
	4	HIGH AUTOMATION				Some Driving Modes	Pully Automated	3/4
	5	FULL AUTOMATION					-----	3/4

The SAE defines five vehicle automation levels. Most predicted benefits require levels 4 or 5.

Exhibit 2 summarizes three autonomous vehicle operational models.

**Table 2 Autonomous Vehicle Operational Models Compared**

	Advantages	Disadvantages	Appropriate Users
<i>Personal autonomous vehicles</i> - Motorists own or lease their own self-driving vehicles	High convenience. Available without delay. Items, such as equipment, tools and snacks, can be left in vehicles.	High costs. Does not allow users to choose different vehicles for different trips, such as cars for commuting or trucks for errands.	People who travel a lot, reside in sprawled areas, want a particular vehicle, or leave items in their vehicles.
<i>Shared autonomous vehicles</i> - Self-driving taxis transport individuals and groups to destinations.	Users can choose vehicles that best meet their needs. Door to door service.	Users must wait for vehicles. Limited service (no driver to help passengers carry luggage safely reach their door). Vehicles may be dirty.	Lower-annual-mileage users.
<i>Shared autonomous rides</i> - Self-driving vans (micro-transit) take passengers to or near destinations.	Lowest costs.	Least convenience, comfort and speed, particularly in sprawled areas.	Lower-income urban residents.

*Autonomous vehicles can be personal or shared. Each model has advantages and disadvantages.*

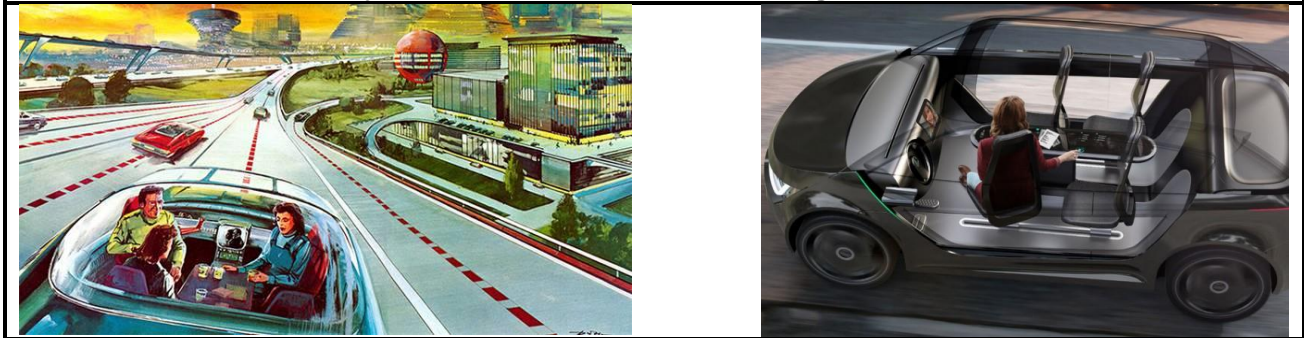
## Benefits and Costs

Autonomous vehicles can provide various benefits and impose various costs.

### *Reduced Stress, Improved Productivity and Mobility*

Autonomous vehicles can reduce driver stress and tedium. Self-driving cars can be mobile bedrooms, playrooms and offices, as illustrated below, allowing passengers to rest or be productive while travelling (WSJ 2017). This can reduce travel time unit costs.

#### **Exhibit 3      Productivity and Relaxation While Travelling**



*Self-driving cars can be mobile bedrooms, playrooms or offices, allowing travellers to rest and work.*

On the other hand, self-driving vehicles can introduce new stresses and discomforts. To minimize cleaning and vandalism costs, self-driving taxis and buses will have “hardened” interiors (vinyl seats and stainless steel surfaces), minimal accessories, and security cameras. Demand response ridesharing (vehicles with flexible routes to pick up and drop off passengers at or near their destinations) will reduce security (passengers may need to share space with strangers), and reduce travel speed and reliability since each additional pick-up or drop-off will impose a few minutes of delay to other passengers, particularly in sprawled areas with dead-end streets. Grush (2016) suggests that travellers will experience “access anxiety,” if they fear that their vehicle cannot reach a desired destination.

Autonomous vehicles can provide independent mobility for non-drivers, including people with disabilities, adolescents, and others or who for any reason cannot or should not drive. This directly benefits those travellers, reduces chauffeuring burdens on their family members and friends, and improves their access to education and employment opportunities, increasing their economic productivity. Some affluent non-drivers living in sprawled areas may purchase personal autonomous vehicles, and urban non-drivers are likely to use autonomous taxis.

Optimistic predictions of autonomous vehicle benefits may cause some communities to reduce support for public transit services which may reduce mobility options for non-drivers. Dedicating highway lanes for autonomous vehicle platooning may reduce capacity for human-operated traffic, making travellers in human-operated vehicles worse off.



### **The Autonomous Vehicle Travel Experience**

Autonomous vehicles are often illustrated (see below) with happy, well-dressed passengers lounging or working in tidy self-driving cars that look like science fiction spaceships. However, the actual experience will probably be less idyllic.



Self-driving vehicles will allow all vehicle occupants to rest, read, work and watch television (rather than only listen to audio), but for safety sake they should wear seatbelts, and like any confined space, vehicle interiors can become cluttered and dirty. Manufacturers will probably produce vehicles with seats that turn into beds and mobile offices (NYT 2017). For the foreseeable future autonomous vehicles are likely to be and unable to operate in heavy rain and snow, or on unpaved roads, and relatively slow and unreliable in mixed urban traffic.

Self-driving taxi and “micro-transit” (van) services will be cheaper than human-operated taxis, but offer minimal service quality. To minimize cleaning and vandalism costs most surfaces will be stainless steel and plastic, and passengers will be monitored by security cameras, yet passengers may still encounter previous occupants’ garbage, stains and odors (Broussard 2018). There will be no drivers to help carry packages or ensure passenger safety.

Like other public transportation, autonomous micro-transit will require passengers to share interior space with strangers, who are mostly friendly and responsible but occasionally unpleasant and frightening. Each additional passenger will add pickup and drop-off delays, particularly for passengers with special needs, such as packages, children or disabilities, who need extra time, and in more sprawled areas with dead-end streets where an additional stop can add several minutes. Because of these limitations, autonomous taxi and micro-transit will most suited to local urban trips, and many travellers will choose to own their own vehicle, or have a human operator, despite the extra cost.

Once the novelty wears off, autonomous vehicle travel will be considered utilitarian and tedious, a useful but not particularly enjoyable or glamorous mobility option, more like an elevator than a spaceship.

### Ownership and Operating Costs

Autonomous vehicles will require additional equipment and services summarized in the box below. Such technologies can add thousands of dollars to vehicle purchase prices and hundreds of dollars of annual fees. For example, a package of optional electronic features such as remote starting, high beam assist, active lane assist, adaptive cruise control and top view camera typically increases new vehicle prices by more than \$5,000, and navigation and security services, such as OnStar and TomTom, cost \$200-600 per year. Since failures could be deadly, autonomous driving systems will need robust, redundant and abuse-resistant components maintained by specialists, similar to aviation service standards, further increasing costs. To monitor passenger behavior, autonomous vehicles will also require in-vehicle security cameras and enforceable behavior rules, plus frequent interior cleaning and repairs (Broussard 2018).

#### **Exhibit 4      Autonomous Vehicle Equipment and Service Requirements**

All Autonomous Vehicles	Shared Autonomous Vehicles
<ul style="list-style-type: none"><li>• Sensors (optical, infrared, radar, laser, etc.).</li><li>• Automated controls (steering, braking, signals, etc.)</li><li>• Software, servers and power supplies.</li><li>• Wireless networks. Short range vehicle-to-vehicle communications and long-range access to maps, software upgrades and road reports.</li><li>• Navigation. GPS systems and special high quality maps.</li><li>• Critical component testing and maintenance.</li></ul>	<ul style="list-style-type: none"><li>• Frequent cleaning and repairs.</li><li>• Dispatching and fleet management.</li><li>• Business administration and insurance.</li><li>• Business profits.</li><li>• Security.</li><li>• Delays and empty vehicle-miles for passenger pick-up and drop-off.</li></ul>

*Autonomous vehicles, particularly those that are shared, will incur additional costs.*

This suggests that Level 4 and 5 autonomous driving capabilities will probably increase vehicle purchase prices by several thousands of dollars and require hundreds of dollars in additional annual services and maintenance costs, adding a few thousand dollars per vehicle-year for the foreseeable future (one to three decades). Experience with previous vehicle innovations, such as automatic transmissions and airbags, discussed later in this report, suggests that autonomous driving capability will initially be available only on higher priced models, and will take one to three decades to be incorporated into middle- and lower-priced models.

Advocates argue that these additional costs will be offset by insurance and fuel cost savings, but that seems unlikely. For example, if autonomous driving cuts insurance costs in half, the \$300-500 annual savings is just 10-20% of estimated additional costs. Additional equipment and larger vehicles to serve as mobile offices and bedrooms are likely to increase rather than reduce energy consumption. Electric vehicles have low fuel costs, in part because they currently pay no road user fees comparable to motor vehicle fuel taxes; cost-recovery road-user fees would increase electric vehicle operating costs 5-10¢ per vehicle-mile (FHWA 2015).

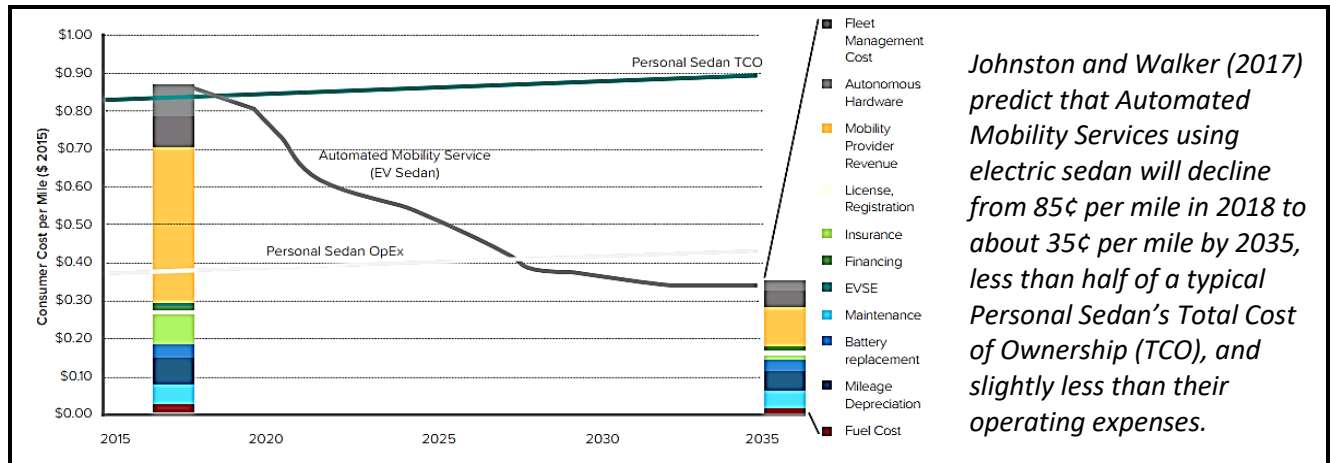
### Cleaning – An Often Overlooked Cost

Although most autonomous taxi passengers are likely to be courteous and responsible, some will probably be messy and a few vandalous. To discourage abuse, autonomous taxis will have surveillance cameras, and their interiors will be plastic and chrome, which may reduce but cannot eliminate these problems, so vehicles will occasionally contain garbage and unpleasant odors, or be damaged.

Autonomous taxis will therefore require frequent inspections and cleaning. They will probably need a quick cleaning that includes an inspection, garbage pick-up, vacuuming and surface wipe-downs approximately every five to ten pick-ups, more comprehensive interior and exterior cleaning each day, plus occasional repairs. Assuming \$5-10 per cleaning this will add \$0.50-1.00 per trip, or 5-10¢ per vehicle-mile, plus travel time and costs for driving to cleaning stations.

This indicates that for the foreseeable future (one to three decades) autonomous vehicle costs will probably average (total annual costs divided by annual mileage) \$0.80-\$1.20 per vehicle-mile, which may eventually decline to \$0.60-\$1.00 per mile, which is somewhat more expensive than human-operated vehicles' \$0.40-\$0.60 per mile average costs (Stephens, et al. 2016). Johnson and Walker (2017) predict that shared, electric, autonomous taxis cost will decline from about 85¢ per vehicle-mile in 2018 to 35¢ per mile by 2035 (Exhibit 5), but they overlook some previously-mentioned costs such as cleaning and roadway user fees, and so are probably underestimates. Shared autonomous rides (self-driving public transit) will probably cost \$0.20-0.40 per passenger-mile, assuming that they average 3-6 passengers (Bösch, et al. 2017).

**Exhibit 5 Automated Versus Personal Car Costs**



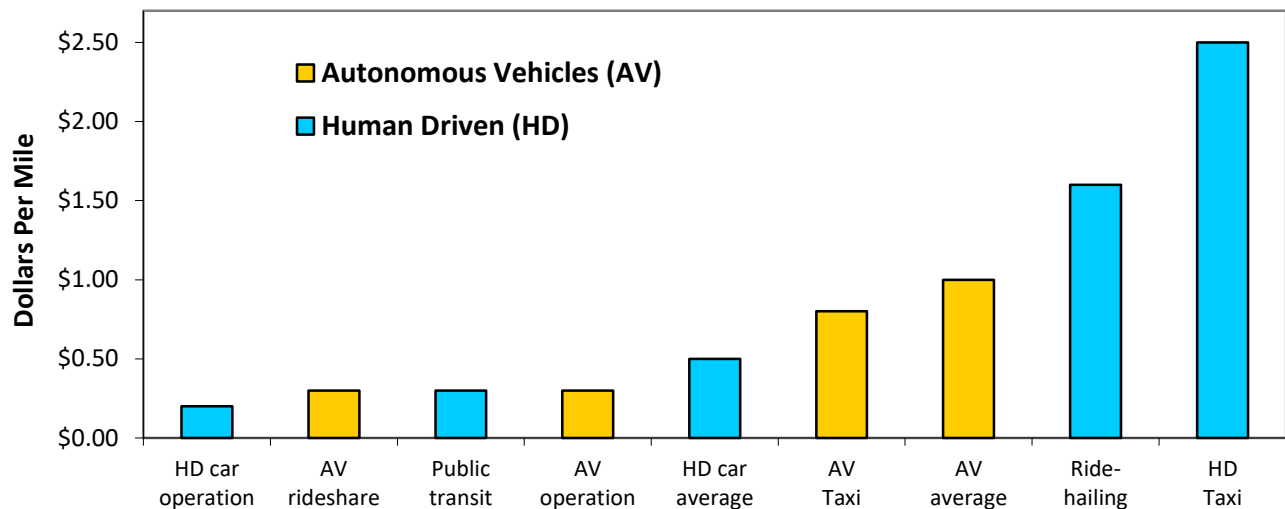
Some studies estimate lower costs (Keeney 2017). For example, Kok, et al. (2017) predict that shared, electric autonomous vehicles operating costs will be less than 10¢ per mile, so their use can be funded through advertising, but such estimates ignore significant costs such as vehicle maintenance and cleaning, business profits, empty vehicle-travel, insurance (based on optimistic assumptions of autonomous vehicle safety), and roadway costs (they assume that electric vehicles should continue to pay no road user fees), and so are probably underestimates.



Automobiles currently have about \$3,600 in fixed expenses (financing, depreciation, insurance, registration fees, residential parking and scheduled maintenance) and \$2,400 in variable expenses (fuel, oil, tire wear and paid parking), and are driven about 12,000 annual miles, which averages about 50¢ per mile, of which about 20¢ per mile is operating expenses (AAA 2017; Litman 2009). Human-operated taxis generally cost \$2.00-\$3.00 per mile, ride-hailing (also called *ridesourcing* and *Transportation Network Companies*, such as Uber and Lyft) about \$1.50-2.50 per mile, and conventional public transit 20-40¢ per mile.

The following figure compares these costs. *Average costs* are what travellers consider when deciding whether to purchase a vehicle; *operation costs* are what vehicle owners consider when deciding how to make a particular trip.

**Exhibit 6 Cost Comparison**



*Autonomous vehicles (AVs) are predicted to cost less than human-driven taxis and ride-hailing services, but more than human-driven personal vehicles (HVs) and public transit services.*

This indicates that in the future personal autonomous vehicles will continue to cost more than human-operated vehicles, but shared autonomous vehicles will be cheaper than human-operated ride-hailing and taxi services. Since most vehicle costs are fixed, owners of personal autonomous vehicles will have little financial incentive to use shared vehicles. However, the availability of shared autonomous vehicles may encourage more households to reduce their vehicle ownership, and so reduce their annual vehicle travel, as discussed later in this report.

Autonomous vehicles can provide large savings for commercial vehicles, such as freight trucks and buses, where driver wages and benefits are a major portion of total costs, although many delivery vehicles require an operator to unload goods.

### Traffic Safety

Optimists claim that, because human error contributes to 90% of crashes, autonomous vehicles will reduce crash rates and insurance costs by 90% (Fagnant and Kockelman 2013; Kok, et al. 2017; McKinsey 2016), but this overlooks additional risks these technologies can introduce (Hsu 2017; ITF 2018; Kockelman, et al. 2016; Koopman and Wagner 2017; Ohnsman 2014):

- *Hardware and software failures.* Complex electronic systems often fail, and even small vehicle operating system failures - a false sensor, distorted signal, or software error - can have catastrophic results. Self-driving vehicles will certainly have failures that contribute to crashes; the question is their frequency compared with human drivers.
- *Malicious hacking.* Self-driving technologies can be manipulated for amusement or crime.
- *Increased risk-taking.* When travellers feel safer they often take additional risks, called *offsetting behavior* or *risk compensation*. For example, if autonomous vehicles are considered very safe, passengers may reduce seatbelt use and other road users may be less cautious (Millard-Ball 2016), described as “over-trusting” technology (Ackerman 2017).
- *Platooning risks.* Many potential benefits, such as reduced congestion and pollution emissions, require *platooning* (vehicles operating close together at high speeds on dedicated lanes), which can introduce new risks, such as human drivers joining platoons and increased crashes severity.
- *Increased total vehicle travel.* By improving convenience and comfort autonomous vehicles may increase total vehicle travel and therefore crash exposure (Trommer, et al. 2016; WSJ 2017).
- *Additional risks to non-auto travellers.* Autonomous vehicles may have difficulty detecting, communicating with and accommodating pedestrians, bicyclists and motorcycles (PBIC 2017).
- *Reduced investment in conventional safety strategies.* The prospect of autonomous vehicles may reduce future efforts to improve driver safety (Lawson 2018).

Reports by eight companies operating autonomous test vehicles in 2017 indicate that *disengagements* (when human drivers override automated systems) exceeded one per 5,600 miles (Edelstein 2018). Common problems included failing to recognize a “no right turn on red signal,” cars that planned to merge into traffic with insufficient space, failing to brake enough at a stop, difficulty detecting vehicles approaching in opposite lanes, problems maintaining GPS location signals, software crashes, inability to recognize construction cones, confusion over unexpected behavior by other drivers, plus other hardware and software problems.

These new risks will probably cause crashes, so net safety impacts are likely to be smaller than the 90% reductions that advocates claim. Sivak and Schoettle (2015a) conclude that autonomous vehicles may be no safer per mile than an average driver, and may increase total crashes when self- and human-driven vehicles mix. Groves and Kalra (2017) argue that autonomous vehicle deployment is justified even if they only reduce crash rates 10%, but their analysis indicates that net safety gains are significantly reduced if this technology increases total vehicle travel. For example, if autonomous vehicles reduce per-mile crash rates 10% but increase vehicle travel 12%, total crashes, including risks to other road users, will increase.

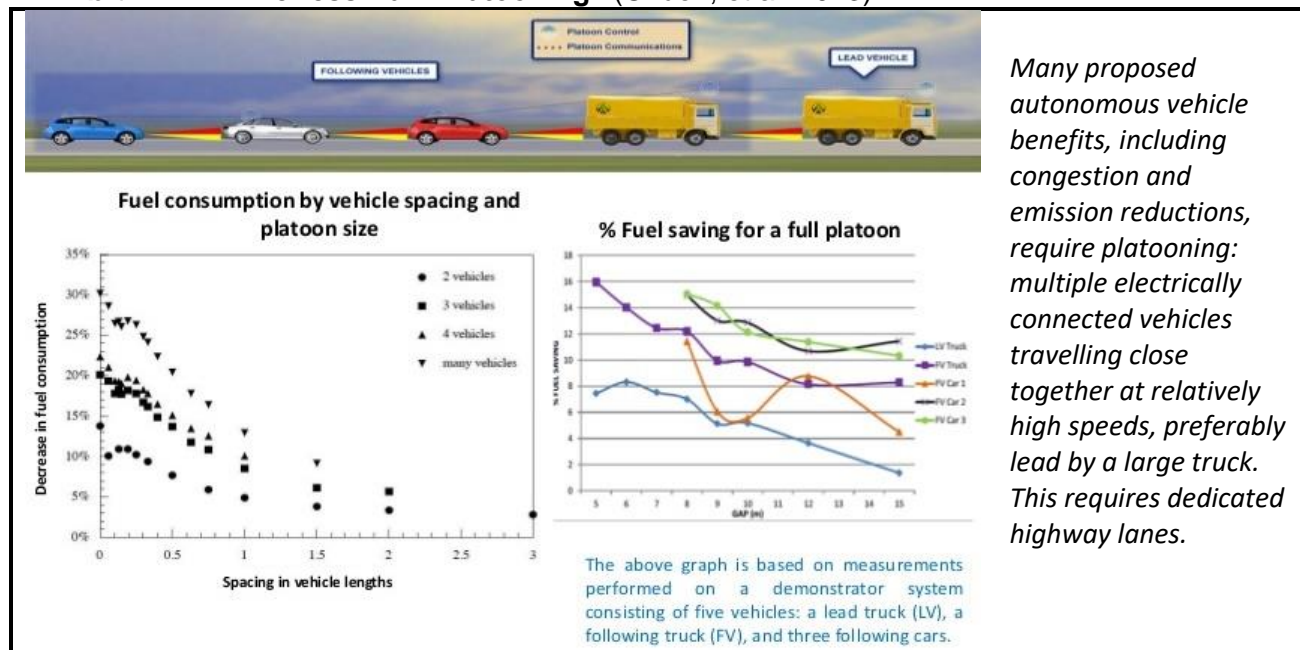
Shared autonomous vehicles can reduce crashes by providing more affordable alternatives to higher-risk drivers. Efforts to reduce higher-risk driving, such as graduated driver's licenses, special testing for senior drivers, and anti-impaired driver campaigns, can be more effective and publicly acceptable if affected groups have convenient and affordable mobility options.

Many factors will affect these safety impacts, including how vehicles are programmed, and whether they increase or reduce total vehicle travel. For example, to maximize mobility autonomous vehicles can be programmed to operate faster, take more risks in unpredictable situations, and platoon; to maximize safety they can be programmed to drive slower, be more cautious, for example, stopping for human instructions in any unexpected situation, and high occupant vehicle (HOV) lanes and road pricing can encourage vehicle sharing.

### External Cost

Advocates claim that autonomous driving will reduce external costs including traffic congestion, energy consumption, pollution emissions, roadway and parking facility costs, although those benefits are uncertain (Eddy and Falconer 2017). To be more space and energy efficient autonomous vehicles require dedicated lanes for platooning (Exhibit 7). This is only feasible on grade separated highways.

#### Exhibit 7 Driverless Car "Platooning" (Chuen, et al. 2013)



Many proposed autonomous vehicle benefits, including congestion and emission reductions, require platooning: multiple electrically connected vehicles travelling close together at relatively high speeds, preferably lead by a large truck. This requires dedicated highway lanes.

Autonomous operation can increase congestion, energy, pollution and roadway costs. By increasing total vehicle travel and vehicle size (if cars become moving offices and bedrooms, as some experts predict) they may increase total pollution emissions. Optimists assume that autonomous vehicles will reduce pollution because they will be all electric and mostly shared,

but as discussed previously, many users will probably choose personal autonomous vehicles, unless widely applied public policies, such as high fossil fuel taxes and high occupancy vehicle lanes on congested roadway, favor electric and shared vehicles.

If they strictly follow traffic laws and maximize caution, such as speed limits and optimal spacing between vehicles, autonomous vehicles may reduce traffic speeds under many conditions. Because some passengers want to rest or work, many users may program their vehicle to accelerate and decelerate more slowly than normal human drivers, reducing traffic speeds (Le Vine, Zolfaghari and Polak 2015). If programmed to wait for human instructions in unexpected conditions, they may frequently block traffic.

Self-driving technologies requires additional equipment, and vehicle manufactures are likely to market seats that turn into beds and mobile offices, which can increase energy consumption and emissions. Autonomous vehicles may require higher roadway maintenance standards, such as clearer line painting and special traffic signals (Lawson 2018). Autonomous vehicles can reduce parking facility costs by allowing vehicles to park further from destinations, but most users will probably want their vehicles available within five or ten minutes, and so must park within a mile or two. Their impacts on overall congestion, energy, emissions and crash costs will depend on how self-driving technologies affect total travel and urban development patterns, as discussed later in this report.

### *Benefit and Cost Summary*

This review indicates that autonomous vehicles are likely to have both benefits and costs (Milakis, van Arem and van Wee 2017). Some of these impacts, including increased vehicle costs, reduced driver stress and productivity gains, directly affect users. Others, such as changes in roadway costs, congestion, accident risk, pollution, and mobility options for non-drivers, are external impacts. The total magnitude of these impacts will depend on how the technologies affect vehicle travel: improved convenience and productivity cause vehicle travel to increase, traffic problems such as congestion, accidents, pollution emissions and roadway costs may increase, as ride-hailing services have done in large cities (Schaller 2017), but if more affordable shared mobility options allow households to reduce their vehicle ownership, and therefore leverage reductions in total vehicle travel, traffic problems should decline. The next section of this report explores these impacts. Exhibit 8 summarizes these benefits and costs.

**Exhibit 8 Autonomous Vehicle Potential Benefits and Costs**

	Benefits	Costs/Problems
<b>Internal (user impacts)</b>	<p><i>Reduced drivers' stress and increased productivity.</i> Motorists can rest, play and work while travelling.</p> <p><i>Mobility for non-drivers.</i> More independent mobility for non-drivers can reduce motorists' chauffeuring burdens and transit subsidy needs.</p> <p><i>Reduced paid driver costs.</i> Reduces costs for taxis and commercial transport drivers.</p>	<p><i>Increased vehicle costs.</i> Requires additional vehicle equipment, services and fees.</p> <p><i>Additional user risks.</i> Additional crashes caused by system failures, platooning, higher traffic speeds, additional risk-taking, and increased total vehicle travel.</p> <p><i>Reduced security and privacy.</i> May be vulnerable to information abuse (hacking), and features such as location tracking and data sharing may reduce privacy.</p>
<b>External (Impacts on others)</b>	<p><i>Increased safety.</i> May reduce crash risks and insurance costs. May reduce high-risk driving.</p> <p><i>Increased road capacity and reduced costs.</i> More efficient vehicle traffic may reduce congestion and roadway costs.</p> <p><i>Reduced parking costs.</i> Reduces demand for parking at destinations.</p> <p><i>Reduced energy consumption and pollution.</i> May increase fuel efficiency and reduce emissions.</p> <p><i>Supports vehicle sharing.</i> Could facilitate carsharing and ridesharing, reducing total vehicle ownership and travel, and associated costs.</p>	<p><i>Additional risks.</i> May increase risks to other road users and may be used for criminal activities.</p> <p><i>Increased traffic problems.</i> Increased vehicle travel may increase congestion, pollution and sprawl-related costs.</p> <p><i>Social equity concerns.</i> May reduce affordable mobility options including walking, bicycling and transit services.</p> <p><i>Reduced employment.</i> Jobs for drivers may decline.</p> <p><i>Increased infrastructure costs.</i> May require higher roadway design and maintenance standards.</p> <p><i>Reduced support for other solutions.</i> Optimistic predictions of autonomous driving may discourage other transport improvements and management strategies.</p>

*Autonomous vehicles can provide various benefits and costs, including external impacts on other people.*



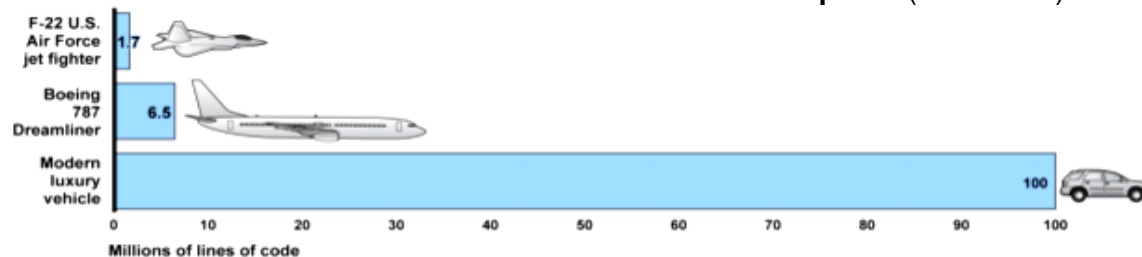
## Development and Deployment Predictions

Many current vehicles have Level 1 and 2 technologies such as cruise control, hazard warning and automated parallel parking. Tesla's *Autopilot* offers automated steering and acceleration in limited conditions, but deployment was delayed after it caused a fatal crash in 2016 (Hawkins 2017). Several companies are now implementing Level 4 pilot projects, which means that vehicles can drive themselves under certain conditions. For example, Waymo and Uber announced plans to begin testing driverless taxi services (Bergen 2017; Lee 2017). Despite this progress, significant technical progress is needed before vehicles can drive themselves under all normal conditions (Simonite 2016). For example, current autonomous vehicles cannot operate reliably in heavy rain or snow, on unpaved roads, or in mixed traffic.

Consider one challenge. For safety sake motorists are advised to *drive defensively*, which means anticipating potential risks such as wild animals and playful children. To do this, autonomous vehicles will need a database that categorizes, for example, fire hydrants as low-risk, pets on leashes as medium risk, and wild animals, such as kangaroos, as high risk. In addition, children sometimes dress in animal costumes, and adolescents in zombie variations. Most drivers can understand such risks. If I say, "Watch out for a group of teenagers in zombie kangaroo costumes," you could probably understand the threat since you too were once a playful youth, but a computer would be flummoxed: such an unusual situation is unlikely be in a standard risk database, so the vehicle would either miss-categorize it, perhaps treating costumed fun-seekers as injured crash victims or a riotous mob, or simply stop and wait for human instructions. These systems can self-learn, and so could eventually recognize new costumes and behaviors, but this will require new software coding that may interact unpredictably with other instructions. This is not to suggest that autonomous driving is impossible or inherently harmful, it simply illustrates one of many problems they face: new risks leading to solutions that further increase system complexity and therefore potential failures.

Operating a vehicle on public roads is complex due to the frequency of interactions with other, often-unpredictable objects including vehicles, pedestrians, cyclists, animals and potholes. Because of these interactions, autonomous vehicles will require orders of magnitude more complex software than aircraft (Exhibit 9). Producing such software is challenging and costly, and ensuring that it never fails is virtually impossible. There will almost certainly be system failures, including some that cause severe accidents.

**Exhibit 9** Aircraft and Automobile Software Code Compared (GAO 2016)



*Vehicles have more complex computer systems than aircraft, due to complex roadway interactions.*

Even after Level 5 technology is fully functional and reliable, additional time will be required for independent testing and regulatory approval. Because vehicles can impose significant external costs, including accident risks and delays to other road users, vehicle technologies require higher testing and regulation standards than most other technological innovations such as personal computers and mobile phones. Under optimistic conditions testing and approval will only require a few years, but the technology may prove unreliable and dangerous, for example, if it causes high-profile crashes, which could require several more years (Bhuiyan 2017). It is likely that different jurisdictions will impose different testing, approval and regulations, resulting in varying rates of deployment.

Most experts acknowledge that significant technical progress is needed before Level 5 automation is reliable, tested and approved (Mervis 2017). For example, Michigan Mobility Transformation Center director Huei Peng said that, “it may be decades before a vehicle can drive itself safely at any speed on any road in any weather” (Truett 2016). Similarly, Toyota Research Institute CEO, Gill Pratt 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” (Ackerman 2017). Uber self-driving vehicle lab director Raquel Urtasun said that, “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” (Marowits 2017).

Artificial intelligence expert Yoshua Bengio said that, “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” (Marowits 2017). Similarly, Heilbronn University artificial intelligence expert Professor Nicolaj Stache said, “The vision that drives us is to replicate the human car driver – only without replicating human mistakes. In other words, we are aiming to substitute the human brain through artificial intelligence. That’s still a long way away, but we are working on it” (Ebert 2016).

In contrast to these cautious predictions by experts, most optimistic predictions are made by people with financial interests in autonomous vehicle industries, based on experience with other types of technology. For example, the widely-cited report, *“Rethinking Transportation 2020-2030: The Disruption of Transportation and the Collapse of the Internal-Combustion Vehicle and Oil Industries”* was written by ReThink, “an independent think tank that analyzes and forecasts the speed and scale of technology-driven disruption and its implications across society.” *Mobility-As-A-Service: Why Self-Driving Cars Could Change Everything*, was published by ARK Investment Management and written by an analyst who “covers autonomous cars, additive manufacturing, infrastructure development, and innovative materials,” with little apparent experience with transportation innovation. *Automotive Revolution – Perspective Towards 2030: How the Convergence of Disruptive Technology-Driven Trends Could Transform the Auto Industry*, was published by the McKinsey Corporation, a business management firm. To their credit, such predictions are often qualified – autonomous vehicles “could” or “might” change everything – but their conclusions are repeated with certitude.

Such reports are primarily oriented toward investors and so focus on the autonomous vehicle sales potential, but policy makers and planners are interested in their fleet penetration and travel impacts. Motor vehicles are durable and expensive; consumers seldom purchase new vehicles simply to obtain a new technology, so innovations generally take decades to fully penetrate vehicle markets. As a result, even if autonomous driving technologies penetrate new vehicle markets in the 2020s, it will be the 2040s or 2050s before most vehicles are capable of autonomous driving. Optimists argue that benefits will be large enough to justify premature scrapping of most vehicle that lack autonomous driving capability, but that seems unlikely under realistic assumptions of their benefits and costs.

In addition to technological progress, market deployment depends on consumer demand: travellers' willingness to pay for autonomous mobility. Surveys indicate significant concerns about autonomous vehicle privacy and safety (Schoettle and Sivak 2014), and until they are proven reliable in all conditions, many travellers will have "access anxiety," they will fear that their vehicle cannot reach desired destinations (Grush 2017). Although current technologies allow autonomous vehicle operation in approximately 90% of conditions, achieving 99% operability (vehicles cannot reach about 1% of desired destinations, or about 10 times a year for a typical motorist) will be exponentially more difficult, and achieving 99.9% of conditions (vehicles are unable to make 0.1% of trips, or about once a year), a reasonable target for regulators and customers, will be exponentially more difficult again (Wharton 2017).

### *Experience with Previous Vehicle Technology Deployment*

Previous vehicle technologies can help predict autonomous vehicle deployment:

- *Automatic Transmissions* (Healey 2012). First developed in the 1930s, it took until the 1980s to become reliable, and affordable. When optional they typically cost \$1,000 to \$2,000. Their current new vehicle market share is about 90% in North America and 50% in Europe and Asia.
- *Air Bags* (Dirksen 1997). First introduced in 1973. Initially an expensive and sometimes dangerous option (they could cause injuries and deaths), they became cheaper and safer, were standard on some models starting in 1988, and mandated by U.S. federal regulation in 1998.
- *Hybrid Vehicles* (Berman 2011). Became commercially available in 1997, but were initially unreliable and expensive. Their performance has improved, but typically adds about \$5,000 to vehicle prices. In 2012 they represented about 3.3% of total vehicle sales.
- *Subscription Vehicle Services*. Navigation, remote lock/unlock, diagnostics and emergency services. OnStar became available in 1997, TomTom in 2002. They typically cost \$200-400 annually. About 2% of U.S. motorists subscribe to the largest service, OnStar.
- *Vehicle Navigation Systems* (Lendion 2012). Vehicle navigation systems became available as expensive accessories in the mid-1980s. In the mid-1990s factory-installed systems became available on some models, for about \$2,000. Performance and usability have since improved, and prices have declined to about \$500 for factory-installed systems, and under \$200 for portable systems. They are standard in many higher-priced models.

Exhibit 11 summarizes their deployment. Most required decades from initial commercial availability to market saturation, and some never became universal.

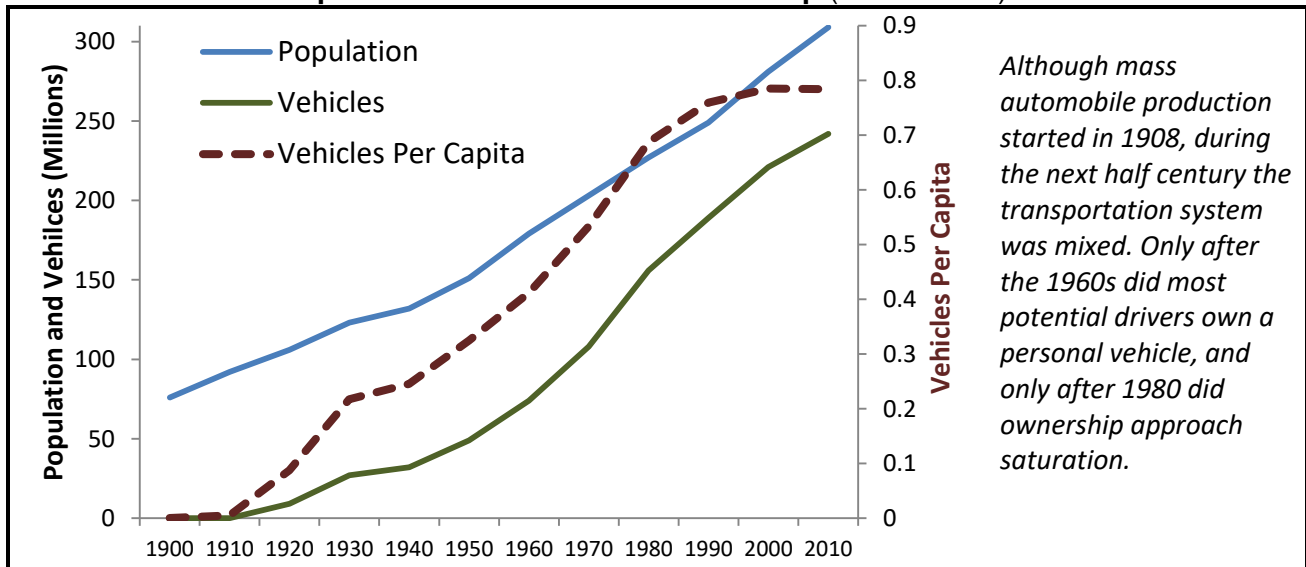
**Exhibit 11 Vehicle Technology Deployment Summary**

Technology	Deployment Cycle	Typical Cost Premium	Market Saturation Share
Automatic transmissions	50 years (1940s-90s)	\$1,500	90% U.S., 50% worldwide
Air bags	25 years (1973-98)	A few hundred dollars	100%, due to federal mandate
Hybrid vehicles	25+ years (1990s-2015+)	\$5,000	Uncertain. Currently about 4%.
Subscription services	15 years	\$250 annual	2-5%
Navigation systems	30+ years (1985-2015+)	\$500 and rapidly declining	Uncertain; probably over 80%.

*New technologies usually require several decades between commercial availability to market saturation.*

The first affordable car, Ford's Model T, began production in 1908, leading to mass automobile ownership, but for several decades the transportation system was mixed, with most travellers relying on walking, bicycling and public transit, in addition to cars. Only after the 1980s did motorization approach saturation, with most potential drivers having a personal vehicle.

**Exhibit 10 U.S. Population and Automobile Ownership (FHWA 2016)**

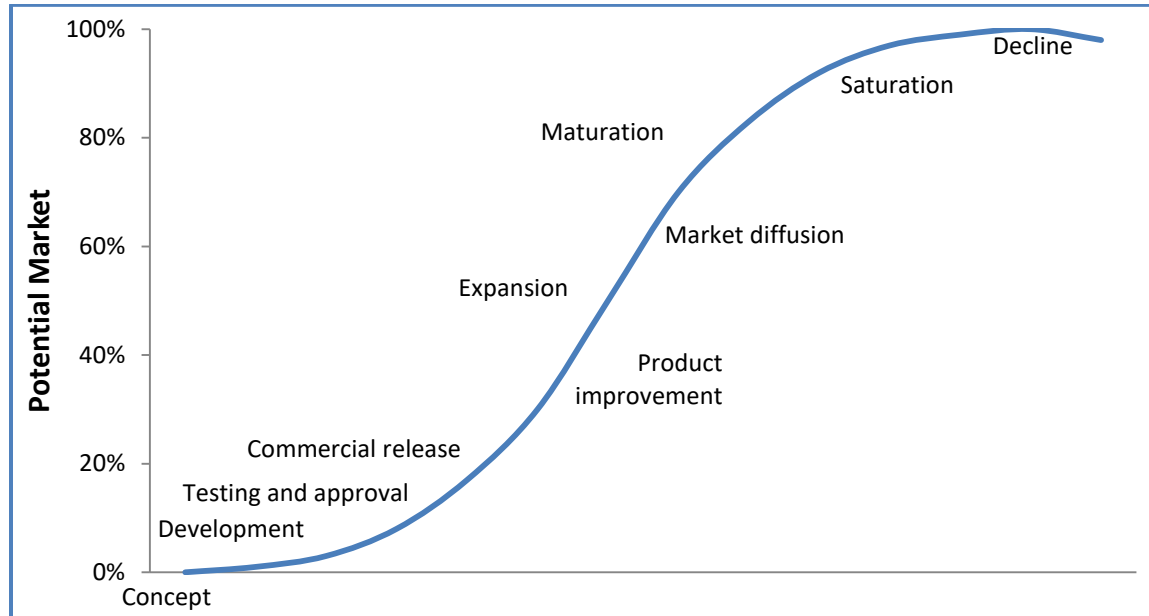


New vehicles are becoming much more durable, which reduces fleet turnover. As a result, new vehicle technologies will probably require three to five decades to penetrate 90% of vehicle fleets. Deployment may be faster in developing countries where fleets are expanding, and in areas with strict vehicle inspection requirements, such as Japan's *shaken* system. Annual mileage tends to decline with vehicle age: vehicles average approximately 15,000 miles their first year, 10,000 miles their 10<sup>th</sup> year, and 5,000 miles their 15<sup>th</sup> year, so vehicles over ten years represent about 50% of vehicle fleets but only 20% of mileage (ORNL 2012, Table 3.8).

### Innovation Deployment Patterns

Innovations generally follow a predictable S-curve deployment pattern, as illustrated in Exhibit 13. An initial concept requires development, testing, approval, commercial release, product improvement, market expansion, differentiation, maturation, and eventually saturation and decline. Autonomous vehicle technology will probably follow this pattern.

**Exhibit 12 Innovation S-Curve**



*Most products follow a predictable deployment pattern, often called in innovation S-curve.*

Autonomous vehicle technologies are currently in development, testing and approval stages. There are several stages and therefore many years, before they are widely commercially available, become reliable and affordable, and therefore start to saturate the vehicle fleet.

### Deployment Predictions

Experience with previous vehicle technologies can help predict autonomous vehicle implementation (Cathers 2014; Grush 2016; Simonite 2016). Exhibit 13 predicts autonomous vehicle sales, fleet and travel rates in future decades, assuming that Level 4-5 vehicles become commercially available in the 2020s but are initially limited in performance and expensive. Due to these limitations, during their first decade only a minority of total vehicle sales are likely to be autonomous, with market shares increasing as their performance improves, prices decline, and consumers gain confidence. In the 2040s approximately half of vehicles sold and 40% of vehicle travel could be autonomous. Without mandates, deployment will probably take several decades to reach market saturation, and a portion of motorists may continue to choose human operated vehicles due to personal preferences and cost savings.

**Exhibit 13 Autonomous Vehicle Implementation Projections**

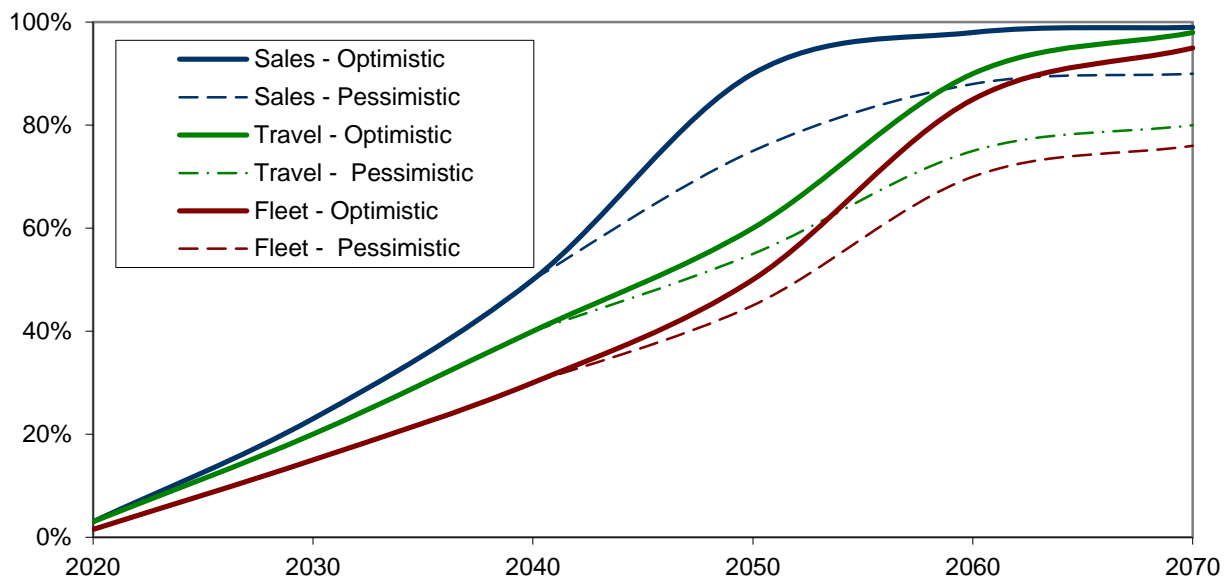


Stage	Decade	Vehicle Sales	Veh. Fleet	Veh. Travel
Available with large price premium	2020s	2-5%	1-2%	1-4%
Available with moderate price premium	2030s	20-40%	10-20%	10-30%
Available with minimal price premium	2040s	40-60%	20-40%	30-50%
Standard feature included on most new vehicles	2050s	80-100%	40-60%	50-80%
Saturation (everybody who wants it has it)	2060s	?	?	?
Required for all new and operating vehicles	???	100%	100%	100%

Autonomous vehicle implementation will probably take several decades.

Exhibit 14 illustrates these deployment rates.

**Exhibit 14 Autonomous Vehicle Sales, Fleet and Travel Projections** (Based on Exhibit 13)



*If they follow previous vehicle technologies autonomous vehicles it will take one to three decades to dominate vehicle sales, and one or two more decades to dominate vehicle travel, and even at saturation a significant portion of vehicle travel may continue to be human operated, indicated by the dashed lines.*

Because bus and truck drivers earn relatively high wages, they are likely to become automated most quickly, particularly for long-haul trips. However, professional drivers provide various services – passenger security and assistance, systems monitoring and minor repairs – that will be lost with fully automated vehicles.

Significantly faster implementation will require more rapid development, deployment and fleet turnover than with previous vehicle technologies. For example, for most vehicle travel to be autonomous by 2035, almost all new vehicles purchased after 2025 would need to be autonomous, and new vehicle purchase rates would need to triple, so fleet turnover that normally takes three decades can occur in one. This would require significant vehicle spending increases, at least in the short-run, and scraping many otherwise functional vehicles because they lack self-driving capability.

Emerging shared mobility services, such as carsharing and ride-hailing are reducing vehicle ownership and parking demand in some situations (DeLuca 2018), and could accelerate autonomous vehicle travel, but there are significant obstacles. As previously described, outside dense urban areas autonomous taxis and micro-transit are relatively inconvenient and inefficient, and so are unlikely to replace most private vehicle travel in suburban and rural areas where most Americans live.

Autonomous vehicle implementation could be slower and less complete than optimistic predictions. Technical challenges may prevent reliable and affordable autonomous vehicles from being commercially available until the 2030s or 2040s. Their costs may be higher and benefits smaller than expected. Consumer acceptance may be reduced by fears, privacy concerns, or preferences, resulting in a significant portion of vehicle travel remaining human-driven even after market saturation, indicated by dashed lines in Exhibit 15.

### Travel Impacts

Many costs and benefits will depend on how autonomous vehicles affect total vehicle travel. They can increase vehicle travel in some ways, and reduce it in others. Exhibit 15 summarizes various ways that autonomous vehicles can affect total vehicle travel.

**Exhibit 15 Autonomous Vehicle Impacts on Total Vehicle Travel**

Increases Vehicle Travel	Reduces Vehicle Travel
Increased vehicle travel by non-drivers.	More convenient shared vehicle services allow households to reduce vehicle ownership and use.
Increased convenience and productivity increases travel.	Shared autonomous vehicles reduce vehicle ownership.
Empty vehicle travel to drop off and pick up passengers	Self-driving buses can improve transit services.
Encourage sprawled development.	Reduced traffic risk and parking facilities can make urban living more attractive.
Reduces traffic congestion and vehicle operating costs, which induces additional vehicle travel.	Reduce some vehicle travel, such as cruising for parking.

*Self-driving vehicles can affect total vehicle travel (VTM) in various ways.*

Autonomous vehicles can increase vehicle travel by non-drivers, such as people with disabilities and adolescents. In a typical community they represent 10-30% of residents but many have relatively low vehicle travel demands, and are now often chauffeured by family members or friends, so self-driving vehicles should cause modest increases in their total vehicle travel.

Autonomous driving also increases driver convenience and productivity, which can stimulate vehicle travel, for example, encouraging users to choose longer commute and errand trips, and more sprawled locations (Stephens, et al. 2016). Autonomous vehicles can also stimulate empty vehicle travel, for example, when picking up or dropping off passengers, or when waiting to be summoned; it will often be cheaper for a car to drive around than to pay parking fees. With current policies these factors are likely to increase total vehicle travel.

Sivak and Schoettle (2015) estimate that accommodating non-drivers' latent travel demands could increase total vehicle up to 11%. Trommer, et al. (2016) predict that autonomous vehicles will increase total vehicle travel 3-9% by 2035. Keeney (2017) predicts a three-fold traffic increase but provides no supporting evidence.

On the other hand, affordable self-driving taxis and micro-transit may allow households to shift from owning personal vehicles to vehicle sharing. This is important because owned and shared vehicles have very different cost profiles which affect vehicle travel. Owned vehicles have high fixed (typically \$4,000 annual) and low variable costs (typically 20¢ per mile), which gives owners an incentive to maximize their driving in order to "get their money's worth," while shared vehicles, such as carsharing and taxis, have minimal fixed costs and high variable costs (typically \$0.50-2.50 per mile), giving users an incentive to minimize their vehicle travel. As a result, households tend to significantly reduce their vehicle travel, typically by 25-75%, when they shift from owning to sharing vehicles (Lovejoy, Handy and Boarnet 2013).

Advocates predict that convenient and affordable autonomous taxis will quickly displace private vehicle (ITF 2014; Keeney 2017). Kok, et al (2017), predict that, "By 2030, within 10 years of regulatory approval of fully autonomous vehicles, 95% of all U.S. passenger miles will be served by transport-as-a-service (TaaS) providers who will own and operate fleets of autonomous electric vehicles providing passengers with higher levels of service, faster rides and vastly increased safety at a cost up to 10 times cheaper than today's individually owned (IO) vehicles."

However, these predictions are based on optimistic assumptions of shared vehicle convenience and affordability. Many travellers will have good reasons to own personal vehicles:

- *Convenience.* Motorists often keep items in their vehicles, including car seats, tools, sports equipment and emergency supplies.
- *Speed and Reliability.* Under optimal conditions taxis can arrive in less than five minutes of a summons, but often take much longer, particularly during busy periods, for special vehicle types (such as a van to carry multiple passengers or a wheelchair), and in suburban and rural areas.
- *Costs.* Vehicle sharing is generally cost effective for motorists who drive less than about 6,000 annual miles. People who live in suburban and rural areas, who usually commute by car, or who for other reasons drive high annual miles will probably choose to own a personal vehicle.
- *Status.* Many people take pride in their vehicles and their driving ability, and so may prefer to own private vehicles, and have the option of driving.

Exhibit 16 summarizes the travellers and trips most suitable for personal or shared vehicle travel. In many cases, shared autonomous vehicles will allow households to reduce but not eliminate personal vehicles, for example, owning one rather than two vehicles.

**Exhibit 16      Personal Versus Shared Vehicles**

Personal Vehicles	Shared Vehicles
Travellers who place a high value on comfort or status.	
Motorists who drive more than 6,000 annual miles, including most suburban and rural residents, and commercial travellers.	Trips currently made by taxi or carshare vehicles.
Motorists who require special accessories in their vehicles.	Utilitarian trips currently made by a private vehicle driven less than 6,000 annual miles.
Motorists who carry equipment, tools or dirty loads.	Urban residents.
Travellers who place high values on privacy.	People who want to save money more than time.

*Some travellers are most suitable for personal vehicles, other for shared vehicles.*

These scenarios illustrate how autonomous vehicles could impact various users' travel:

**Jake** is an affluent man with degenerating vision. In 2026 he gives up driving and purchases an autonomous vehicle. *Impacts:* An autonomous vehicle allows Jake to maintain independent mobility, which increases his vehicle ownership and travel, residential parking demand, and external costs (congestion, roadway costs, parking subsidies, and pollution emissions).

**Bonnie** lives and works in a suburb. She can bike to most destinations but occasionally needs a car. In a city she could rely on taxis, but in suburbs they are slow and expensive. Starting in 2030 a local company started offering convenient and affordable autonomous taxi services. *Impacts:* Autonomous vehicles allow Bonnie to rely on bicycling and shared vehicles rather than a personal car, which reduces her total vehicle travel, residential parking demand, and external costs.

**Melisa and Johnny** have two children. Melisa works at a downtown office. After their second child was born in 2035, they shopped for a larger home. With conventional cars they would need a house within a 30-minute commute of the city center, but the availability of new autonomous vehicles let them consider more distant homes with commutes up to 60-minutes, during which Melisa could rest and work. *Impacts:* Affordable new autonomous vehicles allow Melisa and Johnny to choose an exurban home which increased their total vehicle travel and associated costs.

**Garry** is a responsible driver when sober but dangerous when drunk. By 2040 he had accumulated several impaired citations and at fault accidents. With conventional cars Garry would continue driving impaired until he lost his drivers' license or caused a severe crash, but affordable used self-driving vehicles allow lower-income motorists like Garry to avoid such problems. *Impacts:* Affordable used autonomous vehicles allow Garry to avoid impaired driving, accidents and revoked driving privileges, which reduces crash risks but increases his vehicle ownership and travel, and external costs compared with what would otherwise occur.

Exhibit 17 summarizes the resulting impacts of these various scenarios. In most of these cases autonomous vehicles increase total vehicle mileage.

**Exhibit 17 Autonomous Vehicle Scenario Summary**

	User Benefits	Travel Impacts	Infrastructure Impacts
<b>Jake</b> (affluent and visually impaired)	Independent mobility for non-drivers	Increased vehicle travel and external costs	Increased residential parking and roadway costs
<b>Bonnie</b> (multi-modal traveller)	Vehicle cost savings	Reduced vehicle ownership and travel	Reduced residential parking and roadway costs
<b>Melisa and Johnny</b> (suburban parents)	Improved home location options	Increased vehicle ownership and travel	Increased residential parking and roadway costs
<b>Garry</b> (high-risk driver)	Avoids driving drunk and associated consequences	Less high-risk driving, more total vehicle travel	Increased residential parking and roadway costs

*Autonomous vehicle availability can have various direct and indirect impacts.*

These impacts will vary by travel demands, that is, trip types, as summarized in Exhibit 18.

**Exhibit 18 Autonomous Vehicle Impacts on Various Travel Demands**

Travel Type	Autonomous Vehicle Impacts	Portion of Travel
<b>Freight trucks</b>	Particularly suitable for long-haul freight travel, due to its high labor costs and limited routes, mostly on grade-separated highways.	10%
<b>Small commercial (trades and deliveries)</b>	Trades (plumbers, computer technicians, etc.) carry equipment in their vehicles, and deliveries often require a person to unload, and so are likely to use owned autonomous vehicles with no travel change.	5%
<b>Public transport</b>	Particularly suitable for public transit, due to its high labor costs. Allows micro-transit with frequent and demand-response services.	Currently 2%, but could increase.
<b>Longer-distance (&gt; 50 mile) personal trips</b>	Particularly suitable for longer-distance personal trips, due to tedium. May increase longer-distance travel.	Currently 20%, but could increase.
<b>Local suburban and rural</b>	Affluent suburban and rural residents are likely to purchase private autonomous vehicles and increase total vehicle travel. Lower-income residents are likely to continue driving personal vehicles or use shared autonomous vehicles, which could reduce their total vehicle travel.	50%
<b>Local urban trips</b>	Many are likely to shift from personal cars to shared autonomous mobility services, which is likely to reduce their total vehicle travel.	20%
<b>Non-drivers</b>	Particularly suitable for non-drivers. Many are likely to increase their vehicle travel.	Currently 2-4%, but could increase.

*Autonomous vehicle travel impacts will vary by types of trips.*



A detailed review of these effects, *Travel Effects and Associated Greenhouse Gas Emissions of Automated Vehicles* (Rodier 2018b), identified various ways that autonomous vehicle technologies can affect total vehicle travel, as summarized in Exhibit 19.

**Exhibit 19 Summary of Findings and Quality of Evidence (Rodier 2018b)**

<b>Mechanism</b>	<b>Summary of Findings</b>	<b>Quality of Evidence</b>
<b>Road Capacity</b>	Reduced headways could almost double or triple roadway capacity. Elasticity of VMT with respect to road capacity increase is 0.3 to 0.6 (short run) and 0.6 to 1.0 (long run).	Limited research largely uses microsimulation traffic models. More measured data needed. The body of literature on the effect of expanded road capacity and VMT is relatively strong.
<b>Time Cost</b>	Vary widely, but 75% to 82% of current driver values of time may be reasonable.	Studies largely extrapolate from car and rail passenger experiences, which may not be consistent with automated vehicle travelers' actual experience.
<b>Monetary Cost</b>	Reduced monetary cost from lower insurance and fuel costs. Avoided labor cost could enable fleets of AV taxis and shared taxi with use costs lower than personal vehicles. Elasticity of VMT with respect to gas price is -0.03 to -0.10 (short run) and -0.13 to -0.30 (long run). Elasticity of taxi trips with respect to fares is -0.22.	The magnitude of cost reductions is largely speculative, and few peer reviewed studies evaluate these effects. The body of literature on the effect of gas prices on VMT is relatively strong. Gas price is the largest component of the variable cost of driving a conventional owned vehicle. Only one study in New York City estimates taxi fare elasticity.
<b>Mode Choice</b>	Available research suggests that AVs would reduce transit and non-motorized and increase car mode shares	Limited research confirms expected direction change, but magnitude is highly uncertain due to study quality.
<b>Parking</b>	Fully AV taxis may reduce parking demand by about 90%. However, reduced parking may increase relocation travel.	Only one U.S. study that uses observed travel data. Two other studies are in European cities. All studies use simulation models.
<b>Empty Relocation Travel</b>	Empty relocation travel is positively correlated with distance from the urban core, the price of parking, and per mile user costs, and inversely correlated with ridesharing and transit. Empty relocation travel may contribute significantly to VMT effects of automated vehicles.	Limited research confirms expected direction change, but magnitude is highly uncertain. The share of relocation travel with respect to total VMT may be significant; however, studies do not fully represent induced travel effects and thus may overestimate the relative significance of this effect.
<b>New Travelers</b>	Most studies estimate an increase in VMT on the order of 10% to 14%.	Extrapolations from National Household Travel Survey data. Analysis based on study assumptions.

*Many factors can affect autonomous vehicle travel impacts.*

This suggests that with current policies, autonomous vehicles are likely to significantly increase total vehicle miles travelled (VMT) and pollution emissions, probably by 10-30%, and even more on some major travel corridors. This is likely to increase urban traffic congestion and sprawled development. Electrifying the vehicle fleet could counter emission growth, but unless electric vehicle operation is efficiently priced this will reduce vehicle operating costs which will further increase vehicle travel and traffic impacts. Shared autonomous taxis could significantly reduce vehicle travel and emissions, but only if policies favor their use over personal cars.

## Potential Conflicts and Solutions

There are potential conflicts between user and community goals in autonomous vehicle design and programming. For example, if programmed to maximize sleeping passengers' comfort they may reduce traffic speeds, and if programmed to protect occupants they may increase crash risk to other road users. Some benefits (reduced congestion and possibly pollution emissions) require that autonomous vehicles have dedicated lanes. This will raise debates about the fairness, pricing, regulations and enforcement of these requirements.

There are also potential transportation planning conflicts. By increasing vehicle travel demand and traffic speeds, and displacing public transit, autonomous vehicles could exacerbate traffic congestion, sprawl-related costs, and mobility inequity. For example, if parking is priced but roads are not, autonomous vehicles may cruise urban streets to avoid paying for parking, exacerbating congestion and pollution problems. Some advocates claim that autonomous vehicles eliminate the need for conventional public transit services, but high capacity transit will still be needed on major travel corridors, and autonomous technologies can support transit by reducing operating costs and improving access to stops and stations (ITF 2014; TRB 2017). Shared vehicles reduce parking demand but increase the need for convenient pick-up and drop-off options, which requires better curb management (OECD/ITF 2018). Various public interest organizations have developed guidelines for optimizing the benefits of emerging mobility technologies and services (Fulton, Mason and Meroux 2017; Kaohsiung EcoMobility Festival 2017). The box below summarizes one example.

### **Shared Mobility Principles for Livable Cities** ([www.sharedmobilityprinciples.org](http://www.sharedmobilityprinciples.org))

- |  |  |
|--|--|
| 1. Plan our cities and their mobility together.                              | 6. Lead the transition towards clean and renewable energy.                         |
| 2. Prioritize people over vehicles.  | 7. Support fair user fees across all modes.  |
| 3. Support the shared and efficient use of vehicles, lanes, curbs, and land. | 8. Aim for public benefits via open data.  |
| 4. Engage with stakeholders.   | 9. Work towards integration and seamless connectivity.                             |
| 5. Promote equity.   | 10. In dense urban areas autonomous vehicles should only operate in shared fleets. |

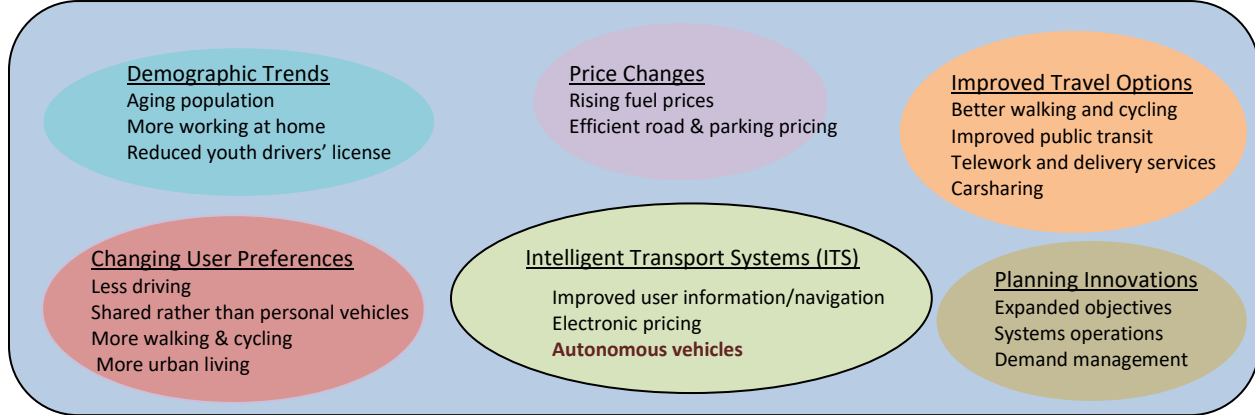
The following policies can help maximize benefits (Schlossberg, et al. 2018; TRB 2017):

- Test and regulate new technologies for safety and efficiency.
- Require autonomous vehicles to be programmed based on ethical and community goals.
- Efficiently regulate and price roads and curb space to prevent congestion.
- Favor shared and higher-occupant vehicles over lower-occupant vehicles on public roads.
- Support high capacity public transit on major travel corridors.
- Reduce parking requirements to take advantage of shared vehicles.
- Efficiently price development to prevent inefficient sprawl.
- Use vehicle traffic reductions to redesign streets and improve urban livability.

## Planning Implications

Autonomous vehicles raise many policy and planning issues (Taeihagh and Lim 2018). Their development is just one of many trends that will affect future transport demands and planning needs, as illustrated in Exhibit 20. Changes in demographics, consumer preferences, prices, information technologies, mobility options, and other planning innovations will also influence how people want to travel. These may have greater impacts than autonomous vehicles for the foreseeable future.

**Exhibit 20 Factors Affecting Transport Demands and Costs**



*Autonomous vehicles are one of many factors affecting future transport demands.*

Some autonomous vehicle benefits, such as reduced driver stress, can occur with Level 2-3 automation, but other benefits, including independent mobility for non-drivers and increased occupant safety require Level 4-5, and most external benefits (reduced traffic congestion, crash risk, pollution, and infrastructure costs imposed on others) can only occur when autonomous vehicles are common, and some require that highway lanes be dedicated to autonomous vehicle platoons. The following matrix summarized the benefits provided by various AV levels.

**Exhibit 21 Autonomous Vehicle Benefits**

Autonomous Vehicle Levels	Mobility for Non-drivers	Reduced Driver Stress	User Savings	Occupant Safety	External Benefits
Level 1-3 personal vehicles		✓		?	
Level 4 + 5 personal vehicles	✓	✓		✓	✓
Shared autonomous vehicles	✓		✓		✓
Shared autonomous rides	✓		✓		✓
Dedicated AV lanes			✓		?

*Autonomous vehicles benefit users by improving their mobility options, reducing stress, saving money and increasing safety. External benefits (reduced crash risk, congestion delay, emissions and parking costs imposed on others) primarily result from shared vehicles and rides that reduce total vehicle travel.*

Exhibit 22 summarizes key autonomous vehicle planning issues.

**Exhibit 22 Key Autonomous Vehicle Planning Issues** (based on Papa and Ferreira 2018)

Issues	Optimistic Outcome	Pessimistic Outcome
<b>Sharing</b>	Policies encourage autonomous vehicle sharing.	AVs are promoted as private luxury goods.
<b>Social exclusion</b>	Policies designed to maximize AV affordability and accessibility ensure that they are widely available.	AVs are only affordable and available by privileged (affluent) users.
<b>Environmental sustainability</b>	AV policies support environmental goals.	AV policies give little consideration of to environmental concerns.
<b>Operated cooperation</b>	AV operating systems are programmed based on cooperative, altruistic and ethical principles.	AV operating systems are programmed based on competitive, aggressive and defensive principles.
<b>Public transport</b>	Public policies support public transport, providing funding and favoring shared vehicles in traffic.	Public policies focus too much on AVs and fail to support public transport.
<b>Intermodal traffic regulations</b>	AV policies and programming respect human life. They minimize crash risks and protect vulnerable road users (e.g., through lower speeds).	Public policies and programming favor AV occupants over other road users, and so will favor affluent over more vulnerable groups.
<b>Network information systems</b>	Data networks are designed make more sustainable and efficient decisions regarding route choice and parking at a fleet level.	Data networks are designed to maximize profits so critical information is only available to affluent users.
<b>Sensitive data management</b>	Personal data are carefully managed based on general public interest.	Data are used for commercial purposes. AVs collect an abundance of sensitive private information.
<b>Parking</b>	Policies facilitate the conversion of parking facilities into recreational, green, and building areas, or into active transport infrastructure.	Parking policies remain as they are, so parking continues to consume valuable land that could be used for more sustainable or social purposes.
<b>Land use policies</b>	Urban areas become more attractive places to live. Transport policies promote quality of life.	Urban land is managed to accommodate AV travel, to the detriment of other social groups.
<b>Transport network design</b>	Transport networks are designed to be safe for all. Urban transport planning favors sustainable transport modes.	Transport networks are restructured to accommodate AVs' needs. Other modes see no comparable protection or investment.

*Autonomous vehicles raise many policy and planning issues.*

The Pedestrian and Bicycle Information Center identifies ten special risks that autonomous vehicles can impose on pedestrians and cyclists, and how these can be minimized (PBIC 2017). Appleyard and Riggs (2018) identify planning principles to ensure that autonomous vehicles support community livability goals by improving driving behavior (slower speeds, and enhanced ability to yield and stop), improving walking and bicycling conditions, and reducing parking supply, but these will only occur if supported by suitable public policies.

There is much that policy makers and planners can do to maximize the benefits and minimize the costs of autonomous vehicle implementation (Henaghan 2018; Largo, et al. 2018). As the technology develops, transportation professionals should help establish performance standards, analyze impacts, and support policies to minimize their costs and maximize their

benefits. Exhibit 23 identifies various planning implications of various planning needs and requirements for autonomous vehicle development.

**Exhibit 23 Autonomous Vehicle Planning Needs and Requirements**

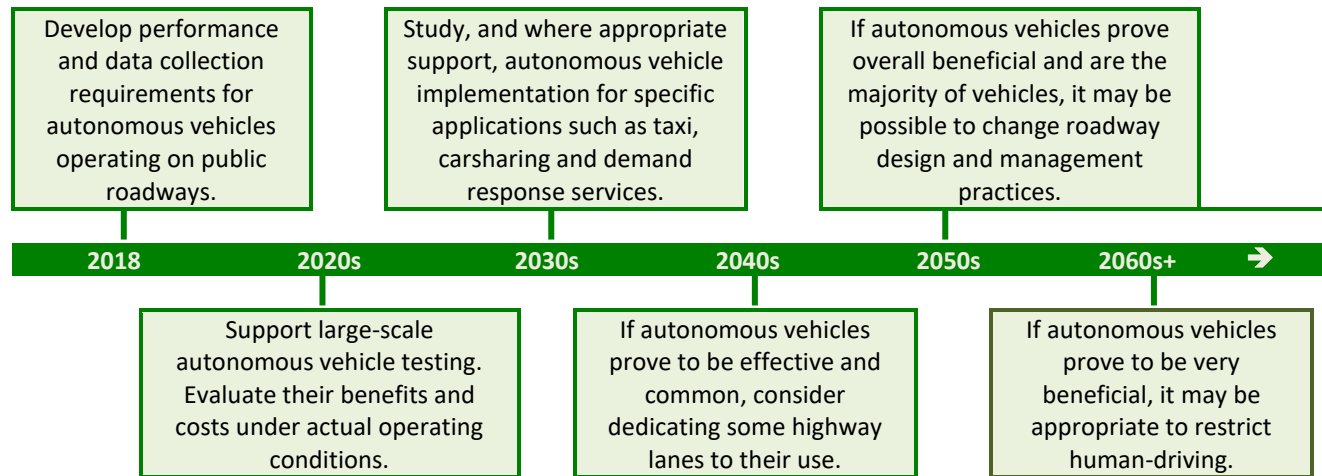
Impact	Needs	Requirements	Time Period
Become legal	Demonstrated functionality and safety	Define performance, testing and data collection requirements for automated driving on public roads.	2018-25
Increase traffic density by vehicle coordination	Road lanes dedicated to vehicles with coordinated platooning capability	Evaluate impacts. Define requirements. Identify lanes to be dedicated to vehicles capable of coordinated operation.	2020-40
Independent mobility for non-drivers	Fully autonomous vehicles available for sale	Allows affluent non-drivers to enjoy independent mobility.	2020-30s
Automated carsharing/taxi	Moderate price premium. Successful business model.	May provide demand response services in affluent areas. Supports carsharing.	2030-40s
Independent mobility for lower-income	Affordable autonomous vehicles for sale	Reduced need for conventional public transit services in some areas.	2040-50s
Reduced parking demand	Major share of vehicles are autonomous	Reduced parking requirements.	2040-50s
Reduced traffic congestion	Major share of urban peak vehicle travel is autonomous.	Reduced road supply.	2050-60s
Increased safety	Major share of vehicle travel is autonomous	Reduced traffic risk. Possibly increased walking and cycling activity.	2040-60s
Energy conservation and emission reductions	Major share of vehicle travel is autonomous. Walking and cycling become safer.	Supports energy conservation and emission reduction efforts.	2040-60s
Improved vehicle control	Most or all vehicles are autonomous	Allows narrower lanes and interactive traffic controls.	2050-70s
Need to plan for mixed traffic	Major share of vehicles are autonomous.	More complex traffic. May justify restrictions on human-driven vehicles.	2040-60s
Mandated autonomous vehicles	Most vehicles are autonomous and large benefits are proven.	Allows advanced traffic management.	2060-80s

*Autonomous vehicles will have various impacts on transportation planning.*



The timeline below summarizes autonomous vehicle planning requirements.

**Exhibit 24 Autonomous Vehicle Planning Requirement Time-Line**



*This timeline summarizes how autonomous vehicles are likely to impact transport planning.*

**Autonomous Taxi Service Impacts**

In 2017 Waymo and Uber announced plans to start testing driverless taxis in the Phoenix, Arizona region. (Bergen 2017; Lee 2017). Within a few months a pedestrian death put the program on hold, but it will probably continue eventually. How soon and how much will these services affect overall travel?

Phoenix was chosen because it has mild climate, wide streets and relatively few pedestrians. The vehicles are relatively slow. Further development and testing is required before the technology can expand to other types of cities, particularly those with extreme weather or congested streets. This service will not expand significantly unless it becomes profitable, which will require reducing costs and achieving a high level of consumer confidence. As a result, it will probably take several years before commercial autonomous taxi services are widely available.

Taxis primarily serve local urban trips when travellers lack a personal vehicle, which represents a minor portion of total travel. To significantly reduce vehicle travel and associated costs, autonomous taxis will need to become inexpensive, ubiquitous and integrated with other mobility options so households can reduce their vehicle ownership and rely more on vehicle sharing. This can be accelerated by public policies that discourage private vehicle ownership and encourage sharing, such as reduced parking supply, High Occupancy Vehicle Lanes, and convenient drop off/pick up areas.

This is consistent with predictions that during the 2020s, autonomous vehicles will have limited availability and performance. If the technology improves and become affordable and reliable, so self-driving taxi services to become profitable, they can expand to serve more areas and trip types. However, until most households shift from owning vehicles to relying on shared mobility services, and until a greater share of households live in compact and multimodal neighborhoods, the new generation of autonomous taxis will affect only a small portion of total travel and provide modest community benefits.

## Conclusions

Recent announcements that autonomous vehicles are being tested on public roads and will soon be commercially available raise hopes that these technologies will quickly solve many transportation problems. Some advocates predict that by 2030 such vehicles will be sufficiently reliable and affordable to displace most human-operated vehicles, providing many benefits to users and society overall. However, there are good reasons to be skeptical.

There is considerable uncertainty concerning autonomous vehicle benefits, costs, travel impacts, deployment speed and consumer demand. Many predictions of autonomous vehicle benefits are speculative and exaggerated. Advocates often ignore significant costs and risks, *rebound effects* (increased vehicle travel caused by faster travel or reduced operating costs), and potential harms to non-users. Benefits are often double-counted, for example, by summing increased safety, traffic speeds and facility savings, although these often involve trade-offs.

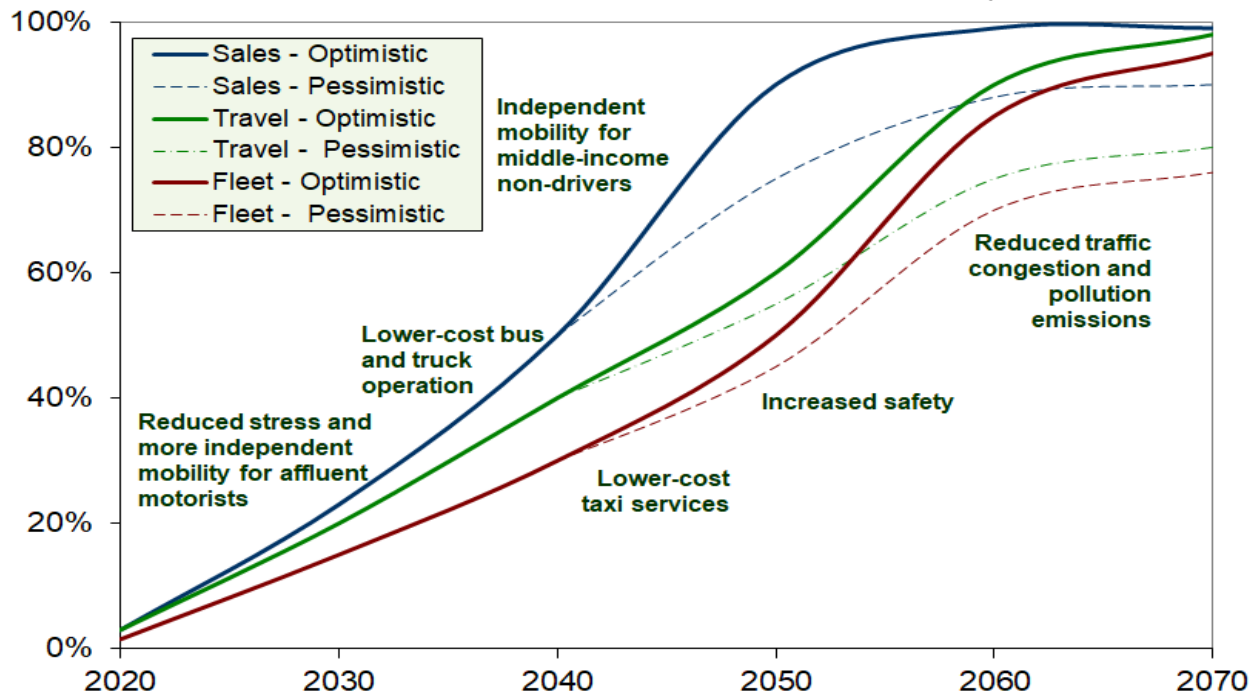
Most optimistic predictions are made by people with financial interests in the industry, based on experience with other disruptive technologies such as personal computers, digital cameras and smart phones. Vehicles typically last an order of magnitude longer, cost two orders of magnitude more, impose greater external costs, and rely more on public infrastructure than other technologies. As a result, vehicle innovations tend to take longer and involve more regulation than most other new technologies.

Operating a vehicle on public roads is complex due to the frequency of interactions with other, often-unpredictable objects including vehicles, pedestrians, cyclists and animals. If they follow previous vehicle technology deployment patterns, autonomous vehicles will initially be costly and imperfect. During the 2020s and perhaps the 2030s, autonomous vehicles will be expensive novelties, unable to operate in conditions such as heavy rain and snow, unpaved roads and mixed urban traffic. They will be purchased by affluent non-drivers and people who frequently drive long distance, but many travellers will not consider the extra costs justified. It will probably be the late 2030s or 2040s before they become affordable to middle-income households, and later before they are affordable to lower-income motorists.

During the 2020 and 2030s, self-driving taxi and “micro-transit” (van) services may become available in many urban areas. They should be cheaper than human-operated taxis, costing about \$0.60-1.00 per mile for a self-driving taxi and 30-60¢ per mile for micro-transit, but offer low service quality: to minimize cleaning and repair costs their interiors will be metal and plastic, and occupants will be monitored by cameras, yet passengers will probably still find previous occupants’ garbage, stains and odors. No drivers will be available to assist passengers and provide security. Additional passengers will add pickup and drop-off delays, particularly in lower-density areas. Because of these limitations, autonomous taxi and micro-transit will only be suitable for a portion of travel, mainly local urban trips. Once the novelty wears off, autonomous taxi use will seem as tedious as commercial airline travel.

Exhibit 25 illustrates a prediction of market penetration and associated benefits.

**Exhibit 25 Autonomous Vehicle Sales, Fleet, Travel and Benefit Projections**



Based on previous vehicle technology deployment patterns, this analysis predicts that it will be at least 2040 before half of all new vehicles are autonomous, 2050 before half of the vehicle fleet is autonomous, and possibly longer due to technical challenges or consumer preferences. Significantly faster deployment will require scraping many otherwise functional vehicles because they lack self-driving capability. Some user benefits can occur when autonomous vehicles are relatively costly and rare, but many benefits, such as independent mobility for moderate-income non-drivers, can only be significant if they become very reliable and affordable, and some benefits, such as reduced traffic congestion and emissions, require dedicated lanes to allow autonomous vehicle platooning.

A critical question is whether autonomous vehicles increase or reduce total vehicle travel and associated external costs. It could go either way, depending on public policies. By allowing vehicle travel by non-drivers, increasing travel convenience and comfort, and allowing vehicles to drive in circles rather than pay for a parking space, they could increase total vehicle mileage and traffic problems. Alternatively, they may also facilitate vehicle sharing, which allows households to reduce vehicle ownership and therefore total driving.

Many motorists may prefer to own personal vehicles for prestige and convenience sake, or use a combination of modes (walking, cycling, conventional public transit and taxi). As a result, shared autonomous vehicles are likely to reduce vehicle travel mostly in compact, multi-modal urban areas, and increase travel in suburban and rural areas. Since most North Americans live in automobile-dependent areas, total vehicle travel will probably increase unless discouraged by public policies such as efficient road pricing and high-occupant vehicle lanes.

Another critical issue is the degree potential benefits can be achieved when only a portion of vehicle travel is autonomous. Some benefits, such as improved mobility for affluent non-drivers, may occur when autonomous vehicles are uncommon and costly, but many potential benefits, such as reduced congestion and emission rates, reduced traffic signals and lane widths, require that most or all vehicles on a road operate autonomously.

A key public policy issue is the degree that this technology may harm people who do not use such vehicles, for example, increased traffic volumes and speeds that degrade walking and cycling conditions, reduced investments in public transit, or requiring restrictions on human-operated vehicles. Platooning benefits require dedicated autonomous vehicle lanes. These issues will probably generate considerable debate over their merit and fairness.

To minimize problems and maximize benefits many experts recommend that public policies encourage shared and electric autonomous vehicles, and limit total vehicle traffic, particularly in denser urban areas. This can be done with High Occupancy Vehicle (HOV) priority lanes which favors shared over single-occupancy vehicles on congested roads, increased fossil fuel taxes, efficient road pricing, convenient passenger pick-up and drop-off facilities, reduced parking requirements and efficient parking pricing. Experts also recommend various technical requirements and regulations to ensure that autonomous vehicles are programmed to minimize risks and delay to other people, particularly pedestrians, bicyclists and public transit users.

Autonomous vehicle implementation is just one of many trends likely to affect future transport demands and costs, and therefore planning decisions, and not necessarily the most important. Its ultimate impacts depend on how it interacts with other trends, such as shifts from personal to shared vehicles. It is probably not a “game changer” during most of our professional lives, and is only a “paradigm shift” to the degree that this technology supports shifts to more efficient and multimodal transport planning.

Transportation professionals (planners, engineers and policy analysts) have important roles to play in autonomous vehicle development and deployment. We can help define the performance standards they must meet to legally operate on public roads. We should evaluate the risks and opportunities they present, and develop policies to ensure that their deployment supports strategic community goals including congestion reduction, public safety and health, and improved opportunity for disadvantaged people. Once they become more common they may affect planning decisions such as the design and management of roadways, parking facilities and public transit.

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