Autonomous Vehicle Implementation Predictions
Implications for Transport Planning
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Waymo's self-driving taxis are a well-publicized example of autonomous vehicles.

Abstract

This report explores the impacts of autonomous (also called *self-driving*, *driverless* or *robotic*) vehicles, and their implications for various planning issues. It investigates how quickly self-driving vehicles are likely to develop and be deployed based on experience with previous vehicle technologies; their likely 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 independent mobility for affluent non-drivers, may begin in the 2030s or 2040s, 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 2050s to 2060s, and some benefits may require prohibiting human-driven vehicles on certain roadways, which could take even longer.

Table of Contents

Driving in mixed traffic involves numerous interactions with diverse pedestrians, animals, bicyclists and vehicles, and so is more complex than flying an airplane. (Keith Shaw)

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 activity and development patterns, and therefore the need for road and parking facilities and public transit services, whether public policies should encourage or restrict their use (APA 2016; Grush and Niles 2018; Guerra 2015; Kockelman and Boyles 2018; Levinson 2015; Milakis, van Arem and van Wee 2017; Sperling 2017).

There is considerable uncertainty about these issues. Optimists predict, based on experience with previous technological innovations, such as digital cameras and smart phones, that autonomous vehicles will soon be sufficiently reliable and affordable to replace most human driving, providing independent mobility to non-drivers, reducing driver stress, and be a panacea for congestion, accident and pollution problems (Johnston and Walker 2017; Keeney 2017; Kok, et al. 2017). There are good reasons to be skeptical of such claims.

Optimistic predictions often overlook significant obstacles and costs. Many technical problems must be solved before autonomous vehicles can operate in all conditions, including inclement weather, unpaved roads and beyond wireless access (Knight 2020). In order to be successful they will require testing and regulatory approval, and must become affordable and attractive to consumers. Motor vehicles are costly, durable, and highly regulated, so new vehicle technologies generally require decades to penetrate fleets. A camera, telephone or Internet failure may be frustrating but is seldom fatal; motor vehicles system failures 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 will probably take longer to develop and provide smaller net benefits than optimists predict.

This has important policy 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 programed based on user preferences (maximizing traffic speeds and occupant safety) or community goals (limiting speeds and risks to 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 community 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 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)

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
Personal autonomous vehicles - Motorists own or lease their own self-driving vehicles.	High convenience. Always available. Users can leave tools and personal gear in vehicles. Provides pride of ownership.	High costs. Does not allow users to choose different vehicles for different uses, such as cars for commuting or trucks for errands.	Affluent people who travel a lot, and want a personal vehicle.
Shared autonomous vehicles - 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.
Shared autonomous rides - Self-driving vans (*micro-transit*) take passengers to or near destinations.	Lowest costs. Minimizes traffic congestion, accident risk and pollution emissions.	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

This section describes autonomous vehicle benefits and 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. Travellers may experience "access anxiety" if their vehicle cannot reach desired destinations, for example, due to inclement weather (snow or heavy rain) or if an area lacks the detailed maps required for autonomous operation (Grush 2016).

Autonomous vehicles can provide independent mobility for people who for any reason cannot or should not drive. This directly benefits those travellers, improving their access to education and employment opportunities, which can increase their productivity, and reduces chauffeuring burdens on their family members and friends.

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 (Creger, Espino and Sanchez 2019). Dedicating highway lanes for autonomous vehicle platooning may reduce capacity for human-operated traffic, harming human-operated vehicle occupants.

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 videos, but for safety sake they should wear seatbelts, and like any confined space, vehicle interiors can become cluttered and dirty. Manufactures will probably produce vehicles with seats that turn into beds and mobile offices (NYT 2017). For the foreseeable future autonomous vehicles will be unable to operate in heavy rain and snow, on unpaved roads, or where GPS service or special maps are unavailable, and they may be relatively slow and unreliable in mixed urban traffic.

Self-driving taxi and micro-transit 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. 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 glamourous mobility option, more like an elevator than a spaceship.

Ownership and Operating Costs

Autonomous vehicles require various equipment and services summarized in the box below. Currently, optional electronic features such as remote starting, high beam assist, active lane assist, adaptive cruise control, and top view camera typically increase new vehicle prices by more than $5,000, and subscriptions to 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, increasing maintenance costs. Shared autonomous vehicles will also require dispatching and fleet management, 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
• Sensors (optical, infrared, radar, laser, etc.). • Automated controls (steering, braking, signals, etc.) • Software, servers and power supplies. • Wireless networks. Short range vehicle-to-vehicle communications and long-range access to maps, software upgrades and road reports. • Navigation. GPS systems and special high quality maps. • Critical component testing and maintenance.	• Dispatching and fleet management. • Business administration and insurance. • Business profits. • Security. • Frequent cleaning and repairs. • Delays and empty vehicle-miles for passenger pick-up and drop-off.

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 add hundreds of dollars in additional annual services and maintenance costs. Experience with previous vehicle innovations, such as automatic transmissions and airbags, 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 (Intellias 2018), 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 motor vehicle fuel taxes; cost-recovery road-user fees would increase electric vehicle operating costs 5-10¢ per vehicle-mile (FHWA 2015).
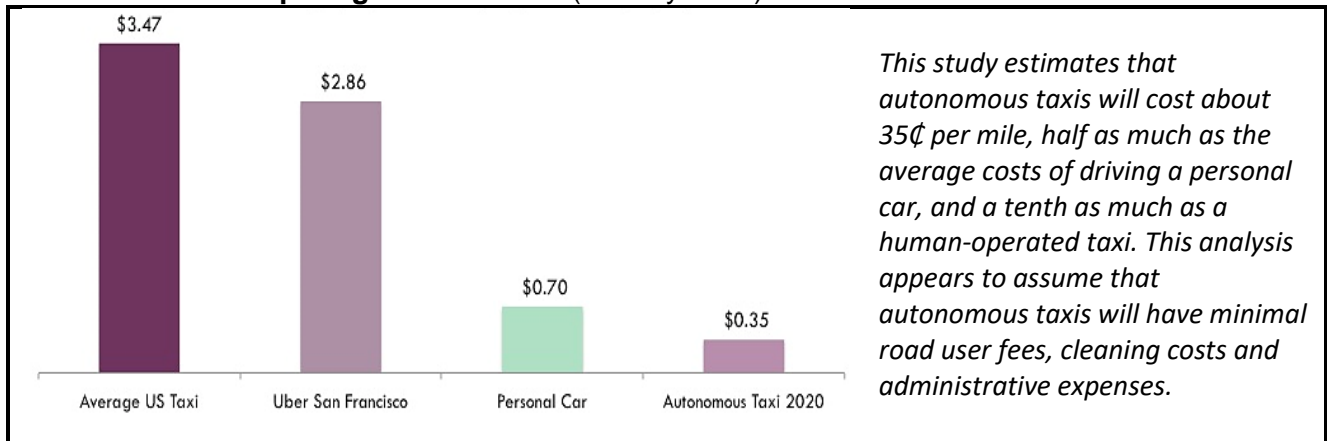
Cleaning – An Often Overlooked Cost
Although most autonomous taxi passengers are likely to be courteous and responsible, some will probably be messy and a few vandalous. To discourage abuse, autonomous taxis will have surveillance cameras, and their interiors will be plastic and chrome, which may reduce but cannot eliminate these problems, so vehicles will occasionally contain garbage and unpleasant odors, or be damaged.

Autonomous taxis will therefore require an inspection and cleaning every five to fifteen trips, 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) private 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 as the technology becomes available in lower-priced models. This 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 costs will decline from about 85¢ per vehicle-mile in 2018 to 35¢ per mile by 2035, but they overlook some previously-mentioned costs such as cleaning and roadway user fees, and so are probably underestimates. Shared autonomous taxi services will probably cost $0.20-0.40 per passenger-mile, assuming that they average 3-6 passengers (Bösch, et al. 2017).

Exhibit 5   **Comparing Cost Per Mile** (Keeney 2017)

This study estimates that autonomous taxis will cost about 35¢ per mile, half as much as the average costs of driving a personal car, and a tenth as much as a human-operated taxi. This analysis appears to assume that autonomous taxis will have minimal road user fees, cleaning costs and administrative expenses.

Some studies estimate lower costs. For example, Kok, et al. (2017) predict that shared, electric autonomous vehicles operating costs will be less than 10¢ per mile, making their use so inexpensive that trips could 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). Electric vehicles have somewhat lower operating costs, in part because they pay no fuel taxes, but significant battery replacement costs. Human-operated taxis generally cost $2.00-$3.00 per mile, ride-hailing (such as Uber and Lyft) about $1.50-2.50 per mile, and conventional 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**
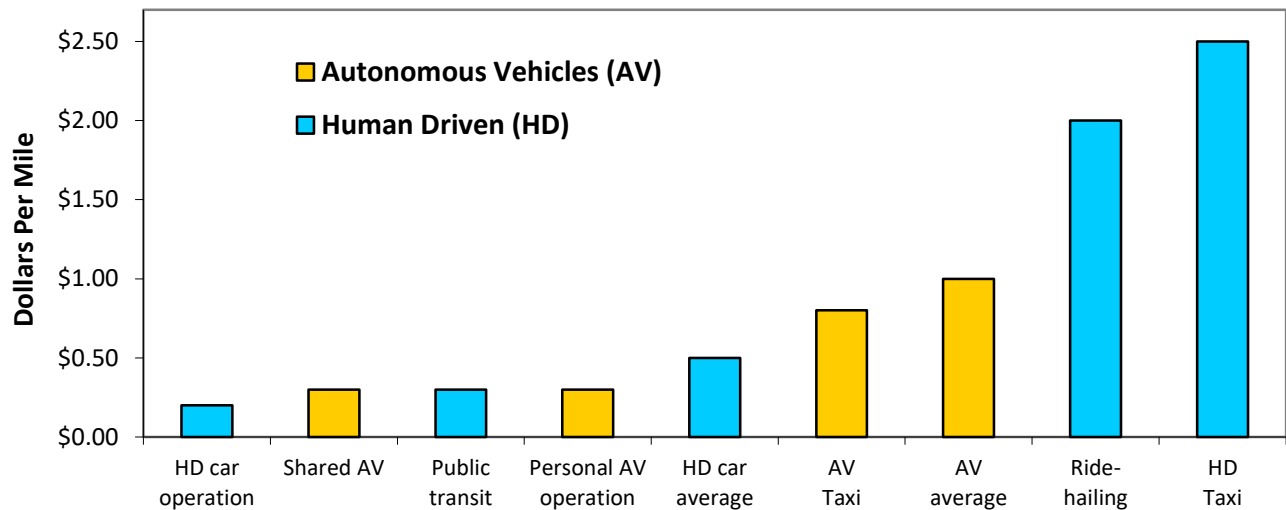
Autonomous vehicles (AVs) are predicted to cost less than human-driven taxis and ride-hailing services, but more than human-driven personal vehicles (HVs) and public transit services.

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 some 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 and Security

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 due to false sensors, distorted signals and software errors. Self-driving vehicles will certainly have failures that contribute to crashes, although their frequency is difficult to predict.

- *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, autonomous vehicle 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 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).

Recent experience indicates that autonomous test vehicles have significant risks (Edelstein 2018). *Disengagements* (when human drivers override automated systems) exceeded one per 5,600 miles. 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% crash 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.
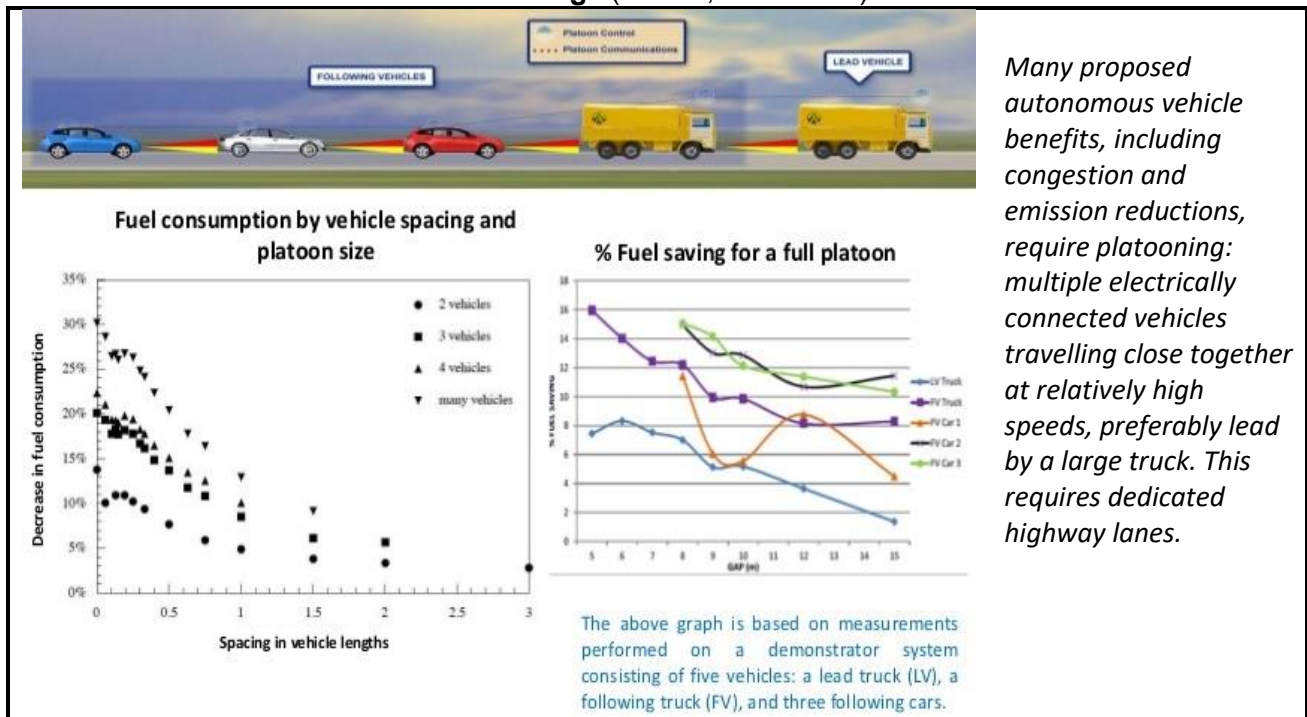
Shared autonomous vehicles can reduce crashes by providing more affordable alternatives to higher-risk drivers. Efforts to reduce higher-risk driving, such as graduated driver's licenses, special testing for senior drivers, and anti-impaired driver campaigns, can be more effective and publicly acceptable if affected groups have convenient and affordable mobility options. For example, parents may purchase autonomous vehicles for their teenagers, and travelers may use autonomous vehicles to avoid impaired and districted driving.

Many factors will affect these safety impacts, including how vehicles are programmed, and how they affect total vehicle travel. For example, to maximize mobility autonomous vehicles can be programmed to drive 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 public policies, such as high efficient road pricing, can encourage vehicle travel reductions.

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; TRB 2019). Many of these benefits require dedicated lanes for platooning (Exhibit 7). This is only feasible under limited conditions, such as 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.

The above graph is based on measurements performed on a demonstrator system consisting of five vehicles: a lead truck (LV), a following truck (FV), and three following cars.

Under many circumstances, autonomous vehicles are likely to increase congestion, energy, pollution and roadway costs. For example, if they strictly follow traffic laws and maximize caution, such as speed limits and optimal spacing between vehicles, they will reduce traffic speeds and increase delays. To maximize comfort, so passengers can rest or work, users may program their vehicle to minimize acceleration and deceleration rates, reducing traffic speeds (Le Vine, Zolfaghari and Polak 2015). If programmed for maximum caution in unexpected conditions, they may frequently stop to wait for human instructions.

Without significant policy reforms, such as higher road user fees and roadway management that favors share vehicles, autonomous vehicles are likely to increase total vehicle travel, and therefore traffic problems, as discussed later in this report. Over the long run they may encourage sprawled, automobile-dependent development, increasing sprawl-related costs, and by reducing public transit demand, reduce non-auto travel options.

Autonomous vehicles may require higher roadway maintenance standards, such as clearer line painting and special traffic signals (Lawson 2018). Autonomous operation can reduce parking 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. To avoid paying for parking, autonomous vehicles may circle city blocks, increasing traffic congestion.

Benefit and Cost Summary

Exhibit 8 summarizes autonomous vehicle benefits and costs, categorized according to whether they are internal (they affect users) or external (they affect other people). Total impacts will depend on how autonomous technologies affect vehicle travel: if they stimulate more driving, external costs are likely to increase, but if they help reduce total vehicle travel, total costs should decline.

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

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

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

Development and Deployment Predictions

New technologies generally follow an S-curve development pattern, as illustrated in Exhibit 9. An initial concept usually experiences 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 9 **Innovation S-Curve**
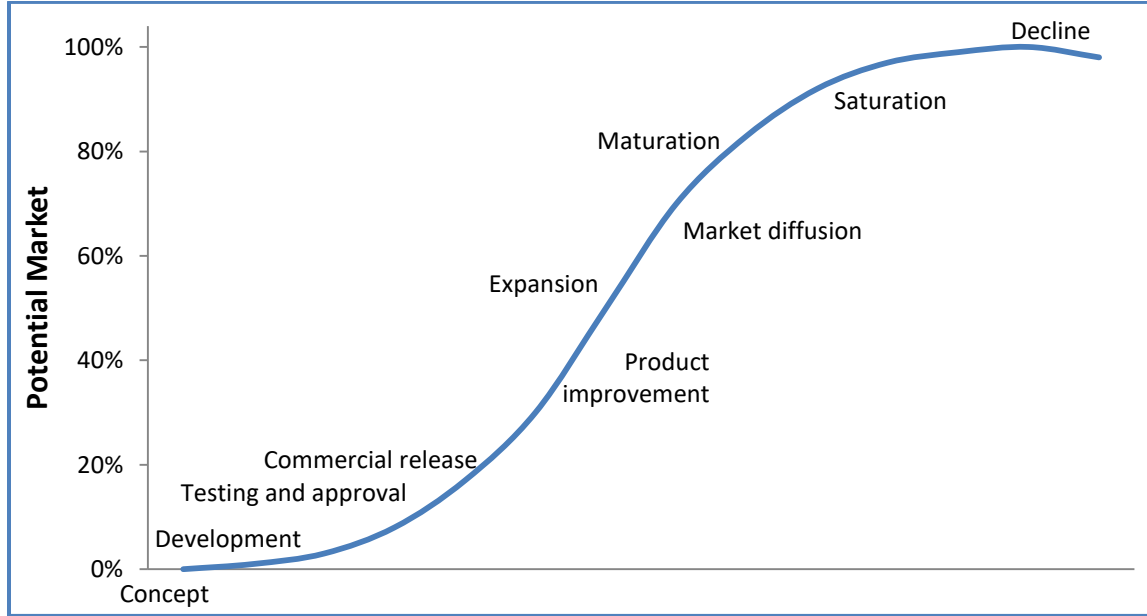
Most innovations follow a predictable deployment pattern, often called in innovation S-curve.

Autonomous vehicle technologies are currently in development and testing stages. They must go through several more stages to become commercially available in most markets, reliable and affordable, and therefore common in the vehicle fleet. Once Level 5 technology is fully functional and reliable, additional time will be required for testing and regulatory approval. Because vehicles can impose significant external costs, including accident risks and delays to other road users, they have 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 there are more high-profile crashes, adding more years (Bhuiyan 2017). It is likely that different jurisdictions will impose different testing, approval and regulations, resulting in varying rates of deployment.

In addition to technological progress, market deployment depends on consumer demand: travellers' willingness to pay for autonomous mobility. Surveys indicate significant concerns about reliability, privacy and safety (Schoettle and Sivak 2014). Travellers will face *access anxiety* if their vehicle cannot reach all 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 reach a desired destination about once a year) will be exponentially more difficult again (Wharton 2017).

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 then aircraft (Exhibit 10). 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 10 **Aircraft and Automobile Software Code Compared** (GAO 2016)

Vehicles need more complex computer systems than aircraft, due to the complexity of roadway interactions.
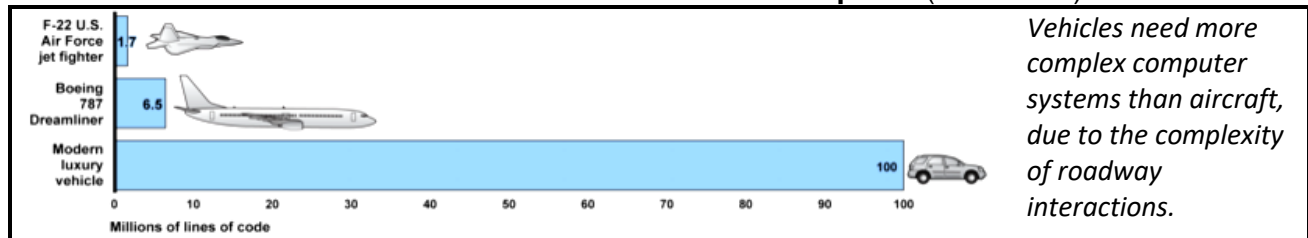
Consider one challenge. For safety sake motorists are advised to *drive defensively*, which means anticipating potential risks such as wild animals and playful children. To do this, autonomous vehicles will need a database that categorizes, for example, fire hydrants as low-risk, pets on leashes as medium 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 warn, "Watch out for 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 its database, so the vehicle would either miss-categorize the risk, perhaps treating costumed fun-seekers as injured crash victims or a riotous mob, or stop and wait for human instructions. These systems can self-learn, and so could understand such behaviors and costumes if they become common, but cannot anticipate new conditions, and each new set of instructions will further increase system complexity and therefore potential risks and delays.

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, although deployment was delayed after it caused a fatal crash in 2016 (Hawkins 2017). Several companies are now implementing Level 4 pilot projects, which tests autonomous vehicles under limited conditions (certain roads, areas, and weather). For example, Waymo and Uber are testing driverless taxi services in a few locations (Bergen 2017; Lee 2017). Despite this progress, many more technical improvements are needed before vehicles can drive themselves under all normal conditions (Simonite 2016).

Most objective experts acknowledge that Level 5 automation requires many more years for development, testing and approval (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, most optimistic predictions are made by people with financial interests in autonomous vehicle industries. 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 business management firm. Although their predictions are often qualified – autonomous vehicles "could" or "might" change everything – their conclusions are often presented with unjustified 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. 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.

Experience with Previous Vehicle Technology Deployment
Previous vehicle technologies can help predict autonomous vehicle deployment.

Ford's Model T began production in 1908, leading to mass automobile ownership. By the 1920s, cities experienced traffic and parking congestion, and by the 1930s there were more vehicles than households, but for decades the transportation system was mixed, with most travellers relying on a combination of walking, bicycling and public transit in addition to cars. Only after the 1980s did motorization approach saturation, with most adults having a personal vehicle.

Exhibit 11 **U.S. Population and Automobile Ownership** (FHWA 2016)

Although mass automobile production started in 1908 with the Ford Model T, it took decades for automobiles to become the dominant travel modes. Only in the 1960s did most potential drivers own a personal vehicle, and only after 1980 did ownership approach saturation.
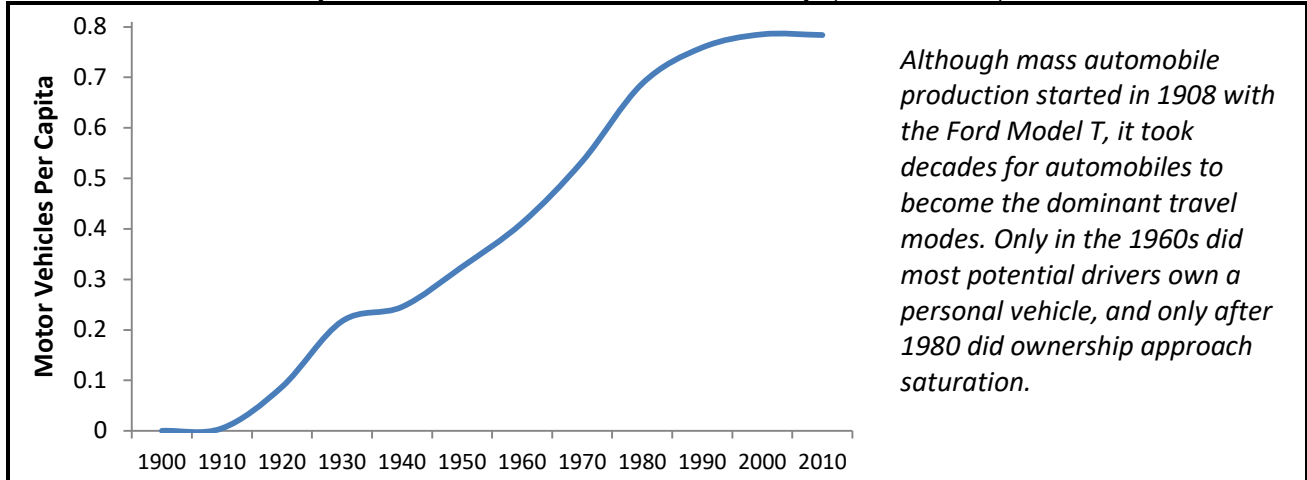
Below are other examples of vehicle technology development and deployment.

- *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 12 summarizes their deployment. All of these technologies required decades from initial commercial availability to market saturation, and some have never became universal.

Exhibit 12 **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.

Because autonomous vehicle technologies are more complex and costly than these previous vehicle technologies, their market acceptance and penetration may take longer (Lavasani and Jin 2016). New vehicles are becoming much more durable, which reduces fleet turnover. As a result, new vehicle technologies normally 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 10th year, and 5,000 miles their 15th year, so vehicles over ten years represent about 50% of vehicle fleets but only 20% of mileage (ORNL 2012, Table 3.8).

Deployment Predictions

Exhibit 13 uses the previous analysis to predict autonomous vehicle sales, fleet and travel market penetration, assuming that Level 5 vehicles become commercially available in the 2030s but are initially expensive and limited in performance. Due to these limitations, during their first decade only a minority of new vehicle are likely to be fully autonomous, with market shares increasing as their prices decline, performance improves, and consumers gain confidence. In the 2050s approximately half of vehicles sold and 40% of vehicle travel could be autonomous. Without mandates, market saturation will probably take several decades, and a portion of motorists may continue to choose human operated vehicles due to costs and preferences. These results are approximately consistent with other estimates by researchers (Cathers 2014; Grush 2016; Lavasani and Jin 2016; Simonite 2016), although slower than the optimistic predictions by some industry experts (Kok, et al. 2017; McKinsey 2016).

Exhibit 13   **Autonomous Vehicle Market Penetration Projections**

Stage	Decade	New Sales	Fleet	Travel
Available with large price premium	2030s	2-5%	1-2%	1-4%
Available with moderate price premium	2040s	20-40%	10-20%	10-30%
Available with minimal price premium	2050s	40-60%	20-40%	30-50%
Standard feature included on most new vehicles	2060s	80-100%	40-60%	50-80%
Saturation (everybody who wants it has it)	2070s	?	?	?
Required for all new and operating vehicles	?	100%	100%	100%

Autonomous vehicle will probably take several decades to penetrate new vehicle sales, fleets and travel.

Exhibit 14 illustrates these deployment rates, including higher and lower estimates.

Exhibit 14   **Autonomous Vehicle Sales, Fleet and Travel Projections** (Based on Exhibit 13)
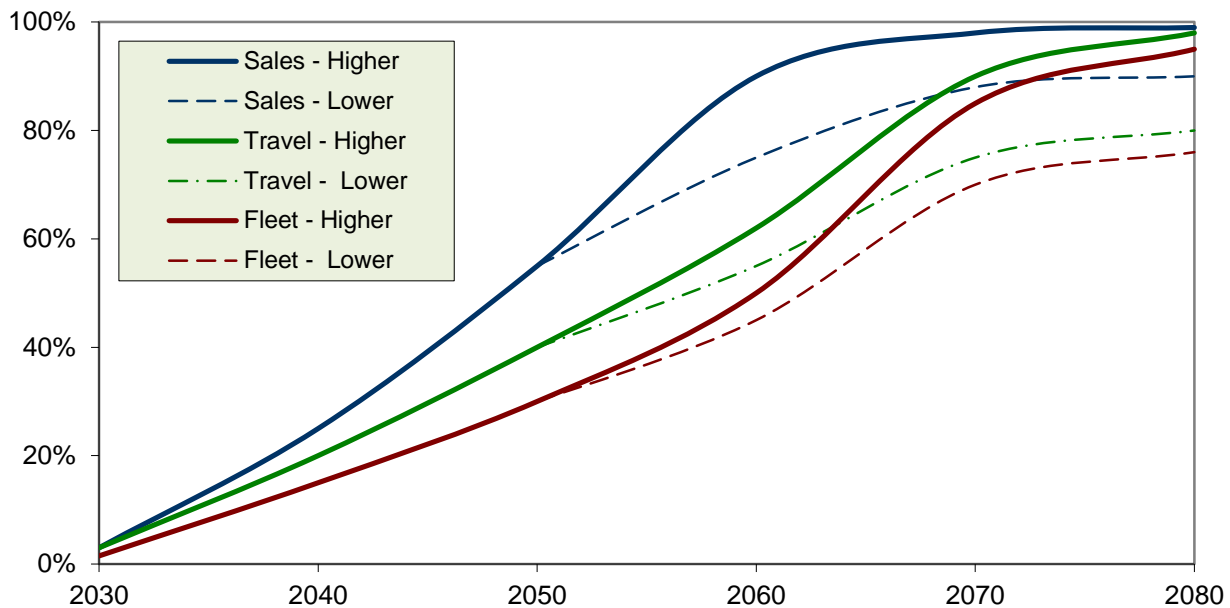
If autonomous vehicles follow previous vehicle technologies, it will take one to three decades for them to dominate new vehicle sales, and one or two more decades to dominate vehicle travel, and even at saturation a portion of vehicle travel may continue to be human operated, indicated by dashed lines.

Because of their high labor costs, buses and trucks are likely to become automated most quickly, particularly for long-haul trips on limited access highways. However, vehicle operators provide various services – passenger assistance and security, system monitoring and maintenance, loading and unloading – and so may be retained in some situations.

Significantly faster implementation will require more rapid development, deployment and fleet turnover than previous vehicle technologies. For example, for most vehicle travel to be autonomous by 2045, almost all vehicles produced after 2035 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 that 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). Autonomous vehicle could accelerate these trends, but 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 the majority of Americans live.

Autonomous vehicle implementation could be slower and less complete than optimistic predictions. Technical challenges may prevent reliable and affordable autonomous vehicles from be commercially available until the 2040s or 2050s. 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 (Miller and Kang 2019). Exhibit 15 summarizes ways that autonomous vehicles may increase or reduce 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 are likely to increase vehicle travel by non-drivers, such as people with disabilities and adolescents. They typically represent 10-30% of community residents but tend to have relatively low vehicle travel demands, and are now often chauffeured by family members or friends, so self-driving vehicles may cause little net increase in their vehicle travel.

Autonomous driving 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 (Fleming and Singer 2019; 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.

Fleming and Singer (2019) surveyed 1,000 U.S. adults concerning their preferences and responses to autonomous vehicles. Although many expect that autonomous driving technology would not significantly affect their vehicle travel, those who do anticipate changes are far more likely to travel more than less. Sivak and Schoettle (2015b) 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. Taiebat, Stolper and Xu (2019) estimate vehicle travel elasticities with respect to fuel and time costs. They find that most households are more sensitive to time than to fuel costs. They predict that autonomous vehicles would increase an average household's vehicle travel by 2–47%, with the largest increases by higher income groups.

Households tend to significantly reduce their vehicle travel when they shift from owning to sharing vehicles (Lovejoy, Handy and Boarnet 2013). As a result, autonomous taxis and micro-transit may allow households to reduce vehicle ownership, and therefore total travel. On the other hand, taxi services require significant *deadheading* (vehicle travel with no passenger to relocate vehicles). Henao and Marshall (2018) estimates that at least 41% of current ride-hailing vehicle travel is deadheading. As autonomous taxi services expand, deadheading may decline but cannot disappear, particularly in suburban and rural areas where demand is dispersed.

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, 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.	Trips currently made by taxi or carshare vehicles.
Motorists who drive more than 6,000 annual miles.	Utilitarian trips currently made by a private vehicle driven less than 6,000 annual miles.
Motorists who require special accessories in their vehicles.	
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.

The following scenarios illustrate how autonomous vehicles would impact various users' travel:

Jake is affluent and vision impaired. He purchases an autonomous vehicle as soon as they become available. *Impacts:* Autonomous vehicles allow Jake to maintain independent mobility which increases his vehicle travel.

Bonnie lives and works in a suburb. She can bike to most destinations but owns a car for occasional trips. When autonomous taxi services become available she gives up her personal vehicle. *Impacts:* Autonomous vehicles allow Bonnie to avoid vehicle ownership and reduce vehicle travel.

Melisa and **Johnny** are shopping for a new home. Autonomous vehicles let them consider more distant houses because Melisa can rest and work while commuting. *Impacts:* Autonomous vehicles allow Melisa and Johnny to choose an exurban home which increased their total vehicle travel.

Garry is a responsible driver when sober but dangerous when drunk. Affordable autonomous vehicles allow him to avoid this risk. *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.

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

Exhibit 17 **Autonomous Vehicle Scenario Summary**

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

Autonomous vehicle availability can have various direct and indirect impacts.

Travel impacts will vary by travel type, as summarized in Exhibit 18.

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

Travel Type	Autonomous Vehicle Impacts	Portion of Travel
Freight trucks	Particularly suitable for long-haul fright travel, due to its high labor costs and limited routes, mostly on grade-separated highways.	10%
Small commercial (trades and deliveries)	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%
Public transport	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.
Longer-distance (> 50 mile) personal trips	Particularly suitable for longer-distance personal trips, due to tedium. May increase longer-distance travel.	Currently 20%, but could increase.
Local suburban and rural	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%
Local urban trips	Many are likely to shift from personal cars to shared autonomous mobility services, which is likely to reduce their total vehicle travel.	20%
Non-drivers	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.*

These impacts are contingent, depending on public policies (Miller and Kang 2019). If public policies make personal autonomous vehicles affordable and attractive, for example, because electric vehicles pay no roadway user fees or have free dedicated lanes, total vehicle travel is likely to increase. If public policies increase road user charges and urban highways have high occupancy vehicle lanes, so shared vehicles are faster than personal vehicles, total vehicle travel is likely to decline.

This suggests that with current policies, autonomous vehicles are likely to significantly increase total vehicle miles travelled, probably by 10-30%, and more on some travel corridors. This is likely to increase urban traffic congestion unless roads are efficiently priced. Electrifying the vehicle fleet will reduce tailpipe emissions, but total impacts will depend on how electricity is generated. Policies that favor shared autonomous travel and compact development can reduce total vehicle travel and traffic problems.

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 19. 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 19   Factors Affecting Transport Demands and Costs
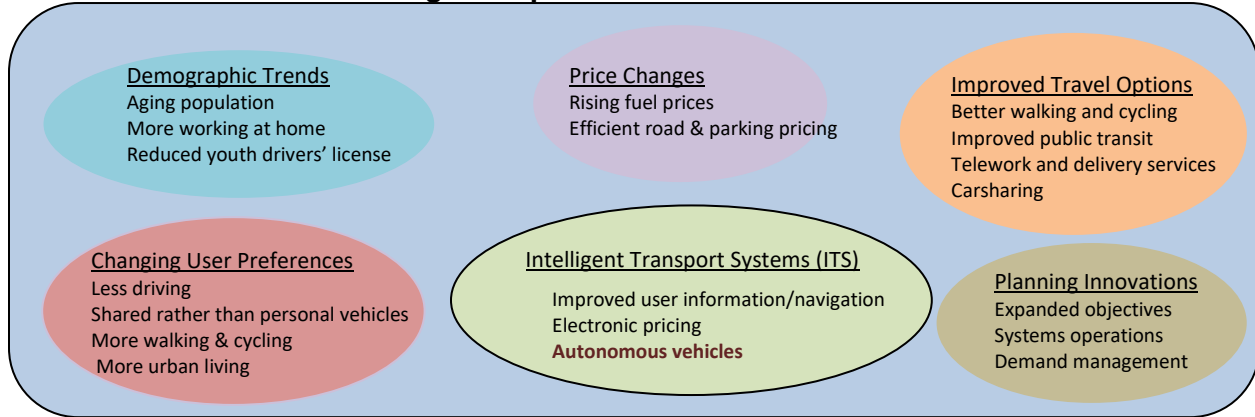
Autonomous vehicles are one of many factors affecting future transport demands.

Some autonomous vehicle benefits, such as reduced driver stress, can occur with Level 2-3 automation, but most benefits, including independent mobility for non-drivers and increased occupant safety require Level 4-5, and many 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 20   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 21 summarizes key autonomous vehicle planning issues.

Exhibit 21   **Key Autonomous Vehicle Planning Issues** (based on Papa and Ferreira 2018)

Issues	Optimistic Outcome	Pessimistic Outcome
Sharing	Policies encourage autonomous vehicle sharing.	AVs are promoted as private luxury goods.
Social exclusion	Policies designed to maximize AV affordability and accessibility ensure that they are widely available.	AVs are only affordable and available by privileged (affluent) users.
Environmental sustainability	AV policies support environmental goals.	AV policies give little consideration of to environmental concerns.
Operated cooperation	AV operating systems are programmed based on cooperative, altruistic and ethical principles.	AV operating systems are programmed based on competitive, aggressive and defensive principles.
Public transport	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.
Intermodal traffic regulations	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.
Network information systems	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.
Sensitive data management	Personal data are carefully managed based on general public interest.	Data are used for commercial purposes. AVs collect an abundance of sensitive private information.
Parking	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.
Curb Access	Curb access is efficiently managed to serve shared vehicle passengers along with other uses.	Curb space is congested and dangerous, and other others (pedestrian and bicyclists) are harmed.
Land use policies	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.
Transport network design	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 22 identifies various planning implications of various planning needs and requirements for autonomous vehicle development.
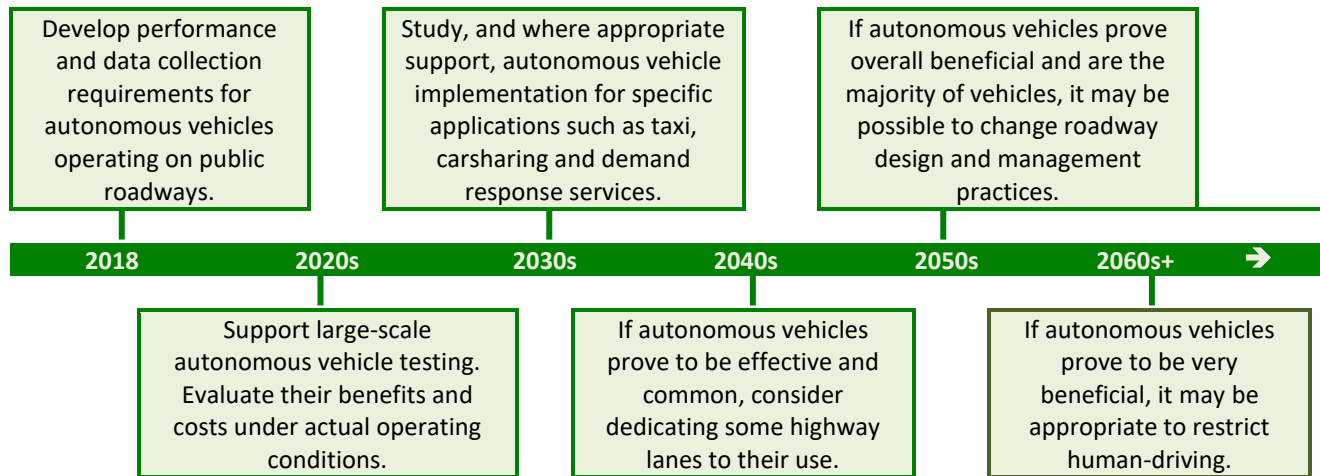
Exhibit 22   **Autonomous Vehicle Planning Needs and Requirements**

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
Address new conflicts and risks	Develop policies to address increased curb and road congestion risks.	Develop efficient curb and roadway management policies, such as curb regulations, congestion pricing and high-occupant vehicle priority policies.	2020-2040
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 23 **Autonomous Vehicle Planning Requirement Time-Line**

Develop performance and data collection requirements for autonomous vehicles operating on public roadways.	Study, and where appropriate support, autonomous vehicle implementation for specific applications such as taxi, carsharing and demand response services.	If autonomous vehicles prove overall beneficial and are the majority of vehicles, it may be possible to change roadway design and management practices.

2018	2020s	2030s	2040s	2050s	2060s+	→

Support large-scale autonomous vehicle testing. Evaluate their benefits and costs under actual operating conditions.	If autonomous vehicles prove to be effective and common, consider dedicating some highway lanes to their use.	If autonomous vehicles prove to be very beneficial, it may be appropriate to restrict human-driving.

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 cities with extreme weather or congestion, and its expansion will depend on the service's profitability, which will require high consumer confidence and satisfaction, and cost reductions. 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 must become inexpensive, ubiquitous and integrated with other mobility options so households can reduce their vehicle ownership and rely on shared vehicle. 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.

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 to minimize conflicts and risks (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)

1. Plan our cities and their mobility together.
2. Prioritize people over vehicles.
3. Support the shared and efficient use of vehicles, lanes, curbs, and land.
4. Engage with stakeholders.
5. Promote equity.
6. Lead the transition towards clean and renewable energy.
7. Support fair user fees across all modes.
8. Aim for public benefits via open data.
9. Work towards integration and seamless connectivity.
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 programed based on ethical and community goals.

- Efficiently regulate and price roads and curb space to minimize conflicts, congestion and risks.

- 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.

Conclusions

Many people hope that autonomous vehicles will soon solve transportation problems. Optimists predict that by 2030, Level 5 vehicle, able to operate autonomously under all normal conditions, will be sufficiently reliable, affordable and common to displace most human-operated vehicles, providing many benefits to users and society overall. However, there are good reasons to be skeptical.

Most optimistic predictions are made by people with financial interests in the industry, based on experience with disruptive technologies such as digital cameras, smart phones and personal computers. They tend to exaggerate benefits, and ignore significant obstacles and costs.

There is considerable uncertainty concerning autonomous vehicle benefits, costs, deployment speed, consumer demand and travel impacts. Operating a vehicle on public roads is complicated due to frequent interactions with other, often-unpredictable objects including animals, pedestrians, cyclists and other vehicle. Significant progress is still needed before autonomous vehicles can operate reliably under all normal conditions, including mixed urban traffic, heavy rain and snow, unpaved and unmapped roads, and poor Internet connections. Several years of testing and regulatory approval will be required before autonomous vehicles can become commercially available. Autonomous operation will add significant costs. The first generations of autonomous vehicles are likely to be expensive and limited in when and where they can operate. These limitations and costs are likely to limit sales. Most motorists will be reluctant to pay thousands of dollars extra for an autonomous vehicle that will sometimes respond, "That destination is not feasible," due to inclement weather or unmapped roads.

Vehicles last longer, cost more, and are more highly regulated than most other consumer goods. As a result, vehicle innovations take longer to transform markets than most other new technologies. It will probably take decades for autonomous vehicles to dominate new vehicle markets and vehicle fleets, and many motorists may prefer human-operated vehicles.

Reliable Level 5 operation will probably not be perfected before 2025, after which they will require several years for testing and regulatory approval. As a result, autonomous vehicles are unlikely to be commercially available and allowed to operate in most areas before 2030. During the 2030s and perhaps into the 2040s, autonomous vehicles are likely to 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 2050s before they are affordable to middle-income households, and longer for lower-income motorists.

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

During the 2030 and 2040s, self-driving taxi and micro-transit services may become available. They should be cheaper than human-operated taxis but offer lower service quality. No drivers will be available to assist passengers, provide security or clean vehicles. Additional passengers will add pickup and drop-off delays, particularly in lower-density areas. Because of these limitations, shared autonomous vehicles will primarily serve local urban trips. Many motorists, particularly in suburban and rural areas, may prefer to own personal vehicles for convenience and prestige sake. As a result, although they may reduce urban vehicle travel, they will probably increase vehicle travel and sprawled development in suburban and rural areas.

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.

Exhibit 24 illustrates a prediction of market penetration and benefits. This indicates that it will be at least 2045 before half of new vehicles are autonomous, 2060 before half of the vehicle fleet is autonomous, and possibly longer due to technical challenges or consumer preferences.

Exhibit 24   **Autonomous Vehicle Sales, Fleet, Travel and Benefit Projections**
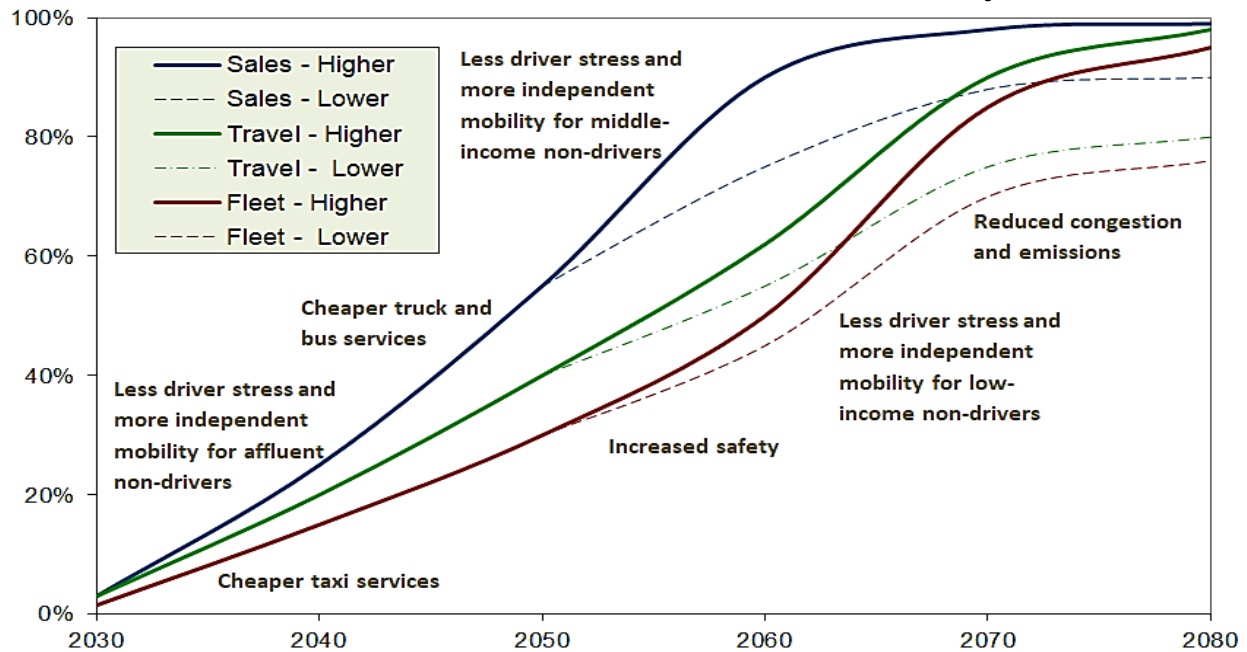
Based on previous vehicle technology implementation patterns, this analysis indicates that it will be at least 2045 before half of all new vehicles are autonomous, 2060 before half of the vehicle fleet is autonomous. Significantly faster deployment will require scraping many otherwise functional vehicles because they lack self-driving capability. Some user benefits can occur when autonomous vehicles are relatively costly and rare, but most benefits, such as independent mobility for moderate-income non-drivers, can only be significant if they become common and affordable, and some benefits, such as increased reduced congestion, require dedicated lanes to allow autonomous vehicle platooning.

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 from personal to shared vehicles and creates more multimodal communities.

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 road, parking and public transit planning decisions.

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