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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.

Summary

This report explores the impacts of autonomous (also called *self-driving*, *driverless* or *robotic*) vehicles, and their implications for transportation planning. It investigates how quickly such vehicles are likely to develop and be deployed based on experience with previous vehicle technologies; their likely benefits and costs; how they will affect travel activity; and their impacts on road, parking and public transit planning. This analysis indicates that Level 5 autonomous vehicles, able to operate without a driver, may be commercially available and legal to use in some jurisdictions by the late 2020s, but will initially have high costs and limited performance. Some benefits, such as independent mobility for affluent non-drivers, may begin in the 2030s but most impacts, including reduced traffic and parking congestion, 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 2060s, and some benefits may require dedicated autonomous vehicle lanes, which raises social equity concerns.

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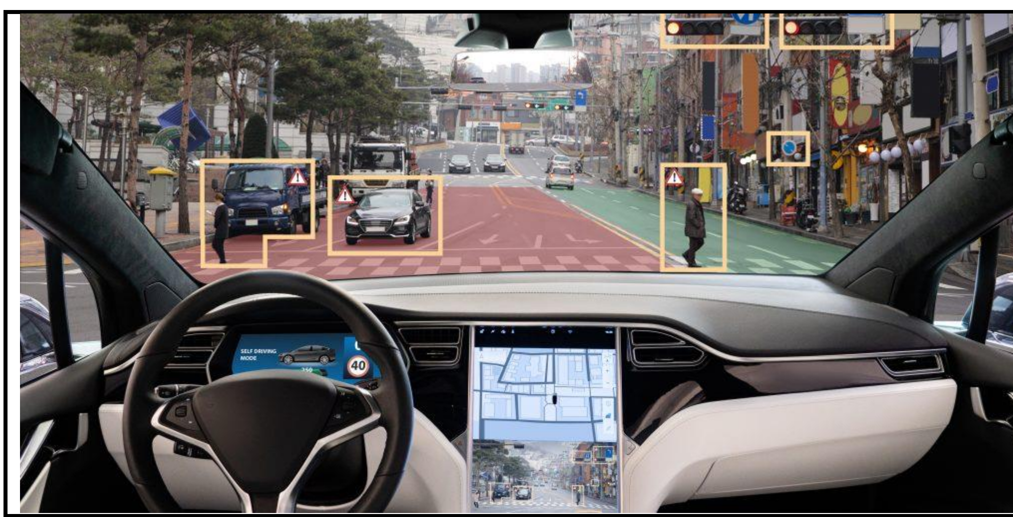


Driving in mixed traffic involves numerous interactions with diverse pedestrians, animals, bicyclists and vehicles, and so is more complex than flying an airplane. (Keith Shaw)

Executive Summary

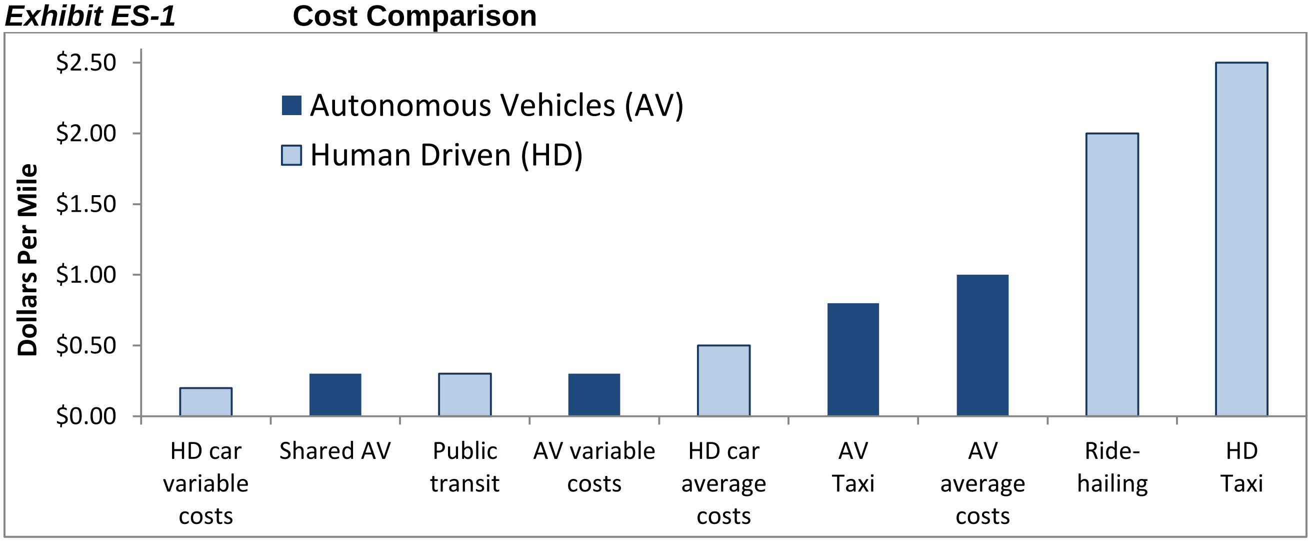
Many decision-makers and practitioners wonder how autonomous (also called *self-driving* or *robotic*) vehicles (AVs) will affect future travel, and therefore the need for roads, parking facilities and public transit services, and what public policies can minimize the problems and maximize the benefits of these new technologies. This report explores these issues.

Optimists predict that by 2030, autonomous vehicles will be sufficiently reliable, affordable and common to displace most human driving, providing huge savings and benefits. 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 ignore significant obstacles to autonomous vehicle development, and exaggerate future benefits.

There is considerable uncertainty concerning autonomous vehicle development, benefits and costs, travel impacts, and consumer demand. Considerable progress is needed before autonomous vehicles can operate reliably in mixed urban traffic, heavy rain and snow, unpaved and unmapped roads, and where wireless access is unreliable. Years of testing and regulatory approval will be required before they are commercially available in most jurisdictions. The first commercially available autonomous vehicles are likely to be expensive and limited in performance. They will introduce new costs and risks. These constraints will limit sales. Many motorists will be reluctant to pay thousands of extra dollars for vehicles that will sometimes be unable to reach a destination due to inclement weather or unmapped roads.

Exhibit ES-1 illustrates autonomous vehicle user costs. They are likely to be more expensive than human-driven private vehicles and public transit, but cheaper than ridehailing and human-driven taxis. Shared autonomous vehicles will be cheaper but less convenient and comfortable than private AVs, so many households, particularly in suburbs and rural areas, will own AVs.

Exhibit ES-1 **Cost Comparison**



Autonomous vehicles (AVs) are likely to cost more than human-driven (HD) private vehicles and public transit, but less than human-driven taxis and ridehailing services.

Autonomous vehicles will have various benefits and costs, including many external costs (costs imposed on other people). All of these impacts should be considered when planning for AVs.

Exhibit ES-2 **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 services 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 cost savings.* 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.	*Increased infrastructure costs.* May require higher roadway design and maintenance standards. *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. *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.

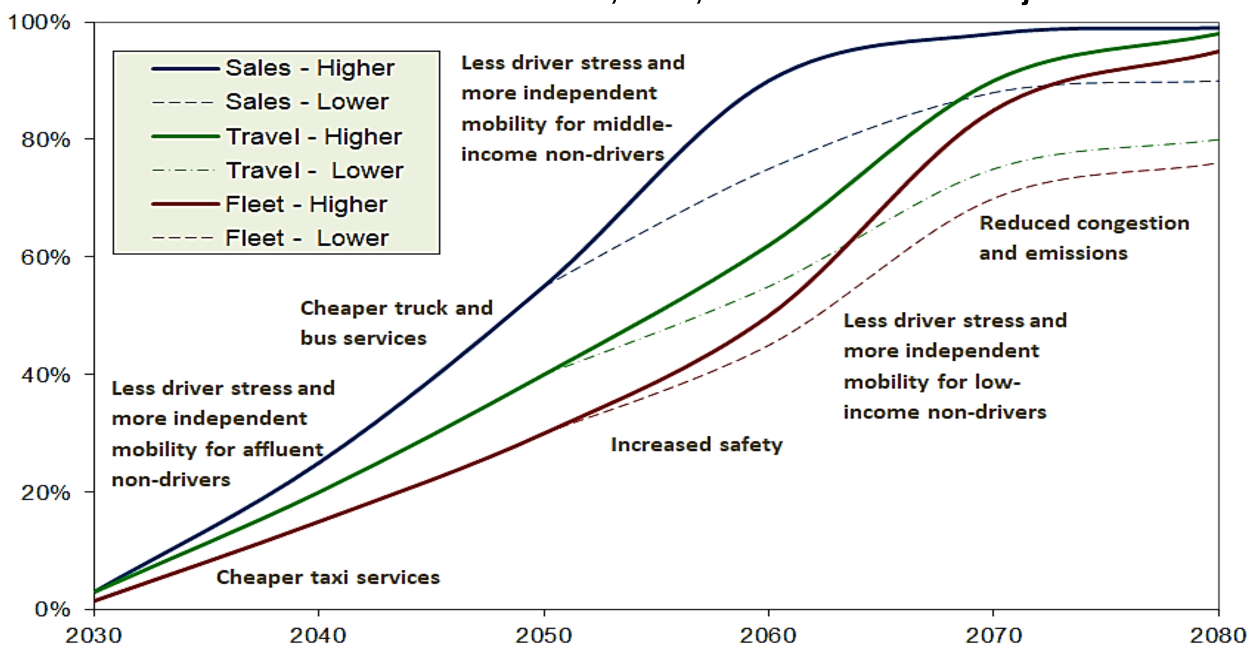
Vehicles last longer, cost more, impose larger external costs, and are more highly regulated than most other consumer goods. As a result, vehicle technologies take longer to penetrate markets than most other sectors. It will probably take decades for autonomous vehicles to dominate new vehicle purchases and fleets, and some motorists may resist using them.

Optimistically, autonomous vehicles will be safe and reliable by 2025, and may be commercially available in many areas by 2030. If they follow the pattern of previous vehicle technologies, during the 2030s and probably the 2040s, they will be expensive and limited in performance, sometimes unable to reach a desired destination or requiring human intervention when they encounter unexpected situations. Customers will include affluent high-annual-mileage motorists and businesses. For the foreseeable future most moderate- and low-income households will continue to use human-operated vehicles.

Shared autonomous vehicles (self-driving taxis) and rides (micro-transit services) may be widely available by the 2030s. Shared *vehicles* have moderate operating costs, and offer moderate convenience and comfort. They should be cheaper than current taxi and ridehailing services, but offer lower quality service since no driver will be available to assist passengers, provide security, or clean vehicles. Vehicle dispatching will sometimes be slow and unpredictable, particularly in suburban and rural areas. Shared *rides* will have the lowest costs but the least convenience and comfort. Because of their high labor costs and predictable routes, long-haul buses and freight trucks are particularly appropriate for autonomous operation, so self-driving buses and trucks may become common in the 2030s and 2040s.

The figure below illustrates these market penetration and benefits projections. This indicates that it will probably be 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. Level 4 autonomy (able to operate autonomously under limited conditions, such as on grade-separated highways) can reduce driver stress and increase productivity, but most benefits require Level 5 autonomy (able to operate autonomously under all normal conditions) so vehicles can transport non-drivers and travel empty to pick up or drop off passengers.

Exhibit ES-2 **Autonomous Vehicle Sales, Fleet, Travel and Benefit Projections**



This analysis suggests that it will be at least 2045 before half of new vehicles are autonomous, and 2060 before half of the vehicle fleet is autonomous. Significantly faster deployment will require scrapping many otherwise functional vehicles that lack self-driving ability. Some benefits, such as reduced driver stress and independent mobility for affluent non-drivers, can occur when autonomous vehicles are relatively costly and rare. However, most benefits, such as independent mobility for moderate-income non-drivers and affordable taxi and micro-transit services, can only be significant if they become common and affordable, and some benefits, such as reduced congestion, will require dedicated lanes to allow platooning.

Many predictions assume that most autonomous vehicles will be electric, which have low fuel costs but require costly batteries and currently pay no fuel taxes. Incorporating battery replacement costs and efficient road user fees increases electric vehicle operating costs to be similar to fossil fuel vehicles.

An important planning issue is whether autonomous vehicles will increase or reduce total vehicle travel and associated traffic problems. It could go either way. By increasing non-drivers' vehicle travel, increasing travel convenience and comfort, reducing vehicle operating costs, generating empty travel, and encouraging longer-distance commutes and more sprawled development, they can increase vehicle travel. This additional vehicle travel provides marginal consumer benefits, and since vehicle travel imposes significant external costs, much of the additional vehicle travel is likely to be economically inefficient: its user benefits will be less than total incremental costs. Alternatively, autonomous operation may facilitate vehicle sharing, allowing households to reduce vehicle ownership and vehicle travel. This suggests that AVs will increase vehicle travel in suburban and rural areas, and reduce it in urban areas. Their net impacts will depend on transport and land use development policies. With current policies, vehicle travel and sprawl are likely to increase 10-30%. More efficient pricing, and roadway management which favors shared vehicles, can reduce vehicle travel and associated problems.

Another critical issue is the degree that 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 vehicles operate autonomously in dedicated lanes.

Autonomous vehicle implementation is just one of many trends likely to affect future transport demands and impacts, and not necessarily the most important. Their ultimate impacts depend on how autonomous vehicles interact with other trends, such as shifts from private to shared vehicles. Autonomous vehicles will probably not be a "game changer" during most of our lives, and will only cause a "paradigm shift" if this technology causes large shifts from private to shared vehicles and creates more multi-modal communities.

Transportation professionals have important roles to play in autonomous vehicle development and deployment. We must anticipate how new technologies and services are likely to affect road, parking and public transit needs, and how to respond to minimize problems and maximize total benefits. We can help define the standards they must meet to legally operate on public roads. We should evaluate their benefits and costs and develop policies to maximize net benefits and ensure that their deployment supports strategic community goals.

Introduction

The future is ultimately unknowable but planning requires predicting impending conditions and needs. Many decision-makers and practitioners (planners, engineers and analysts) wonder how autonomous (also called *self-driving* or *robotic*) vehicles will affect future travel demands, and therefore the need for roads, parking facilities and public transit services, and what public policies can minimize their risks and maximize the benefits (APA 2016; Berrada and Leurent 2017; Grush and Niles 2018; Guerra 2015; Kockelman and Boyles 2018; Milakis, van Arem and van Wee 2017; Shaheen, Totte and Stocker 2018; Sperling 2017).

There is considerable uncertainty about these issues. Optimists predict, based on experience with previous technological innovations such as digital cameras, smart phones and personal computers, that autonomous vehicles will soon be sufficiently reliable and affordable to replace most human driving, providing huge savings and benefits (Johnston and Walker 2017; Keeney 2017; Kok, et al. 2017). However, 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 reliably in all normal conditions (Knight 2020; Leonard, Mindell and Stayton 2020). They will require years of 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. Autonomous driving can create new problems; a camera, telephone or computer failure may be frustrating but is seldom fatal; motor vehicle system failures can be frustrating *and* deadly to occupants and other road users. As a result, autonomous vehicles will probably take longer to develop and provide smaller net benefits than optimists predict.

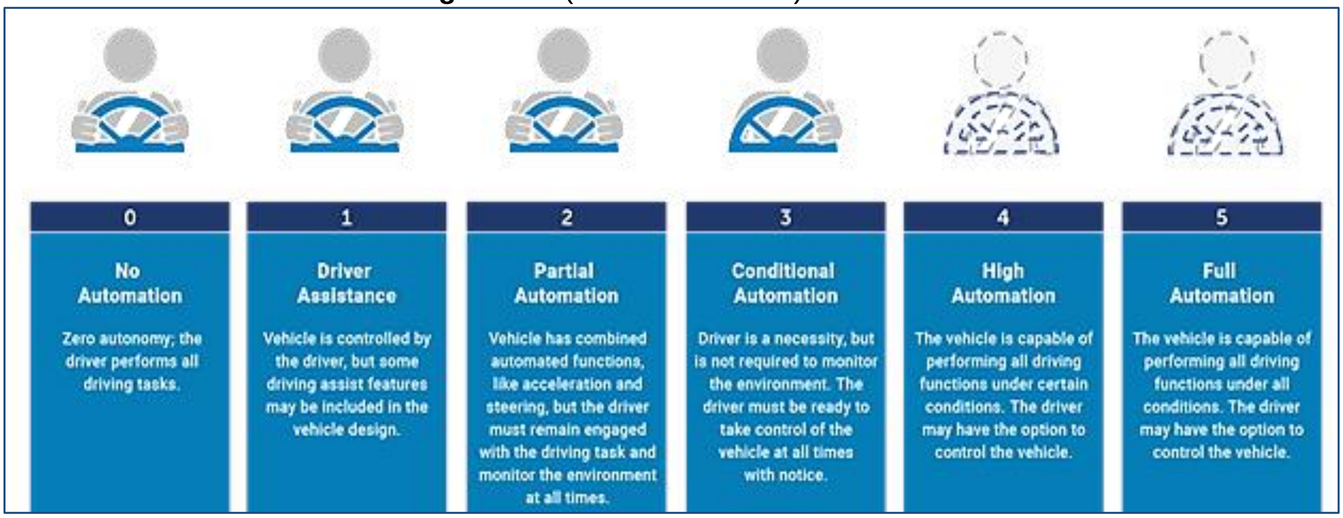
This has important policy implications (Papa and Ferreira 2018; Speck 2017). Vehicles rely on public infrastructure and can impose large external costs, and so require more planning and regulation than most other technologies. For example, many predicted autonomous vehicle benefits, including congestion and pollution reductions, require dedicated lanes to allow *platooning* (numerous vehicles driving close together at relatively high speeds), and autonomous vehicles can be programed to prioritize user benefits such as maximizing travel speed and occupant comfort, or community benefits such as minimizing delay and risks to other road users. Policy makers must decide whether to build special autonomous vehicle lanes, how to price them, and how to regulate their operation in maximize total benefits (Zipper 2021).

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

Exhibit 1 describes the five levels of autonomous driving. Level 4 offers autonomous mobility under some conditions and Level 5 offers autonomous mobility under all normal conditions.

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



The SAE defines five vehicle automation levels. Most predicted benefits require level 5, which allows vehicles to transport non-drivers and goods, and travel empty to pick up passengers.

Exhibit 2 compares four vehicle operating models.

Exhibit 2 **Operating Models Compared**

	Private Human-Driven Vehicles	Private Autonomous Vehicles	Shared Autonomous Vehicles	Shared Autonomous Rides
	Motorists own or lease, and drive, a vehicle.	*Households own or lease self-driving vehicles.*	*Self-driving taxis offer serve individuals.*	*Micro-transit serves multiple passengers.*
Advantages	Low costs. Always available. Users can leave gear in vehicles. Pride of ownership.	High convenience. Always available. Users can leave gear in vehicles. Pride of ownership.	Users can choose vehicles that best meet their needs. Door to door service.	Lowest total costs. Minimizes congestion, risk and pollution emissions.
Disadvantages	Requires driving ability, and associated stress.	High costs. Users cannot choose different vehicles for different uses. Likely to increase vehicle travel and associated costs.	Users must wait for vehicles. Limited services (no driver to help passengers carry luggage or ensure safety.	Least speed, convenience and comfort, particularly in sprawled areas.
Appropriate users	Lower- and moderate-income suburban and rural residents.	Affluent suburban and rural residents.	Lower-annual-mileage users.	Lower-income urban residents.

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

Benefits and Costs

This section describes autonomous vehicle benefits and costs.

Reduced Driver Stress, Improved Productivity and Mobility

Autonomous vehicles can reduce drivers' stress and tedium, and increase their productivity. They can be mobile offices and bedrooms, as illustrated below, allowing passengers to rest or work while travelling (WSJ 2017). This reduces travel time unit costs (cost per hour). However, for safety sake occupants should wear seatbelts, restricting use of in-vehicle beds, and like any confined space, vehicle interiors are likely to become cluttered and dirty (Broussard 2018).

Exhibit 3 **Productivity and Relaxation While Travelling**

Autonomous vehicles can be mobile offices and bedrooms, allowing travelers to work and rest.

Self-driving vehicles can introduce new stresses and discomforts. Travelers may experience "access anxiety" if vehicles are sometimes unable to reach desired destinations, for example, due to heavy rain or snow, or if an area lacks the detailed maps required for autonomous operation (Grush 2016). Self-driving taxi and micro-transit services will be cheaper than human-operated taxis but offer lower service quality since there will be no drivers to help carry packages or ensure passenger safety. To minimize cleaning and vandalism costs most surfaces will be stainless steel and plastic, and security cameras will monitor passengers, yet they may still encounter previous occupants' garbage, stains and odors (Broussard 2018). Shared autonomous rides (micro-transit) require passengers to share space with strangers, and each additional pick-up or drop-off can impose delays, reducing speeds and reliability.

Autonomous vehicles can provide independent mobility for people who for any reason cannot or should not drive. This directly benefits those travelers, and by improving their access to education and employment opportunities, can increase their productivity, and reduce chauffeuring burdens on their family members and friends. On the other hand, 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.

Ownership and Operating Costs

Autonomous vehicles require various equipment and services summarized in the box below. Currently, a set of optional vehicle accessories, such as remote starting, adaptive cruise control, active lane assist and safety cameras, typically cost several thousand dollars, and subscriptions to navigation and security services, such as OnStar and TomTom, cost $150-750 annually.

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. • Short range vehicle-to-vehicle communication networks, plus Internet access for maps, software upgrades and road reports. • Navigation. GPS systems and special maps. • Critical component maintenance, repair and testing.	• Dispatching and fleet management. • Business administration and insurance. • Business profits. • Security. • Frequent cleaning and repairs. • Delays and empty vehicle-miles for passenger loading.

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

Since failures could be deadly, autonomous vehicles will need robust and redundant components, installed and maintained by specialists, increasing maintenance costs. Current advanced driver assistance system sensors (cameras, radar and ultrasound) approximately double minor collision damage costs, typically adding $3,000 to a repair bill (AAA 2018), suggesting that autonomous vehicles will increase vehicle repair costs.

Cleaning and Repairs – Often Overlooked Costs
Although most autonomous taxi passengers are likely to be courteous and responsible, some will probably be messy and a few will be vandalous. To discourage abuse, autonomous taxis interiors will be hard metal and plastic services, with surveillance cameras, which may reduce but cannot eliminate these problems, so vehicles will occasionally have garbage, unpleasant odors, or damage. Autonomous taxis will probably need cleaning every 5-15 trips, plus occasional repairs. Assuming $5-10 per cleaning this will add $0.33-2.00 per trip, plus travel time and costs for driving to cleaning stations.

Optimists often assume that most autonomous vehicles will be electric, which they predict will have low operating costs (less than 5₵ per mile), but these are underestimates. Vehicle batteries must be replaced approximately every 100,000 miles, which currently costs $3,000-15,000, or 3-10₵ per vehicle-mile. This may decline with production innovations, but probably not much, since future vehicles will require increasingly sophisticated batteries, to maximize performance. Electric vehicles currently pay no fuel taxes; cost-recovery road-user fees would increase electric vehicle operating costs 5-10¢ per vehicle-mile. Incorporating these factors increases electric vehicle operating costs to 10-25₵ per mile, similar to fossil fuel vehicles.

What are Efficient Road User Fees?
Efficient road user fees recover roadway costs, with additional charges for congestion, accident and pollution costs imposed on others. Government roadway expenditures total about $250 billion annually which serves about 3,200 billion vehicle-miles, which averages about 8₵ per mile (FHWA 2016); optimal fees are somewhat lower fees for automobiles and higher for heavy vehicles which impose greater roadway costs. Under urban-peak conditions, decongested fees of 5-25₵ per mile are typically required to reduce traffic volumes to roadway capacity.

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 probably take decades to become standard on lower-priced models.

This suggests that autonomous driving capabilities will probably add several thousand dollars to new vehicle purchase prices and hundreds of dollars in additional annual services, maintenance and repair costs. In total this should add a few thousand dollars in annualized expenses, at least for the first few decades of their commercial availability, until competition and depreciation make these technologies available on cheaper models and used vehicles.

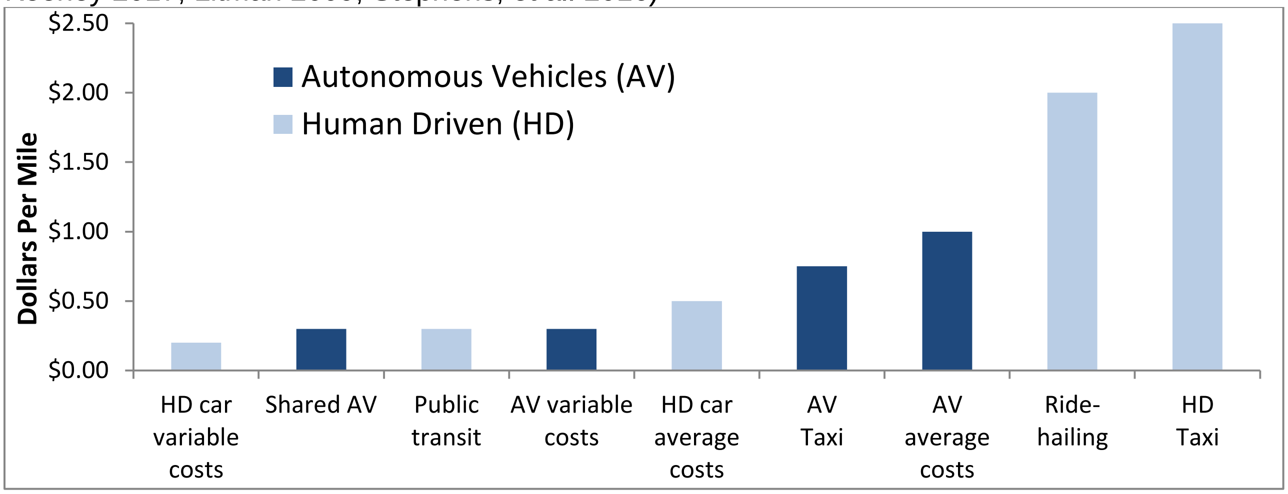
Advocates argue that these additional costs will be offset by insurance and fuel cost savings (Intellias 2018), but that seems unlikely. For example, if autonomous driving cuts collision insurance costs in half, the $300-500 annual savings is just 10-20% of estimated additional costs. Fuel cost savings are also likely to be small, and additional equipment and larger vehicles to serve as mobile offices and bedrooms may increase rather than reduce energy consumption.

This indicates that for the foreseeable future 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 cheaper models. Shared autonomous *vehicles* (self-driving taxis) will probably cost $0.50 to $1.00 per vehicle-mile, and shared autonomous *rides* will probably cost $0.20-0.40 per passenger-mile (Nunes and Hernandez 2020). This is cheaper than human-operated taxis and taxis ($1.50 to $3.00 per mile), but more expensive than personal vehicle operating costs or public transit fares (20-40¢ per passenger-mile).

Some studies estimate lower costs. For example, Kok, et al. (2017) predict that shared, electric autonomous vehicles will cost less than 10¢ per mile, cheap enough that many trips could be funded through advertising, but such estimates ignore costs such as cleaning and vandalism repairs, profits, empty vehicle travel, insurance (many assume 90% lower insurance premiums), and roadway user fees, and so are probably underestimates.

Autonomous vehicles can provide particularly large savings for commercial vehicles, such as freight trucks and buses, due to their high labor costs. However, this will not necessarily eliminate the need for on-board workers since many delivery vehicles require an operator to unload goods, and buses may still need conductors to provide passenger services and security.

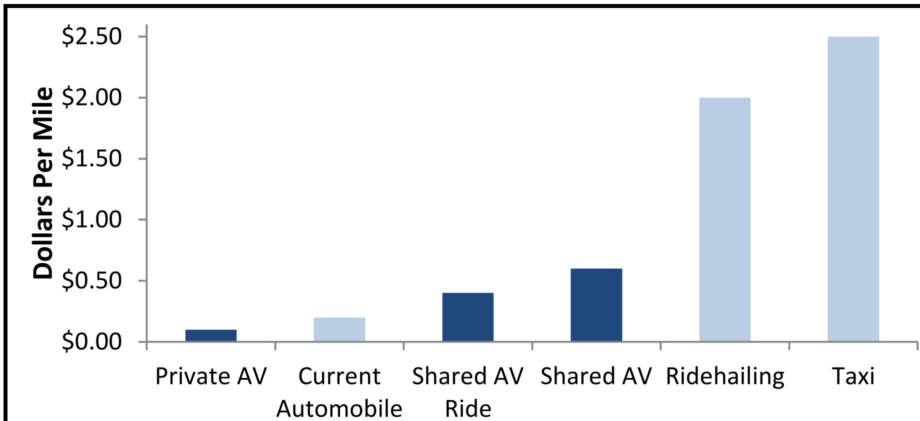
Exhibit 5 **Cost Comparison** (AAA 2017; Bösch, et al. 2017; Johnson and Walker 2017; Keeney 2017; Litman 2009; Stephens, et al. 2016)



Autonomous vehicles (AVs) are likely to cost more than human-driven private vehicles (HVs) and public transit, but less than human-driven taxis and ridehailing services.

Exhibits 5 and 6 compare estimates user costs. *Average costs* are what travelers consider when deciding whether to purchase a vehicle; *variable* (operating) costs are what vehicle owners consider when deciding how to make a particular trip. Electric autonomous vehicles are likely to be cheaper to operate than most current vehicles. Shared autonomous vehicles will be cheaper than taxi and ridehailing services but more expensive than the variable costs of a current automobile, but can provide overall savings for people who travel less than about 6,000 annual vehicle-miles. This will increase vehicle travel and total costs by autonomous vehicle owners, but reduce vehicle travel and costs for those who shift from owning to sharing vehicles.

Exhibit 6 **Variable Costs**



Although automobiles are expensive to own they are relatively cheap to drive, with variable costs (fuel, tire wear, etc.) currently averaging about 20₵ per vehicle mile. This is more than an electric autonomous vehicle but less than shared autonomous rides and vehicles, ridehailing and taxi services.

Public policies will affect these costs. Governments may impose new road user fees to recover roadway costs and reduce traffic problems, which would increase electric vehicle operating costs and make shared vehicle travel more attractive.

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% (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 travelers feel safer they tend to 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 travelers.* 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).
- *Higher vehicle repair costs due to additional equipment*. Additional sensors and control systems, and increased quality control, are likely to significantly increase collision repair costs (AAA 2018).

These new risks will probably cause crashes, so autonomous vehicles will not really achieve the 90% crash reductions that advocates predict. Analysis of factors that contributed to traffic crashes Mueller, Cicchino, and Zuby (2020) concluded that by improved sensing and response, autonomous vehicles could prevent up to 34% of crashes, and more if the technology eliminates all traffic violations, but predictions of 90% crash reductions are exaggerated. Sivak and Schoettle (2015a) conclude that autonomous vehicles will have crash rates similar to an average driver, and total crashes may increase when autonomous 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 total crashes can increase if autonomous operation increases total vehicle travel, for example, if they reduce per-mile crash rates 10% but increase vehicle travel 12%, total crashes, including risks to other road users, will increase.

Autonomous vehicles are vulnerable to hacking. In one experiment, researchers demonstrated that adding graffiti-like marks to a roadside stop-sign caused software to read an inaccurate "Speed Limit 45" (Eykholt, et al. 2018). There will be an on-going arms race between hackers and software designers over autonomous vehicles control, which will add costs and risks.

Autonomous vehicles currently have relatively high operational failure rates. In 2019, the best test vehicles experienced one disengagement (when human drivers overrode automated systems) per 16,666 miles, but most were more frequent (Hyatt 2020). Many disengagements involved non-critical risks and occurred on lower-speed surface streets, and disengagement rates have declined, but this indicates that in 2020 autonomous vehicle operating technologies are not ready for implementation, particularly in mixed urban traffic.

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 after drinking alcohol or taking drugs.

Many factors will affect these impacts, including how vehicles are programmed, and how they affect total vehicle travel. For example, to increase travel speeds autonomous vehicles can be programmed to drive faster, use shortcuts through neighborhoods, and take more risks; to minimize traffic problems they can be programmed to drive slower, be more cautious, and avoid driving on congested roads or neighborhood streets.

The Autonomous Vehicle Trolley Problem
"The trolley problem" refers to various scenarios that ethicists use to consider who should be protected from an out-of-control vehicle, for example, if it should be directed to kill fewer rather than more, older rather than younger, or more rather than less productive people.

Although all vehicles face these trade-offs, decisions by human drivers are generally spontaneous; with autonomous vehicles they are explicitly programed. This raises a public policy issue: who should decide how vehicles are programed when making risk trade-offs.

For example, should autonomous vehicles operate at legal speed limits or to match average traffic speeds on a roadway? How should they prioritize risks to vehicle occupants over risks to other road users? How should an autonomous vehicle respond if faced with unexpected conditions?

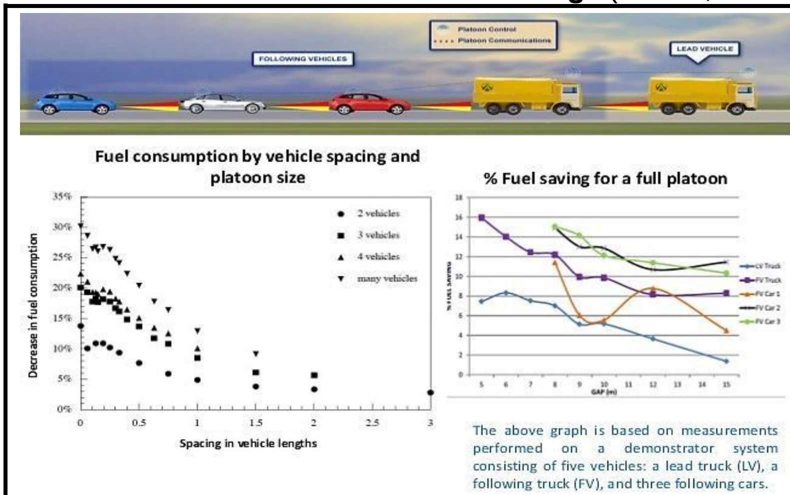
To protect other road users and minimize other external costs, professional organizations should provide guidance concerning how autonomous vehicles should be programed to trade-off costs and risks, and governments should establish regulations to ensure that autonomous vehicles are programed.

Sohrabi, Khreis and Lord (2020) identified 32 pathways through which autonomous vehicles can affect public health, of which 17 are negative and 8 are positive health impacts. To maximize health benefits they recommend equipping AVs with electric motors, regulating urban development, implementing transportation demand management strategies, controlling AV ownership, and imposing ride-sharing policies.

External Cost

Optimists claim that autonomous driving will significantly reduce external costs including traffic congestion, parking costs, crash risks and pollution emissions, but these impacts are uncertain (Eddy and Falconer 2017; Rodier 2018; TRB 2019). Under many circumstances they may increase some external costs. For example, if programmed to maximize passenger safety and comfort so they can rest or work while travelling they will reduce traffic speeds. Unless implemented with effective demand management incentives they are likely to increase total vehicle travel, traffic problems and sprawl, which can increase total congestion, crashes and pollution and other costs (Nadafianshahamabadi, Tayarani and Rowangould 2021). Some benefits require dedicated lanes for platooning (Guhathakurta and Kumar 2019; Heaslip, et al. 2020), which are costly and only feasible on some highways, and they may require special signs, roadway markings, signals and transponders that add costs (Lawson 2018). Shared autonomous vehicles will need docking stations and passenger loading areas (Marsden, Docherty and Dowling 2020; Zhang and Wang 2020).

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



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

Optimists often assume that most autonomous vehicles will be electric, which reduce but do not eliminate pollution emissions, since a major portion of electricity is generated by pollution-emitting fossil fuels (Larco, et al. 2018; Reighmuth 2020), and electric vehicles produce non-exhaust particulate emissions from brake, tire and road wear, which are a major health hazard, particularly in dense urban areas (Air Quality Expert Group 2020).

Overall impacts will depend on how autonomous vehicles are designed and regulated. If programmed for maximum caution and passenger comfort, they will drive slowly and frequently stop to when faced with unexpected conditions, which will reduce traffic speeds and cause delays (Le Vine, Zolfaghari and Polak 2015). If programmed to maximize travel speeds they may increase risks to other road users and take shortcuts through neighborhoods.

Social Equity Impacts
Autonomous vehicles are likely to have various social equity impacts, as summarized below.

1. Horizontal equity with respect to subsidies
A basic economic principle is that markets (a transport system can be considered a market for mobility) are most efficient and equitable if prices (what consumers pay to use a good) reflect the costs of producing that good, or described differently, consumers should generally "get what they pay for and pay for what they get" unless subsidies are specifically justified.

To reduce congestion, crash risk, energy consumption and pollution emissions autonomous vehicles require dedicated travel lanes, and electric vehicles currently receive large purchase subsidies and are exempt from the road user fees that fossil fuel vehicle users pay through fuel taxes. As a result, without new cost-recovery pricing systems, electric autonomous vehicles may receive inequitable subsidies.

2. External traffic costs
External traffic costs (congestion, pedestrian delay, road and parking facility costs, crash risk and pollution emissions that vehicle travel imposes on other people) are inequitable.

Optimists predict that electric autonomous vehicles will reduce these costs, but their actual impacts are uncertain, and will depend on whether they induce more total vehicle travel, and public policies. If given dedicated lanes, autonomous vehicles can increase vehicle throughput, but under most circumstances their congestion impacts are likely to be mixed. They are likely to reduce crashes caused by human error, but will introduce new risks including hardware and software failures, malicious hacking, increased risk-taking if other road users feel safer, and the additional exposure caused by induced vehicle travel. Electric autonomous vehicles should reduce but not eliminate pollution emissions compared with fossil fueled vehicles. These benefits may be partly offset if autonomous driving increases total vehicle travel.

3. Horizontal equity with respect to road space
Road space is a scarce and valuable resource. Horizontal equity requires giving priority to space-efficient vehicles, such as vanpools and buses, so their passengers are not delayed by congestion caused by users of space-intensive modes, such as single-occupant automobiles.

Private autonomous vehicles are likely to have low occupancy rates. As previously described, without efficient road pricing it will often be cheaper for motorists to program their autonomous cars to circle the block or return home, to avoid paying for off-street parking, which will contribute even more to traffic congestion. To maximize equity, public roads should be managed and priced to favor space-efficient modes, including shared autonomous taxis and microtransit, and to limit traffic volumes to roadway capacity. This will be increasingly important as autonomous vehicles become more common, which will increase potential travel demands.

4. Vertical equity with respect to abilities and needs

This assumes that transportation policies should favor people with special needs, such as people with disabilities or impairments, families with children, travellers carrying baggage, or non-drivers located in automobile-dependent areas.

Autonomous vehicles can provide more independent mobility for people with some disabilities, such as visual impairments, and because of their lower costs, autonomous taxis can provide an affordable option for non-drivers for some trips.

5. Vertical equity with respect to income – affordability

This perspective assumes that public policies should favor poorer over wealthier people, and increase affordable transportation options, particularly to access essential services and activities (healthcare, basic services, education, jobs, etc.).

For the next two or three decades autonomous driving capability is predicted to increase annual costs by a few thousand dollars, to approximately $10,000 per vehicle-year, to pay for additional hardware and software, maintenance, and mapping subscriptions. Autonomous taxis will probably cost $0.50 to $1.00 per mile, which is cheaper than human-powered taxies but more expensive than a personal human-operated automobile. This suggests that personal autonomous vehicles will not be affordable to lower-income households, and policies that favor their use, such as dedicated lanes, will be regressive. Autonomous taxi services can increase affordability compared with owning a personal vehicle for people who drive relatively low annual miles. Affordable transportation is usually defined as costing less than 15% of a household's total expenditure budget, so a $40,000 annual expenditure household (second income quintile) can afford to spend up to $6,000 per year on transportation, which can only pay for about 5,000 annual autonomous taxi-miles each for two adults.

This implies that most low- and moderate-income households can only can only benefit from autonomous vehicles as part of a multimodal lifestyle; autonomous vehicles will not help them afford the high-annual-miles generally required for living in sprawled locations.

In summary, autonomous vehicles are likely to support some equity goals but contradict others. Autonomous vehicles can provide independent mobility for some disadvantaged groups, such as people with visual impairments, and can reduce taxi and public transit operating costs, which increases affordability for people who drive less than about 5,000 annual miles. Private autonomous vehicles will be costly, so subsidies for their use tend to be unfair and regressive. They can reduce affordability and fairness, and harm non-drivers overall, if they induce additional vehicle travel and sprawl, which increases external costs (congestion, infrastructure costs, crash risk and pollution emissions imposed on other people), or if they increase automobile dependency and sprawl, which reduces affordable transport options.

Benefit and Cost Summary

The table below compares costs and benefits of various vehicle types.

Exhibit 8 **Costs Compared**

	Private Human-driven Vehicle	Private Autonomous Vehicle	Shared Autonomous Vehicle	Shared Autonomous Ride
Financial costs	Low fixed costs (particularly used cars), moderate variable.	High fixed costs, low variable costs.	Minimal fixed costs, moderate variable costs.	Minimum fixed costs, low variable costs.
Convenience	High. A private vehicle is available any time.	High. A private vehicle is available any time. Provides vehicle travel to non-drivers.	Moderate. Vehicles will often require several minutes to arrive. Provides door-to-door service.	Moderate. Collecting passengers will often take several minutes. Does not provide door-to-door service.
Comfort	Low to moderate, depending on driving conditions.	High. Users have their own vehicles with chosen amenities.	Moderate. Shared, vehicles may be abused.	Lowest. Travelers share vehicles with strangers.
External costs (congestion, facilities, crashes and pollution)	Moderate to high.	High. Likely to increase total vehicle travel which will increase external costs.	Moderate. May increase total vehicle travel in some circumstances and reduce it in others.	Lowest. Can reduce total vehicle travel and associated costs
Social equity impacts	Moderate to high. Inequitable.	Moderate to high. Least equitable.	Moderate to low. Mixed equity impacts.	Lowest. Most equitable.
Most appropriate uses	Moderate- and low-income suburban and rural residents.	Affluent suburban and rural residents	Suburban and urban travelers.	Urban travelers.

Vehicle types vary in their costs, convenience and comfort, and therefore their impacts on total vehicle travel.

Fulton, Compostella and Kothawala (2020) perform similar analysis of the monetary and non-monetary factors that affect travel decisions including travel time, stress, convenience, reliability, and preferences regarding driving and sharing vehicles.

Of course, these impacts will depend on specific vehicle features. Larger, higher-speed vehicles tend to be more costly than smaller, lower-speed vehicles, and electric vehicles have lower operating costs than fossil fuel vehicles. Financial costs are likely to be much higher during the first decade or two that autonomous vehicles are commercially available, and should decline as this technology becomes available in lower-priced models, and eventually in used vehicles.

Exhibit 9 summarizes autonomous vehicle benefits and costs, categorized according to whether they are internal (affect users) or external (affect other people). Total impacts will depend on how they affect total 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 9 **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 services 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 cost savings.* 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.	*Increased infrastructure costs.* May require higher roadway design and maintenance standards. *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. *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.

Some benefits, such as reduced driver stress and increased productivity, can occur with Level 4 automation (able to operate autonomously under certain conditions, such as grade-separated highways during clear weather), but most benefits require Level 5 automation (able to operate autonomously under all normal conditions), which allows vehicles to transport non-drivers and drive empty.

Travel Impacts

A key factor in this analysis is how autonomous vehicles will affect total vehicle travel (Miller and Kang 2019; Nunes et al. 2021; Rodier 2018). Exhibit 10 summarizes potential impacts.

Exhibit 10 **Potential Autonomous Vehicle Travel Impacts**

Increases Vehicle Travel	Reduces Vehicle Travel
Increased vehicle travel by non-drivers.	
Empty vehicle travel to drop off and pick up passengers, deliver goods, and travelling to maintenance stations.	
Reduced vehicle operating costs (due to electrification) increases vehicle travel.	More convenient shared vehicle services allow households to reduce vehicle ownership, which leverages vehicle travel reductions.
Increased passenger convenience and productivity encourages people to travel more.	Self-driving buses, and better last-mile access, improve transit services.
Over the long run encourages more sprawled development and reduced public transit service.	Reduced traffic risk and parking facilities make urban living more attractive.

Autonomous vehicles can affect total vehicle travel in various ways.

Autonomous vehicles are likely to significantly increase non-drivers' vehicle travel, particularly if they are electric. By increasing passenger comfort and productivity, autonomous operation can make long-distance trips, including commutes, more endurable, increasing vehicle travel and sprawl. Electric vehicles cost about half as much to operate as comparable fossil-fuel vehicles. Because they cost more to own but less to drive than current automobiles, they give vehicle owners even more incentive to maximize their annual vehicle travel, in order to get their money's worth from these large fixed investments. This is likely to increase annual vehicle mileage, particularly by suburban and rural autonomous vehicle owners (Nunes et al. 2021). One study found that families given free chauffeuring services increased their vehicle travel by 80%, with large increases in longer distance and zero-occupancy travel (Harb, et al. 2018).

By providing more affordable taxi and public transit services, improving walking and bicycling conditions, and reducing parking needs, autonomous vehicles may encourage urban living and vehicle sharing (Lovejoy, Handy and Boarnet 2013), which can reduce vehicle travel. As a result, total travel impacts depend on the portion of households that choose urban rather than suburban or rural locations, and the portion that share rather than own autonomous vehicles.

Optimists predict that shared autonomous taxis will soon displace most private vehicles (ITF 2014; Keeney 2017). For example, Kok, et al (2017), predicted 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 travelers have good reasons to own rather than share 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 and ridehail vehicles arrive a few minutes of being summoned, but can take much longer, particularly during busy periods, for special vehicle types (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 private vehicle.
- *Status.* Many people take pride in their vehicles and driving ability, and so may prefer to own private vehicles that are capable of human operation.

Shared rides have lower costs but less convenience and comfort, since trips take longer to collect passengers, generally cannot offer door-to-door service, and passengers must travel in confined spaces with strangers. Vehicle dispatching adds delays and uncertainty, particularly in suburban and rural areas, where an autonomous taxi pickup may take 10-20 minutes. Vehicle sharing generates *deadheading* (zero-passenger vehicle travel) for example, when loading passengers. More than 40% of current ridehailing vehicle travel is deadheading (Henao and Marshall 2018). If sharing services become common in an area, deadheading may decline but cannot disappear, particularly in suburban and rural areas where destinations are dispersed.

Exhibit 11 compares the travelers and trips most suited to various vehicles.

Exhibit 11 **Most Suitable Travelers and Trips**

Human-Driven	Private Autonomous	Shared Autonomous
Moderate- and lower-income drivers, who purchased older, used vehicles. Motorists who prefer driving their vehicles for enjoyment or perceived safety sake. Travelers who place a high value on privacy.	Travelers who place a high value on comfort or status. Motorists who drive more than 6,000 annual miles. Motorists who often carry equipment, tools, or special accessories in their vehicles.	Trips currently made by taxi or carshare vehicles. Utilitarian trips currently made by a private vehicle driven less than 6,000 annual miles. Urban residents. People who want to save money more than time.

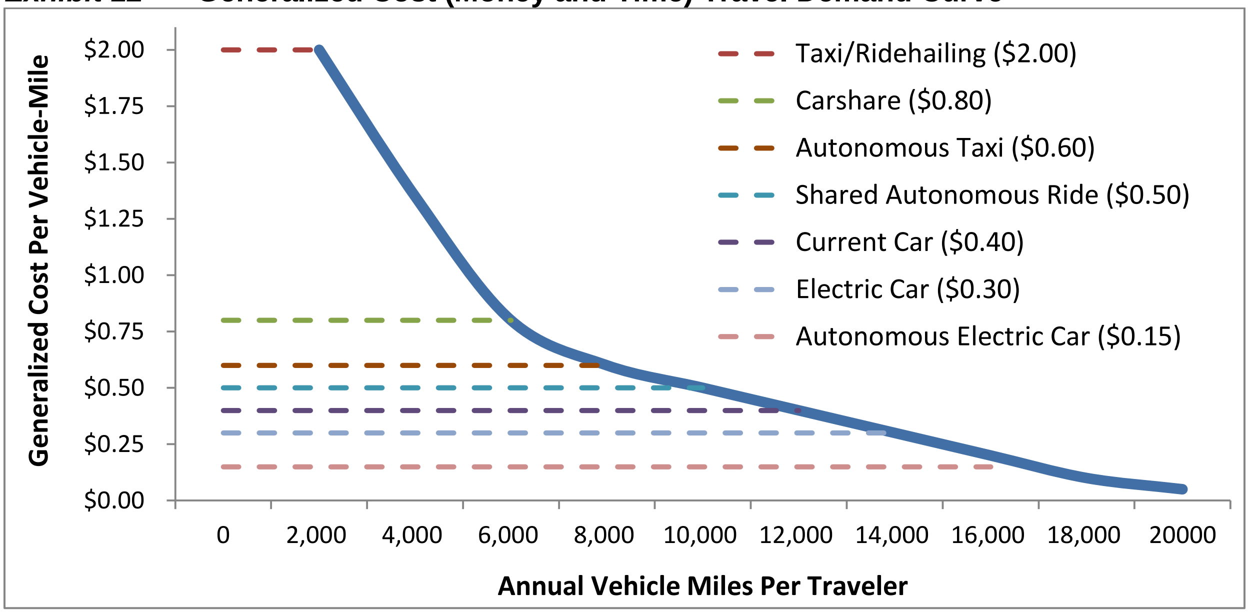
Some travelers are most suitable for private vehicles, other for shared vehicles.

One way to predict autonomous vehicle travel impacts is to consider how they affect *generalized costs*, which include travel time and vehicle operating costs. As these costs decline, people tend to travel more. Drivers typically value their time at 20-40% of wage rates (e.g., a \$20/hr. automobile worker would pay \$1-2 to save ten minutes), or about 20₵ per mile. Autonomous vehicles probably reduce drivers' travel time costs by about half. Vehicle and ride sharing introduce delays and inconvenience compared with owning a personal vehicle.

Taxi and ridehailing typically cost about $2.00 per mile, current gasoline cars about 20₵ per mile, and electric cars about 5₵ per vehicle-mile, considering just short-term vehicle operating costs (fuel and tire wear).

Exhibit 12 compares these costs on a travel demand curve, which illustrates how prices affect vehicle travel. Taxi and rideshare travel are relatively costly, so people who rely on these modes tend to generate relatively few vehicle-miles. Carsharing, autonomous taxis and autonomous rides are cheaper than taxis but more expensive and less convenient than private automobiles, resulting in moderate annual vehicle travel by people who rely on them. Conventional, fossil fuel automobile owners typically drive about 10,000 annual miles, and electric car owners are likely to drive somewhat more due to their low fuel costs. Electric autonomous vehicle owners are likely to increase automobile travel due to their low fuel and travel time costs.

Exhibit 12 **Generalized Cost (Money and Time) Travel Demand Curve**



As generalized costs decline, annual vehicle travel increases. Currently, automobile owners typically drive about 10,000 annual miles. People who rely on autonomous taxis and rides are likely to travel less due to higher financial costs and reduced convenience, while people who own private electric autonomous vehicles are likely to travel more due to lower operating and travel time costs, and high convenience.

Of course, these costs and consumer responses are difficult to predict and will depend on other factors, including quality of mobility services available, land use development conditions, and individual preferences. However, it is safe to predict that people who rely on shared autonomous vehicles will on average travel less, and those who own personal electric autonomous vehicle will travel more, than they would with conventional, fossil fuel, human-operated vehicles. Public policies can affect the amount of travel generated by these modes by affecting their financial and travel time costs, for example, through fuel and road user fees, and roadway management strategies that make shared vehicles more convenient and faster to use.

Some recent studies have investigated autonomous vehicle travel impacts. A survey of 1,000 U.S. adults found that many do not expect autonomous vehicles to significantly affect their travel, but those who do are far more likely to predict vehicle travel increases than declines (Fleming and Singer 2019). Sivak and Schoettle (2015b) estimate that accommodating non-drivers' latent travel demands could increase total vehicle travel 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) predict that autonomous vehicles will increase average household's vehicle travel by 2–47%, with the largest increases by higher income groups.

The table below summarizes these impacts.

Exhibit 13 **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, so they are likely to own autonomous vehicles. Delivery companies can use autonomous vehicles to reduce costs. This may increase total vehicle travel.	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 private vehicles or use shared autonomous vehicles, which could reduce their total vehicle travel.	50%
Local urban trips	Many are likely to shift from private cars to shared autonomous mobility services, which is likely to reduce their total vehicle travel.	20%
Non-drivers	Non-drivers are likely to increase their vehicle travel.	2-4% but increasing.

Autonomous vehicle travel impacts will vary by types of trips.

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 private 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 14 summarizes the impacts of these various scenarios. In most of these scenarios autonomous vehicles increase total vehicle travel

Exhibit 14 **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 traveler)	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.

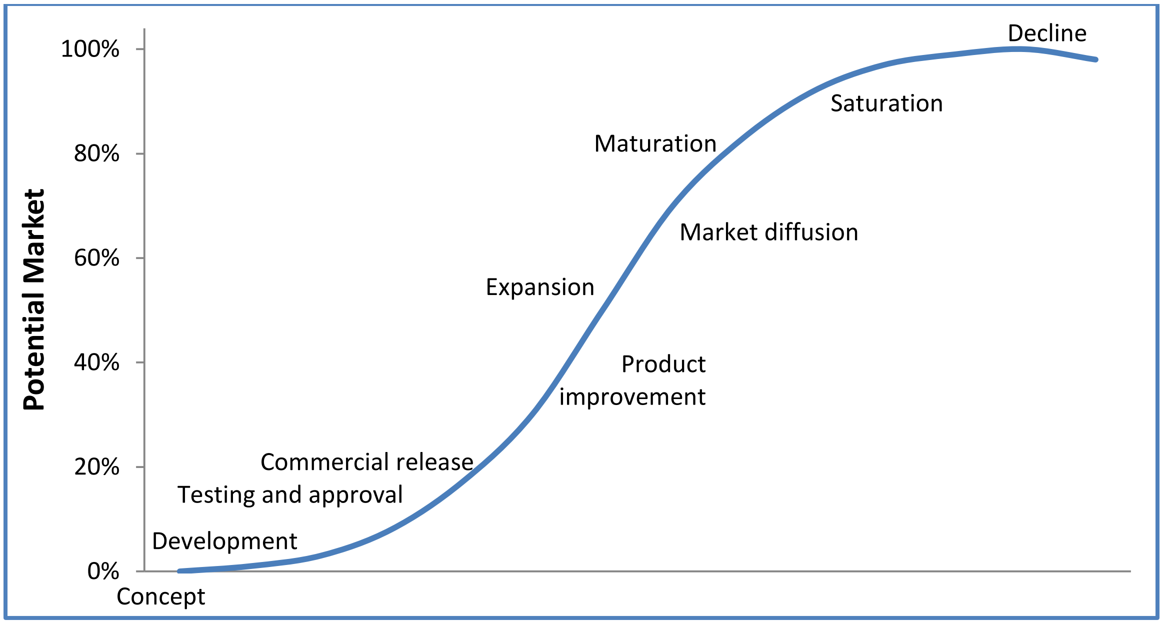
This suggests that with current policies, autonomous vehicles are likely to increase total vehicle travel by 10-30%, and possibly more, increasing traffic congestion and roadway infrastructure costs, and possibly crash risk and pollution emissions, depending on the type of travel that increases. Public policies will affect these impacts (Miller and Kang 2019). If policies make private autonomous vehicles affordable and attractive, for example, because electric vehicles pay minimal road user fees and autonomous vehicles have dedicated lanes, total vehicle travel is likely to increase. If they are charged efficient road user fees and roads have high occupancy vehicle lanes, shared rides will become more attractive, reducing total vehicle travel.

This additional vehicle travel tends to provide small marginal benefits, since it consists of travel that users most willingly forego if their costs increase. To value such benefits economists use the *rule of half*, which states that the benefits of additional travel are worth half the total per-trip saving (Litman 2009, "Evaluating Transportation Benefits"; World Bank 2005). For example, if a 10¢ per mile cost reduction caused a motorists to travel 1,000 additional vehicle-miles, the net benefit can be valued as $50, calculated at (10₵ x 1,000)/2 = $50). Since vehicle travel imposes significant external costs, including congestion, infrastructure costs, and possibly crashes and pollution emissions, much of the additional vehicle travel is likely to be economically inefficient; its incremental benefits are less than its incremental costs.

Development and Deployment Predictions

New technologies generally follow an S-curve development pattern, as illustrated in Exhibit 15. 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 15 **Innovation S-Curve**



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

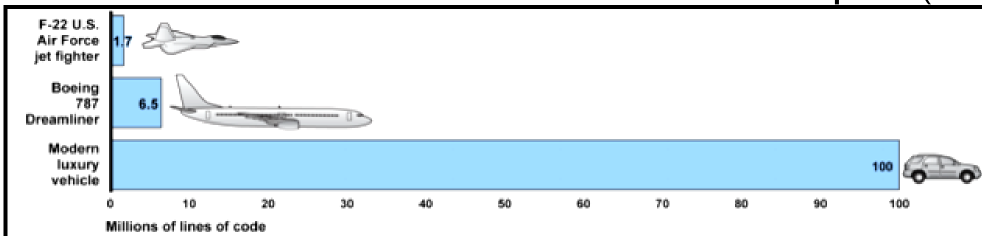
Autonomous vehicles are currently in development and testing stages. Many current vehicles have Level 2 and 3 technologies such as cruise control, hazard warning and automated parallel parking. Tesla's *Autopilot* offers automated steering and acceleration in limited conditions, although deployment was delayed after it caused a fatal crash in 2016 (Hawkins 2017). Several companies have Level 4 pilot projects, which are testing autonomous vehicles in certain conditions (CPUC 2020), but despite this progress, many technical improvements are needed before vehicles can operate autonomously under all normal conditions (Simonite 2016).

Autonomous vehicle technologies will need to go through several more stages to become widely commercially available, reliable and affordable, and therefore common in the vehicle fleet. Because vehicles can impose significant external costs, such as congestion and crash risks, 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 if the technology proves to be unreliable and dangerous, for example, if autonomous vehicles cause high-profile crashes, it may take longer (Bhuiyan 2017). It is likely that different jurisdictions will impose different testing, approval and regulations, resulting in varying rates of deployment.

In 2015, autonomous vehicle expert Chris Urmson famously predicted that his son would never need a driver's license because self-driving would be ubiquitous by the time he reached driving age in 2019, but in a 2019 interview he predicted a much more modest, "hundreds or maybe thousands of self-driving vehicles on the road within five years" (The Economist 2019). Although current technologies allow vehicles to operate autonomously on grade-separated highways, in good weather, achieving 95% operability (vehicles are unable to reach desired destination a few times each month) will be difficult (Leonard, Mindell and Stayton 2020). Achieving 99.9% operability (vehicles are unable to reach desired destinations only about once a year) will be far more difficult still (Wharton 2017).

Operating a vehicle on public roads is complex due to the frequency of interactions with often-unpredictable objects including potholes, vehicles, pedestrians, cyclists and animals. As a result, autonomous vehicles require orders of magnitude more complex software then aircraft (Exhibit 16). Producing such software is challenging and costly, and it is sure to have errors. There will almost certainly be system failures, some causing severe accidents.

Exhibit 16 **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 dressed 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.

In addition to technological progress, market deployment depends on consumer demand: travelers' willingness to pay for autonomous mobility. Surveys indicate significant consumer concerns (Schoettle and Sivak 2014). Travelers will face *access anxiety* if their vehicle cannot reach all desired destinations (Grush 2017).

Although optimists predict that most vehicles will operate autonomously by 2030 (Johnston and Walker 2017; Keeney 2017; Kok, et al. 2017), most of them have financial interests in autonomous vehicle industries, and base their predictions on experience with electronic technologies such as digital camera, smart phones and personal computers rather than motor vehicle innovations. For example, the widely-cited report, "*Rethinking Transportation 2020-2030*" 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 has 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; 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 vehicles that lack autonomous driving capability, but that seems unlikely under realistic assumptions of their benefits and costs.

Most objective experts acknowledge that Level 5 automation will require many more years for development and testing (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 …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). Chris Urmson, CEO of Aurora, a leading autonomous vehicle development firm, in 2015 hoped that self-driving cars would eliminate the need for his son to obtain a driver's license when he became eligible in 2019, but that year admitted that only "hundreds or maybe thousands of self-driving vehicles" will operate on public road by 2024.

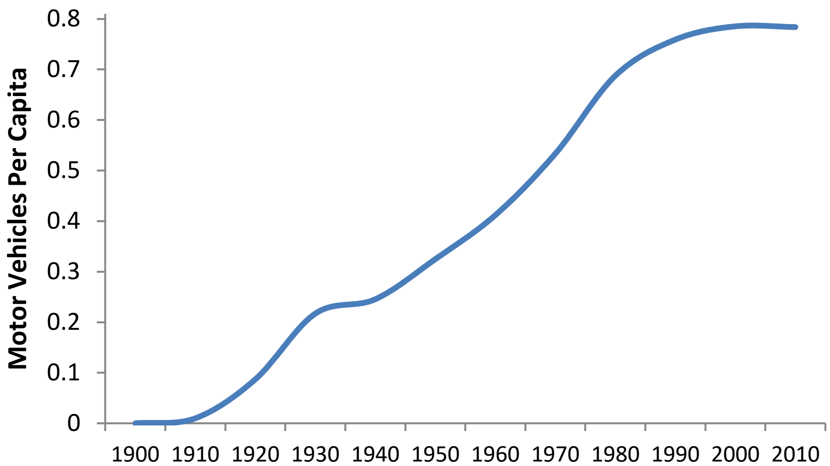
The following section uses experience with previous vehicle technologies to provide realistic predictions of autonomous vehicle development and deployment.

Experience with Previous Vehicle Technology Deployment

Previous vehicle technologies can help predict autonomous vehicle deployment.

Mass automobile production began in 1908 with the Ford Model T. By the 1920s, cities experienced traffic and parking congestion, and by the 1930s vehicles outnumbered households, but the transport system remained mixed, with most people relying on walking, bicycling and public transit in addition to their cars. Only after the 1960s did most adults have a private vehicle, and only after the 1980s did the market approach saturation.

Exhibit 17 **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 private 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 for them to become reliable and affordable. When optional, they typically cost $1,000 to $2,000. They are included in 90% of new vehicle 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 caused injuries and deaths), they became cheaper and safer, became standard on some models starting in 1988, and mandated by U.S. federal regulation in 1998.
- *Hybrid Vehicles* (Berman 2011). These 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 2016 they represented about 2% of total vehicle sales.
- *Remote lock/unlock, diagnostics, emergency response and navigation services.* OnStar became available in 1997, TomTom in 2002. Such services typically cost $150-750 annually.
- *Vehicle Navigation Systems* (Lendino 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. Vehicle navigation apps, such as Google Maps and Waze, are available for free or a modest fee.

- *Electric vehicles* ("History of Electric Vehicles" Wikipedia). Battery-electric cars developed in the late 1800s, but were uncommon during most of the Twentieth Century. In the 1990s, major manufactures produced improved models, such as General Motor's EV1, and by 2020 many companies sold high quality electric cars. Despite this progress, only about 1% of total vehicle sales are electric and high-performance models are expensive.

Exhibit 18 summarizes their deployment. All of these technologies required decades from initial commercial availability to market saturation, and some have never became universal.

Exhibit 18 **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	$400 annual	5-10%
Navigation systems	30+ years (1985-2015+)	$500 and rapidly declining	Uncertain; probably over 80%.
Electric vehicles	100+ years	$10,000 for high-performance	Probably 80%+

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

Because autonomous vehicle technologies are more complex and costly than these technologies, their market acceptance and penetration are likely to take longer (Lavasani and Jin 2016). New vehicles are becoming 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 10^{th} year, and 5,000 miles their 15^{th} 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 19 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 have limited performance. During their first decade only a minority of new vehicles are likely to be fully autonomous, with market shares increasing as their performance improves, prices decline, and consumers gain confidence. By 2045 as much as half of new vehicle sales 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 researchers' estimates (Grush 2016; Lavasani and Jin 2016; Simonite 2016), although slower than the optimistic predictions by some industry experts (Kok, et al. 2017; McKinsey 2016).

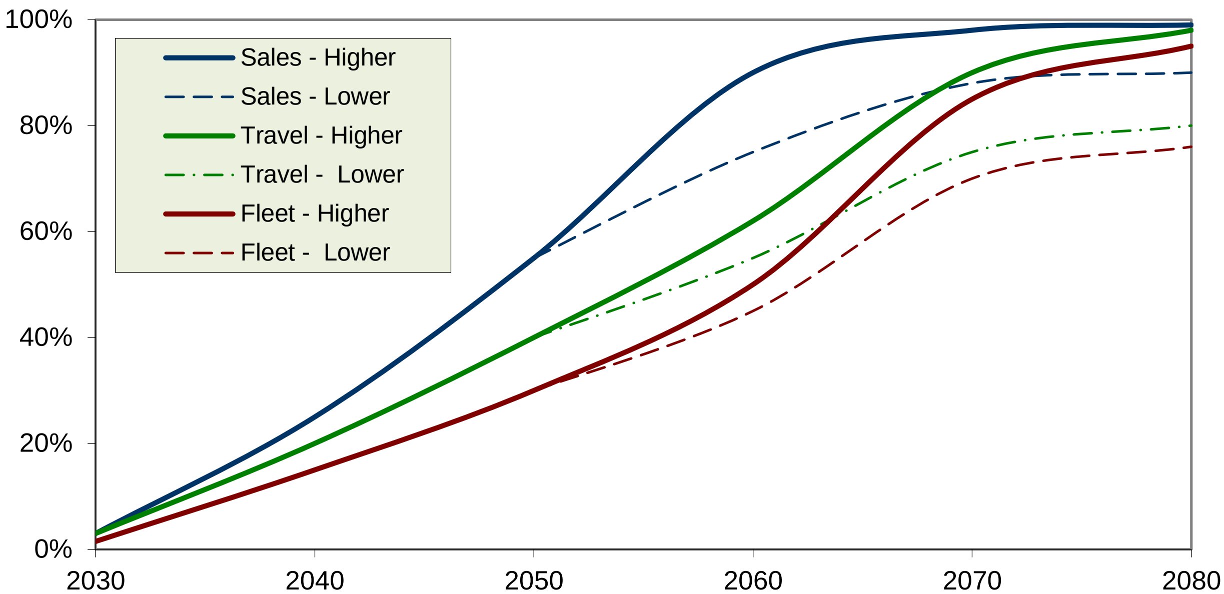
Exhibit 19 **Autonomous Vehicle Market Penetration Projections**

Stage	Decade	New Sales	Fleet	Travel
Development and testing	2020s	0%	0%	0%
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 20 illustrates these deployment rates, including higher and lower estimates.

Exhibit 20 **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, commercial vehicles are likely to be automated most quickly, particularly for long-haul travel on limited access highways. However, commercial drivers provide various services, including passenger assistance and security, monitoring and maintenance and loading, so some vehicle operator jobs will change but not disappear.

Significantly faster implementation would 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, new vehicle purchase rates and spending would need to increase significantly so fleet turnover that normally takes three decades can occur in one, and many otherwise functional vehicles would be scrapped simply because they lack self-driving capability.

Shared mobility services, such as carsharing and ridehailing, are already 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 they are inconvenient and inefficient, and so are unlikely to replace the majority of private vehicle travel in suburban and rural areas where most Americans currently live.

The following factors affect the speed of autonomous vehicle deployment:

- **The speed of technological development.** Level 4 technologies (vehicles able to operate autonomously in limited conditions) are currently available, but significant technological progress is needed before vehicles can operate autonomously under all normal conditions. Reliable Level 5 operation may be available in five years or may require another 25 years.
- **Testing and regulatory approval.** Testing and approval standards are currently under development, but several more years may be required for these standards to be adopted in most jurisdictions, and additional time will be required for large-scale testing.
- **Incremental costs.** Autonomous vehicles require additional equipment and services which add costs. For the foreseeable future (one to three decades) autonomous operation will only be available in relatively expensive new vehicles, adding thousands of dollars in annual expenses compared with human-operated vehicles. High incremental costs will reduce the portion of new vehicles that have this technology, reducing the speed of fleet penetration.
- **Consumer travel and housing preferences and development practices.** Currently, most North American households live in automobile-dependent communities and own private vehicles. Autonomous vehicle sharing is most appropriate for households that live in more multi-modal communities where they travel less than about 6,000 annual miles by automobile. As a result, shared autonomous vehicle travel will become more common if many households are able to move into multi-modal communities. Consumer acceptance may be reduced by safety fears, privacy concerns, or preferences, resulting in a significant portion of vehicle travel remaining human-driven even after market saturation
- **Service quality and affordability.** If autonomous taxis are convenient, comfortable and affordable, many people may shift from owning to sharing vehicles. However, if they are unreliable, uncomfortable or expensive, more households will continue to own private vehicles.
- **Public policies.** Implementation could be accelerated if public policies encourage autonomous vehicle development and purchase, if road and parking pricing, and roadway management favor shared vehicles, if highway lanes are dedicated to autonomous vehicle platooning, if development policies allow more infill development, if autonomous operation is required for new vehicles, or if governments support scrapping a major portion otherwise functional vehicles because they lack autonomous driving capability.

Planning Implications

Autonomous vehicles raise various planning issues (Taeihagh and Lim 2018):

Roadway Design

Autonomous vehicles may require new roadway design features such as improved lane markings, signs designed to be read electronically, and wireless repeaters in tunnels to provide internet access. Autonomous driving may allow narrower traffic lanes, but to accommodate trucks and buses, large reductions are only feasible on special lanes limited to car traffic. As autonomous vehicles become more common, governments will be asked to dedicate highway lanes to their use, to allow platooning. Similarly, autonomous vehicles could eliminate the need for traffic signals, but this is only feasible in areas where all vehicle traffic is autonomous. To encourage shifts from lower- to higher-occupancy vehicle travel on congested corridors, governments may need to establish more HOV priority lanes.

Transportation Pricing

As previously described, with current policies, electric autonomous vehicles are likely to increase vehicle travel and traffic problems, typically by 10-30%, by reducing travel time and vehicle operating costs, stimulating more sprawled development and increasing deadheading (empty vehicle travel). In addition, electric vehicles currently pay no road user fees, which is unfair. To address these problems governments will need to impose new fees, which could include a combination of road user charges of 4-8₵ per vehicle-mile, plus decongestion pricing of 5-30₵ per vehicle mile when operating in congested conditions(Simoni, et al. 2019).

Curb Management

To facilitate vehicle sharing, cities will need to manage curbs to provide convenient passenger loading and unloading (Marsden, Docherty and Dowling 2020; OECD/ITF 2018). This involves providing passenger loading areas, or by managing on-street parking to increase turnover so at least one unoccupied space is usually available near every destination.

Parking Planning

Autonomous vehicles can affect future parking demands in many ways (Chai, et al. 2020; González-González, Nogués and Stead 2020; Marsden, Docherty and Dowling 2020; Zhang and Kaidi Wang 2020). Electric autonomous vehicles will require special parking facilities with electric charging stations and vehicle cleaning and maintenance services. Optimists predict that autonomous vehicles will significantly reduce parking demands and costs. A shift from private to shared vehicles can reduce total vehicle ownership and parking needs, and private vehicle owners may program their cars to return home after dropping off passengers, although that will increase traffic problems and add delays and uncertainty as to when passengers could be picked up. Most travelers will probably want their vehicles to be available within a few minutes, which will require parking within a mile or two of their destination. This may allow more off-site and shared parking, reducing but not eliminating urban parking demands.

Public Transit Needs

Autonomous vehicles can affect public transit demands in several ways.

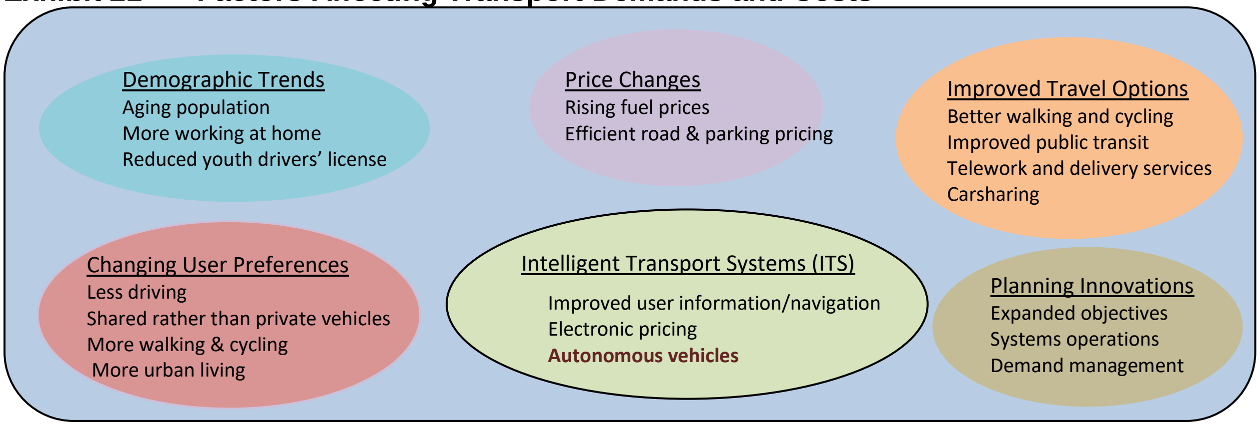
- Since labor represents the majority of transit operating costs, autonomous technologies could significantly reduce the costs of providing transit services. With a given budget, transit agencies can provide more frequent service using smaller vehicles, and in some situations, have flexible routes that deliver passengers closer to their destinations (paratransit).
- Cheaper taxi services can provide convenient mobility for non-drivers, either door-to-door or as a feeder to bus stops and train stations. This should be particularly effective in suburban and rural areas where conventional transit is inefficient.
- They can reduce conventional transit demand, which reduces revenue, cost efficiency and political support, resulting in reduced service quality. Because paratransit requires more road space and energy than public transit, shifts from public transit to autonomous vehicles are likely to increase traffic congestion, accidents and pollution emissions.

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). To avoid potential problems many experts recommend that governments impose efficient road pricing, develop high occupancy vehicle lanes and improve public transit services on busy travel corridors in order to limit traffic congestion and maintain transit system efficiency.

Other Trends Affecting Travel Demands

Autonomous vehicle development is just one of many trends that will affect future transport demands and planning needs, as illustrated in Exhibit 21. Changes in demographics, consumer preferences, prices, information technologies, mobility options, and other planning innovations may have greater impacts than autonomous vehicles for the foreseeable future.

Exhibit 21 **Factors Affecting Transport Demands and Costs**



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

Some benefits, such as reduced driver stress, can occur with Level 2-4 automation, but most benefits require Level 5 automation, and some only occur when they are shared, or if have dedicated lanes. The following matrix summarized the benefits provided by various AV types.

Exhibit 22 **Autonomous Vehicle Benefits**

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

Various types of autonomous vehicles provide different types of benefits. Many benefits require Level 5 and shared vehicles.

Exhibit 23 is a timeline for autonomous vehicle planning issues.

Exhibit 23 **Autonomous Vehicle Planning Issues** (Henaghan 2018; Largo, et al. 2018)

Issue	Analysis Required	Policies Required	Time
Reliability and safety	Evaluate reliability and safety. Establish regulatory framework.	Define performance, testing and data requirements for AV operation on public roads.	2020-30
Overall travel impacts	Investigate travel changes, and likely benefits and costs.	Transport management to reduce congestion, accidents and emissions.	2020-2040
Local vehicle traffic impacts	Investigate changes in motor vehicle traffic and their impacts.	Decongestion pricing, vehicle restrictions, HOV priority, and policies that favor shared rides.	2020-40
Safety	Investigate new risks, crash impacts particularly to other road users.	Regulate AVs to ensure safety for all road users. Price and manage roads for safety.	2020-60s
Mobility for non-drivers	Autonomous vehicle availability and affordability to non-drivers.	Policies that ensure that AVs serve people with disabilities and low incomes.	2020-30s
Impacts on vehicle sharing	Quality of shared autonomous vehicles and rides	Regulate and encourage shared autonomous vehicles and rides	2030-40s
Energy and emission impacts	AV fuel type and consumption. Impacts on total vehicle travel.	Encourage efficient and electric AVs. Price and manage roads to minimize total vehicle travel.	2030-60s
Parking and passenger loading	Impacts on vehicle ownership and use, and parking and loading needs.	Reduce parking requirements and efficiently manage parking and curb space.	2040-50s
Roadway design	Impacts on roadway traffic and design needs.	Change roadway designs. Consider creating AV lanes. Determine their funding and pricing.	2050-70s
Plan for mixed traffic	Degree of conflicts between AVs and other road users.	Develop polices and facility designs to minimize conflicts and risks.	2040-60s
Autonomous vehicle mandates	Potential benefits of mandating AVs.	If benefits are very large, require all vehicles to be AVs and restrict human driving.	2060-80s

This table identifies various needs and requirements to achieve autonomous vehicle planning objectives.

Because pedestrians and bicyclists are difficult for sensors to see, and less predictable than motor vehicles, autonomous vehicles may impose special risks on non-motorized travelers. The Pedestrian and Bicycle Information Center identifies ten 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 needs.

Autonomous vehicle benefits will depend on public policies. The following table compares optimistic and pessimistic outcomes of autonomous vehicle policies.

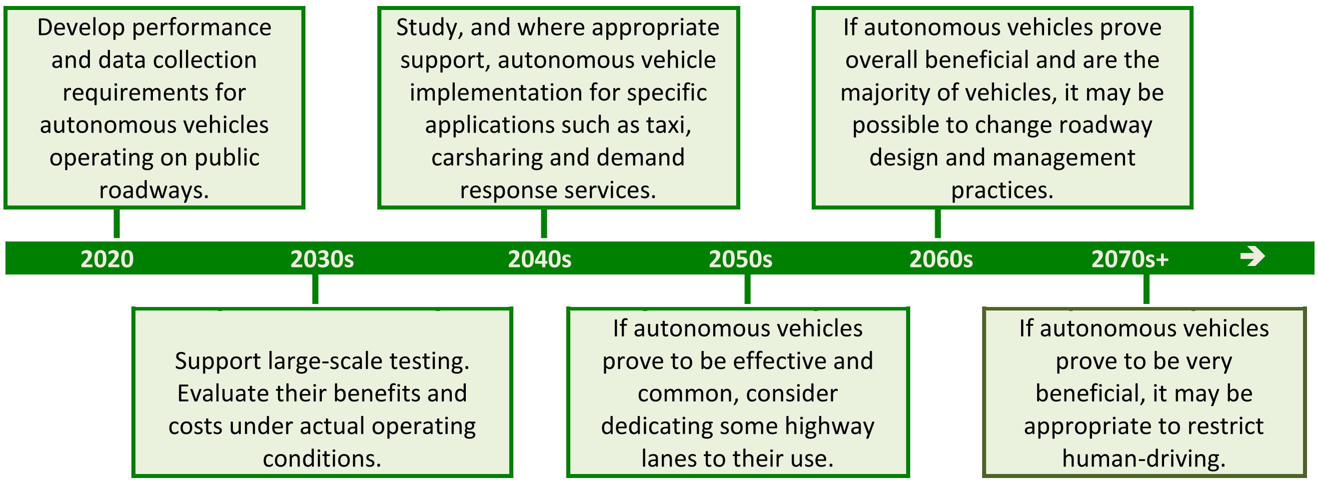
Exhibit 24 **Optimistic and Pessimistic Outcomes** (based on Papa and Ferreira 2018)

Issues	Optimistic Outcome	Pessimistic Outcome
Sharing	Policies encourage vehicle sharing.	AVs are promoted as private luxury goods.
Social inclusion	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 goals.
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 management	AVs are programmed to minimize risks and delay to other road users.	AVs are programed to favor occupants over other road users.
Data Network	Data networks are designed to maximize overall transport system efficiency and sustainability.	Data networks are designed to maximize profits, so critical information is sold.
Sensitive data management	Personal data are carefully managed based on general public interest.	Abundant personal data collected by AVs are used for commercial purposes.
Parking	Parking facilities are converted into buildings, active transport infrastructure and greenspace.	Parking policies remain as they are, so parking continues to consume valuable land.
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 planning	Transport planning is multi-modal, and favors resource-efficient modes.	Transport planning favors AVs, for example, with dedicated lanes and low user fees.

Autonomous vehicles raise many policy and planning issues.

The timeline below summarizes autonomous vehicle planning requirements.

Exhibit 25 **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 started 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 was soon reestablished.

Phoenix was chosen because it has a 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 more severe 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 travelers lack a private 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 vehicles. 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 passenger loading 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 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 multi-modal neighborhoods, 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 passenger 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 dedicated autonomous vehicle lanes, which raise fairness, pricing and enforcement concerns.

There are also potential planning conflicts. By increasing total vehicle travel, encouraging dispersed development, and displacing public transit, autonomous vehicles could exacerbate congestion, sprawl and inequity problems. Shared vehicles reduce parking demand but increase the need for passenger loading facilities (OECD/ITF 2018). Some public interest organizations have developed guidelines for optimizing autonomous vehicle benefits (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 strategies can help maximize autonomous vehicle benefits and minimize their social costs (Larco, et al. 2018; González-González, Lynott 2018; Nogués and Stead 2020; Schlossberg, et al. 2018; TRB 2017; WEF 2020):

- Emphasize social goals such as transport system efficiency and equity.
- Test and regulate new technologies for safety and efficiency.
- Ensure responsible collection, storage and sharing of key data, such as vehicle trips and conflicts to measure positive and negative impacts. Encourage data system and platform interoperability.
- Require autonomous vehicles to be programed based on ethical and community goals.
- Implement policies, such as efficient pricing and vehicle priority in traffic, to favor higher value trips and more space-efficient travel, and to limit vehicle traffic volumes to optimal levels.
- Ensure that shared autonomous services are affordable and serve people with special needs.
- Integrate shared autonomous services into multi-modal transportation systems, for example, to provide last-mile access to public transit stations and to reduce traffic lanes so more road space is available for bikelanes, sidewalks and greenspaces.
- Incorporate *universal design* that accommodates people with special needs and abilities.
- Use vehicle traffic reductions to redesign streets and improve urban livability.
- Reduce parking minimums and public parking to take advantage of shared vehicles. Use reduced parking needs to increase urban densities and greenspace.
- Efficiently price development to prevent inefficient sprawl.

Conclusions

Many people wonder how soon autonomous vehicles will help solve transportation problems. Optimists predict that by 2030, autonomous vehicles will be sufficiently reliable, affordable and common to displace most human driving, providing huge savings and benefits. 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 ignore significant obstacles to autonomous vehicle development and exaggerate future benefits.

There is considerable uncertainty concerning autonomous vehicle development, demands, benefits, costs, and travel impacts. Operating a vehicle on public roads is complicated due to frequent interactions with often-unpredictable animals, people and vehicles. Considerable progress is needed before autonomous vehicles can operate reliably in mixed urban traffic, heavy rain and snow, unpaved and unmapped roads, and with unreliable wireless service. Years of testing and regulatory approval are required before they are commercially available in most jurisdictions. The first commercially available autonomous vehicles are likely to be expensive, limited in performance, and will introduce new risks. These constraints will limit sales. Many motorists will be reluctant to pay thousands of extra dollars for vehicles that will sometimes be unable to reach a destination due to inclement weather or unmapped roads. Vehicles last longer, cost more, impose larger external costs, and are more highly regulated than most other consumer goods, so new vehicle technologies are slow to penetrate markets. It will probably take decades for most vehicles to be autonomous, and some motorists may resist them.

Optimistically, Level 5 autonomous vehicles will be safe and reliable by 2025. A few more years will be required for testing and regulatory approval, so by 2030, autonomous vehicles may be commercially available and allowed to operate in many areas. If they follow the pattern of previous vehicle technologies, during the 2030s and probably the 2040s, they will be expensive and limited in performance, sometimes unable to reach a desired destination or requiring human intervention when they encounter unexpected situations. Customers will include affluent high-annual-mileage motorists, and businesses that use vehicles to transport equipment and goods. For the foreseeable future most moderate- and low-income households will continue to use human-operated vehicles. It will probably be the 2050s before private autonomous vehicles are affordable to most middle- and lower-income motorists.

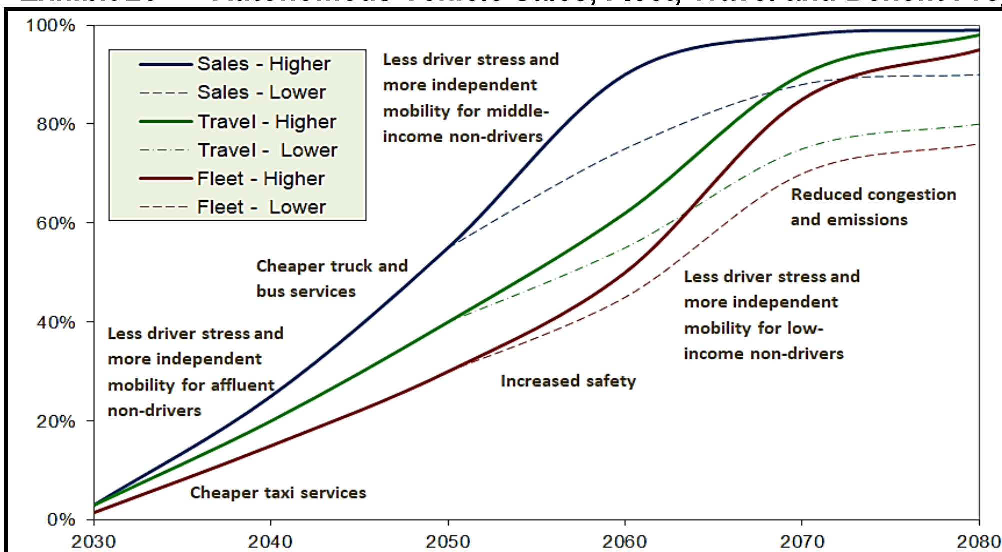
Shared autonomous vehicles (self-driving taxis) and rides (micro-transit services) are being tested in some jurisdictions but it will probably be the 2030s before they are widely available. Shared *vehicles* have moderate operating costs and offer moderate convenience and comfort. They should be cheaper than current taxi and ridehailing services, but offer less service since no driver will be available to assist passengers, provide security, or clean vehicles. Vehicle dispatching will sometimes be slow and unpredictable, particularly in less dense areas. Shared *rides* have the lowest costs but the least convenience and comfort since collecting passengers add delays, they cannot provide door-to-door service, and passengers must share confined spaces with strangers. Because of these limitations, shared vehicles and rides will primarily serve urban trips and are unlikely to dominate suburban and rural travel.

This analysis suggests that it will be at least 2045 before most vehicles are autonomous, and longer before they are affordable. Significantly faster deployment will require scrapping most otherwise functional vehicles that lack self-driving ability. Some benefits, such as reduced driver stress and independent mobility for affluent non-drivers, can occur when autonomous vehicles are relatively costly and rare. However, 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 reduced congestion and emissions, require dedicated lanes to allow platooning. Their social equity impacts are mixed, they are likely to reduce some external costs but increase others, and they can benefit some disadvantaged groups but harm others, particularly if they induce additional vehicle travel and sprawl. Self-driving taxies and micro-transit services can provide greater efficiency and equity benefits, particularly if public policies favor shared vehicle travel, with decongestion pricing and high-occupancy vehicle lanes.

Many predictions assume that most autonomous vehicles will be electric, which have low fuel costs but require costly batteries and currently pay no fuel taxes. Incorporating battery replacement costs and efficient road user fees increases electric vehicle operating costs to be similar to fossil fuel vehicles. Because of their high labor costs and predictable routes, self-driving buses and trucks may become common relatively quickly but many of these vehicles will still need employees on board to provide passenger assistance, security, loading and unloading.

The figure below illustrates market penetration and benefit predictions. Level 4 autonomy (able to operate autonomously under limited conditions, such as on grade-separated highways) can reduce driver stress and increase productivity, but most benefits require Level 5 autonomy (able to operate autonomously under all normal conditions) so vehicles can transport non-drivers and travel empty to pick up or drop off passengers. Some benefits, such as independent mobility for affluent non-drivers, may occur while autonomous vehicles are expensive and rare, but most benefits require that they be affordable and common, which will take decades.

Exhibit 26 **Autonomous Vehicle Sales, Fleet, Travel and Benefit Projections**



This analysis suggests that it will be at least 2045 before half of new vehicles are autonomous, and 2060 before most of the vehicle fleet is autonomous. Some benefits can occur when autonomous vehicles are expensive and rare, but most benefits will only be significant when they are affordable and common.

An important planning issue is whether autonomous vehicles will increase or reduce total vehicle travel and associated traffic problems. It could go either way. By increasing non-drivers' vehicle travel, increasing travel convenience and comfort, reducing vehicle operating costs, generating empty travel, and encouraging longer-distance commutes and more sprawled development, they can increase vehicle travel. This additional vehicle travel provides marginal consumer benefits, and since vehicle travel imposes significant external costs, much of the additional vehicle travel is likely to be economically inefficient: its user benefits will be less than total incremental costs. Alternatively, autonomous operation may facilitate vehicle sharing, allowing households to reduce vehicle ownership and vehicle travel. This suggests that AVs will increase vehicle travel in suburban and rural areas, and reduce it in urban areas. Their net impacts will depend on transport and land use development policies. With current policies, vehicle travel and sprawl are likely to increase 10-30%. More efficient pricing, and roadway management which favors shared vehicles, can reduce vehicle travel and associated problems.

Another critical issue is the degree that 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 vehicles operate autonomously in dedicated lanes.

Some public interest organizations have developed guidelines for optimizing autonomous vehicle benefits. These emphasize social goals such as overall system-wise safety and efficient, and transportation demand management to limit vehicle travel to roadway capacity and favor high-occupancy over lower-occupancy vehicles.

Autonomous vehicle implementation is just one of many trends likely to affect future transport demands and impacts, and not necessarily the most important. Their ultimate impacts depend on how autonomous vehicles interact with other trends, such as shifts from private to shared vehicles. Autonomous vehicles will probably not be a "game changer" during most of our lives, and will only cause a "paradigm shift" if this technology causes large shifts from private to shared vehicles and creates more multi-modal communities.

Transportation professionals have important roles to play in autonomous vehicle development and deployment. We must anticipate how new technologies and services are likely to affect road, parking and public transit needs, and how to respond to minimize problems and maximize total benefits. We can help define the standards they must meet to legally operate on public roads. We should evaluate their benefits and costs and develop policies to maximize net benefits and ensure that their deployment supports strategic community goals.

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