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Autonomous Vehicle Implementation Predictions

Implications for Transport Planning

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The Google Corporation's self-driving car is a well-publicized example of an autonomous vehicle.

Abstract

This report explores the impacts that autonomous (also called *self-driving*, *driverless* or *robotic*) vehicles are likely to have on travel demands and transportation planning. It discusses autonomous vehicle benefits and costs, predicts their likely development and implementation based on experience with previous vehicle technologies, and explores how they will affect planning decisions such as optimal road, parking and public transit supply. The analysis indicates that some benefits, such as independent mobility for affluent non-drivers, may begin in the 2020s or 2030s, but most impacts, including reduced traffic and parking congestion (and therefore road and parking facility supply requirements), independent mobility for low-income people (and therefore reduced need to subsidize 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 prohibiting human-driven vehicles on certain roadways, which could take longer.

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Computers Versus Automobiles

According to popular legend,[1] Bill Gates once compared computers with automobiles and concluded, "If GM had kept up with the technology like the computer industry, we would be driving $25 cars that got 1,000 miles to the gallon."

In response, according to the legend, General Motors issued the following press release.

If General Motors developed technology like Microsoft, motor vehicles would have the following characteristics:

1. Automobiles would frequently crash for no apparent reason. This would be so common that motorists would simply accept it, restart their car and continue driving.

2. Occasionally, for no reason, all doors would lock, and motorists could only enter their vehicle by simultaneously lifting the door handle, turning the key, and holding the radio antenna.

3. Vehicles would occasionally shut down completely and refuse to restart, requiring motorists to reinstall their engine.

4. Every time GM introduced a new model, car buyers would have to relearn to drive because all controls would operate in a new manner.

5. Whenever roadway lines are repainted motorists would need to purchase a new car that accommodates the new "operating system."

6. Cars could normally carry only one passenger unless the driver paid extra for a multi-passenger license.

7. Apple would make a car powered by the sun, more reliable, five times as fast, that required half the effort to drive, but could operate on just five per cent of roads.

8. Oil, water temperature and alternator warning lights would be replaced by a single 'general car default' warning light.

9. Airbags would ask, 'Are you sure?' before deployment.

10. Vehicle buyers would be required to also purchase a set of deluxe road maps from Rand-McNally (a GM subsidiary), regardless of whether or not they want it. A trained mechanic would be required to delete them from the glove compartment.

11. To shut off the engine drivers would press the 'start' button.

[1] www.snopes.com/humor/jokes/autos.asp

Introduction

Autonomous (also called *self-driving*, *driverless* or *robotic*) vehicles have long been predicted in science fiction and discussed in popular science media. Recently major corporations have announced plans to begin selling such vehicles in a few years, and some jurisdictions have passed legislation to allow such vehicles to operate legally on public roads (Wikipedia 2013).

Levels of Autonomous Vehicles (NHTSA 2013)

***Level 1* – Function-specific Automation:** Automation of specific control functions, such as cruise control, lane guidance and automated parallel parking. Drivers are fully engaged and responsible for overall vehicle control (hands on the steering wheel and foot on the pedal at all times).

***Level 2* - Combined Function Automation:** Automation of multiple and integrated control functions, such as adaptive cruise control with lane centering. Drivers are responsible for monitoring the roadway and are expected to be available for control at all times, but under certain conditions can disengaged from vehicle operation (hands off the steering wheel and foot off pedal simultaneously).

***Level 3* - Limited Self-Driving Automation:** Drivers can cede all safety-critical functions under certain conditions and rely on the vehicle to monitor for changes in those conditions that will require transition back to driver control. Drivers are not expected to constantly monitor the roadway.

***Level 4* - Full Self-Driving Automation:** Vehicles can perform all driving functions and monitor roadway conditions for an entire trip, and so may operate with occupants who cannot drive and without human occupants.

There is much speculation concerning autonomous vehicle impacts. Advocates predict that consumers will soon be able to purchase affordable self-driving vehicles that can greatly reduce traffic and parking costs, accidents and pollution emissions, and chauffeur non-drivers around their communities, reducing roadway costs, eliminating the need for conventional public transit services (Keen 2013). Under this scenario, the savings will be so great that such vehicles will soon be ubiquitous and virtually everybody will benefit. However, it is possible that their benefits will be smaller and their costs greater than these optimist predictions assume.

There is extensive technical literature concerning autonomous vehicle technical development (TRB 2011), enthusiastic promotion in popular publications (Bamonte 2013; Bilger 2013; Motavalli 2012), interest by businesses (KPMG 2012), and some criticisms (Arieff 2013; Blumgart 2013). *The Economist* sponsored an insightful debate whether completely self-driving cars are feasible in the foreseeable future (Saffo and Bergbaum 2013). However, only recently have transportation practitioners started to explore how autonomous vehicles will affect planning decisions such as roadway design, parking costs and public transit demand (Fagnant and Kockelman 2013; ITIF 2013; Lutin, Kornhauser and Lerner-Lam; Narla 2013). This report investigates these issues. It critically examines autonomous vehicles' potential benefits and costs, provides predictions of their development and deployment based on experiences with previous vehicle technologies, and discusses their implications for transport planning issues such as road and parking supply and public transit demand.

Potential Impacts (Benefits and Costs)

Table 1 summarizes expected autonomous vehicle benefits and costs.

Table 1 **Autonomous Vehicle Potential Benefits and Costs**

Benefits	Costs/Problems
Reduced driver stress. Reduce the stress of driving and allow motorists to rest and work while traveling.	*Increases costs.* Requires additional vehicle equipment, services and maintenance, and possibly additional roadway infrastructure.
Reduced driver costs. Reduce costs of paid drivers for taxis and commercial transport.	*Additional risks.* May introduce new risks, such as system failures, be less safe under certain conditions, and encourage road users to take additional risks (offsetting behavior).
Mobility for non-drivers. Provide independent mobility for non-drivers, and therefore reduce the need for motorists to chauffeur non-drivers, and to subsidize public transit.	*Security and Privacy concerns.* May be vulnerable to information abuse (hacking), and features such as GPS tracking and data sharing may raise privacy concerns.
Increased safety. May reduce many common accident risks and therefore crash costs and insurance premiums. May reduce high-risk driving, such as when impaired.	*Induced vehicle travel and increased external costs.* By increasing travel convenience and affordability, autonomous vehicles may induce additional vehicle travel, increasing external costs of parking, crashes and pollution.
Increased road capacity, reduced costs. May allow platooning (vehicle groups traveling close together), narrower lanes, and reduced intersection stops, reducing congestion and roadway costs.	*Social equity concerns.* May have unfair impacts, for example, if they lead to reduced convenience and safety of other modes.
More efficient parking, reduced costs. Can drop off passengers and find a parking space, increasing motorist convenience and reducing total parking costs.	*Reduced employment and business activity*. Jobs for drivers should decline, and there may be less demand for vehicle repairs due to reduced crash rates.
Increase fuel efficiency and reduce pollution. May increase fuel efficiency and reduce pollution emissions.	*Misplaced planning emphasis.* Focusing on technological solutions may discourage communities from implementing conventional but cost-effective transport projects such as pedestrian and transit improvements, pricing reforms and other demand management strategies.
Supports shared vehicles. Could facilitate carsharing (vehicle rental services that substitute for personal vehicle ownership), which can provide various savings.	

Autonomous vehicles can provide various benefits and impose various costs.

Some impacts, such as reduced driver stress and increased urban roadway capacity, can occur under level 2 or 3 implementation, which provides limited self-driving capability under certain conditions, but many benefits, such as significant crash reductions, road and parking cost savings and affordable mobility for non-drivers, require that level 4 vehicles become common and inexpensive.

Estimated Costs

Autonomous vehicle costs are uncertain. They require a variety of special equipment, including sensors, computers and controls, which currently cost tens of thousands of dollar but are likely to become cheaper with mass production (KPMG 2012). However, because system failures could be fatal to both vehicle occupants and other road users, all critical components will need to meet high manufacturing, installation, repair, testing and maintenance standards, similar to aircraft components, and so will probably be relatively expensive. Autonomous vehicle operation may require subscriptions to special navigation and mapping services (this market is Google Corporation's motivation to support autonomous vehicle research). Other, simpler technologies add hundreds of dollars to vehicle retail prices. For example, optional rearview cameras, GPS and telecommunications systems, and automatic transmissions typically cost $500 to $2,000 extra, and navigation and security services such as OnStar and TomTom have $200 to $350 annual subscription fees. Autonomous vehicles require these plus other equipment and services (see Box below).

Autonomous Vehicle Equipment and Service Requirements

- Automatic transmissions.
- Diverse and redundant sensors (optical, infrared, radar, ultrasonic and laser) capable of operating in diverse conditions (rain, snow, unpaved roads, tunnels, etc.).
- Wireless networks. Short range systems for vehicle-to-vehicle communications, and long-range systems to access to maps, software upgrades, road condition reports, and emergency messages.
- Navigation, including GPS systems and special maps.
- Automated controls (steering, braking, signals, etc.)
- Servers, software and power supplies with high reliability standards.
- Additional testing, maintenance and repair costs for critical components, such as automated testing and cleaning of sensors.

Manufacturers will need to recover costs of development, ongoing service (special mapping and software upgrades) and liability, plus earn profits. This suggests that when the technology is mature, self-driving capability will probably add several thousand dollars to vehicle purchase prices, plus a few hundred dollars in annual maintenance and service costs, increasing annualized costs $1,000 to $3,000 per vehicle. These incremental costs may be partly offset by fuel and insurance savings. Motorists spend on average approximately $2,000 for fuel and $1,000 for insurance per vehicle-year. If autonomous vehicles reduce fuel consumption by 10% and insurance costs by 30%, the total annual savings will average $500, which will not fully offset predicted incremental annual costs.

Estimated Benefits

Advocates may overstate benefits. For example, some suggest that because driver error contributes to more than 90% of traffic accidents, self-driving cars will eliminate 90% of crashes (KPMG 2012; Fagnant and Kockelman 2013). However, autonomous vehicles will probably introduce new risks, including system failures ("death by computer") and cyberterrorism (Bilger 2013). Experience with other safety innovations indicates that net benefits are often smaller than expected due to *offsetting behavior* (the tendency of road users to take additional risks when they feel safer; also called *risk compensation*) and *rebound effects* (increased vehicle travel resulting from faster or cheaper travel) (Ecenbarger 2009; Lin 2013). For example, because they feel safer vehicle occupants may reduce seatbelt use; other road users may become less cautious; vehicles may operate faster and closer together which increases crash severity, and human drivers may be tempted to join autonomous vehicle platoons for faster travel – it may become a sport – which will introduce new enforcement requirements and risks.

Estimated congestion and parking cost reductions, energy savings and emission reductions are also uncertain due to interactive effects. For example, the ability to work and rest while traveling may induce some motorists to choose larger vehicles that can serve as mobile offices and bedrooms ("commuter sex" may be a marketing strategy for such vehicles) and drive more annual miles. Self-driving taxis and self-parking cars will require empty backhauls, so each passenger-mile sometimes generates two vehicle-miles of travel. Although the additional vehicle travel provides user benefits (otherwise, users would not increase their mileage) it can increase external costs, including congestion, roadway and parking facility costs, accident risk imposed on other road users, and pollution emissions. Some strategies such as platooning may be limited to grade-separated roadways, so autonomous vehicles may increase congestion on surface streets. Autonomous vehicles may reduce public transit travel demand, leading to reduced service, and stimulate more sprawled land use development patterns which reduce transport options and increase total vehicle travel.

Shared Vehicles

Some advocates claim that autonomous vehicles will provide large savings by allowing travelers to rely on shared, self-driving taxis instead of personal vehicles, reducing ownership and parking costs (Fagnant and Kockelman 2013; Schonberger and Gutmann 2013). These impacts and benefits are difficult to predict. Many motorists prefer to own personal vehicles for identity (to display their style and success) and convenience (because they often leave equipment in vehicles or carry dirty loads). Their convenience and cost profiles are likely to range between carsharing ($0.60- $1.00 per vehicle-mile, reflecting average vehicle ownership and operating costs, plus some administrative costs) and human-operated taxis ($2.00-3.00 per vehicle-mile, reflecting costs of vehicle ownership, operation, administration, plus dispatch and driver labor).

Autonomous taxis are likely to incur these additional costs:

- *Additional vehicle travel to trip origins.* This may be modest in dense urban areas where such taxis are widely distributed, but is likely to add 10-20% to total vehicle travel in lower-density suburban and rural areas, or for specialized vehicles such as vans and trucks.
- *Cleaning and vandalism.* Other types of shared vehicles, such as taxis and public transit, are often abused. They will require cleaning when passengers smoke, spill food and drinks, spit, bring pets, or leave garbage in vehicles, and repairs when vehicles are vandalized. To minimize these risks self-driving taxis will need hardened surfaces, durable fabrics, minimal moving parts, surveillance (cameras that record passenger behavior), and aggressive enforcement. Assuming that vehicles make 200 weekly trips, 5-15% of passengers leave messes with $10-30 average cleanup costs, and 1-4% vandalize vehicles with $50-100 average repair costs, these costs would average between $200 and $1,700 per vehicle-week.
- *Reduced comfort and privacy.* Vehicles designed to minimize cleaning and vandalism risks will probably have less comfort (no leather upholstery or carpeted floors), fewer accessories (limited sound systems), and less reliability (since vehicles will frequently need cleaning and repairs) than personal vehicles. Passengers will need to accept that their activities will be recorded.

Personal automobiles typically cost about $4,000 annually in fixed expenses plus 20¢ per mile in operating costs. It is generally cheaper to rely on conventional taxis ($2.00-3.00 per mile) rather than own a vehicle driven less than about 2,500 annual miles, or rely on carsharing services ($0.60-1.00 per mile) rather than own a personal vehicle driven less than about 6,000 annual miles. This suggests that autonomous vehicles will be a cost effective alternative to owning a vehicle driving less than 2,500 to 6,000 annual miles, depending on cleaning and repair costs. This represents a minority of total vehicles. Table 2 summarizes the types of trips most suitable for self-driving taxis.

Table 2 **Likely Uses of Self-Driving Taxis**

Suitable Uses	Unsuited Uses
Trips currently made by taxi or carshare vehicles. Utilitarian trips currently made by a private vehicle driven less than 6,000 annual miles.	Motorists who take pride in vehicles. Motorists who drive more than 6,000 annual miles. Passengers who place high values on comfort. Passengers who place high values on privacy. Motorists who require special accessories. Motorists who normally carry tools or dirty loads in their vehicles (e.g., trades workers).

Self-driving taxis may allow some motorists to reduce their vehicle ownership, but impacts are likely to be modest and will depend on factors such as cleaning and vandalism costs, user comfort and privacy.

Because of these additional costs, and reduced passenger comfort and privacy, it seems unlikely that most motorists will shift from owning vehicles to relying on self-driving taxis.

Impacts on Total Vehicle Travel

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

> **Jake** is an affluent man with degenerating vision. In 2026 his doctor convinced him to give up driving. He is able to purchase an early autonomous vehicle instead of shifting to walking, public transit and taxis.
>
> *Impacts:* An autonomous vehicle allows Jake to continue using a car, which increases his independent mobility, total vehicle ownership and travel, residential parking demand, and external costs (congestion, roadway costs, parking subsidies, and pollution emissions), compared with what would otherwise occur.
>
> **Bonnie** lives and works in a suburb. She can bike to most destinations but occasionally needs a car. In a city she could rely on taxis and carsharing, but such services are slow and expensive in suburbs. However, when she started shopping for a car in 2030 a local company began offering fast and affordable automated taxi services.
>
> *Impacts:* Autonomous vehicles allow Bonnie to rely on shared vehicles rather than purchase a car, which reduces her total vehicle travel, residential parking demand, and external costs.

Malisa and **Johnny** have two children. Malisa works at a downtown office. After their second child was born in 2035, they shopped for a larger home. With conventional cars they would only consider houses within a 30-minute drive of the city center, but relatively affordable new autonomous vehicles let them consider more distant home locations, with commutes up to 60-minutes, during which Malisa could rest and work.

Impacts: Affordable new autonomous vehicles allows Malisa and Johnny to choose an exurban home location, which increased their total vehicle costs, accident risk, parking and roadway costs, and the costs of providing public services such as utilities and emergency response.

Garry is hard-working and responsible when sober, but a dangerous driver when drunk. By 2040 he had accumulated several impaired citations and caused a few accidents. With conventional cars Garry would continue driving impaired until he lost his drivers' license or caused a severe crash, but affordable used self-driving vehicles allow lower-income motorists like Garry to avoid such problems.

Impacts: Affordable used autonomous vehicles allow Garry to avoid impaired driving, accidents and revoked driving privileges, which reduces crash risks but increases his vehicle ownership and travel, and external costs compared with what would otherwise occur.

Table 3 summarizes the resulting impacts of these various scenarios. This suggests that in many cases autonomous vehicles will increase total vehicle mileage.

Table 3 **Autonomous Vehicle Scenario Summary**

	User Benefits	Travel Impacts	Infrastructure Impacts
Jake	Independent mobility for non-drivers	Increased vehicle travel and external costs	Increased residential parking and roadway costs
Bonnie	Vehicle cost savings	Reduced vehicle ownership and travel	Reduced residential parking and roadway costs
Melisa and Johnny	Improved home location options	Increased vehicle ownership and travel	Increased residential parking and roadway costs
Garry	Avoids driving drunk and associated consequences	Less high-risk driving, more total vehicle travel	Increased residential parking and roadway costs

Autonomous vehicle availability can have various direct and indirect impacts.

Development and Deployment

Table 4 summarizes likely stages of autonomous vehicle development and deployment.

Table 4 **Autonomous Vehicle Implementation Stages** (Wikipedia 2013; NHTSA 2013)

Stage	Notes
Level 2 – Limited automation (steering, braking and lane guidance)	This is the current state of art, available on some new vehicles.
Coordinated platooning	Currently technically feasible but requires vehicle-to-vehicle communications capability, and dedicated lanes to maximize safety and mobility benefits.
Level 3 – Restricted self-driving	Currently being tested. Google experimental cars have driven hundreds of thousands of miles in self-drive mode under restricted conditions.
Level 4 – Self-driving in all conditions	Requires more technological development.
Regulatory approval for automated driving on public roadways.	Some states have started developing performance standards and regulations that autonomous vehicles must meet to legally operate on public roads.
Fully-autonomous vehicles available for sale.	Several companies predict commercial sales of "driverless cars" between 2018 and 2020, although their capabilities and prices are not specified.
Autonomous vehicles become a major portion of total vehicle sales.	Will depend on performance, prices and consumer acceptance. New technologies usually require several years to build market acceptance.
Autonomous vehicles become a major portion of vehicle fleets.	As the portion of new vehicles with autonomous driving capability increases, their portion of the total vehicle fleet will increase over a few decades.
Autonomous vehicles become a major portion of vehicle travel.	Newer vehicles tend to be driven more than average, so new technologies tend to represent a larger portion of vehicle travel then the vehicle fleet.
Market saturation.	Everybody who wants an autonomous vehicle has one.
Universal	All vehicles operate autonomously.

Autonomous vehicle implementation will involve several phases.

Currently (2013), many new vehicles have some level 1 automation features such as cruise control, obstruction warning, and parallel parking. In 2014 or 2015, some manufactures plan to offer level 2 features such as automated lane guidance, accident avoidance, and driver fatigue detection. Coordinated platooning is now technically feasible but not operational because many benefits require dedicated lanes. Google level 3 test vehicles have reportedly driven hundreds of thousands of miles under restricted conditions: specially mapped routes, fair weather, and human drivers able to intervene when needed (Muller 2013). Some manufacturers aspire to sell level 4 automation vehicles within a few years but details are uncertain; early versions will probably be limited to "controlled" environments such as freeways (Row 2013).

Despite this progress, significant technical improvement is needed to progress from *restricted level 3* to *unrestricted level 4* operation). Such vehicles must anticipate all possible conditions and risks, with fail-safe responses. Since a failure could be deadly to vehicle occupants and other road users, automated driving has high performance requirements. Sensors, computers and software must be robust, redundant and resistant to abuse. Several more years of development and testing will probably be required before regulators and potential users gain confidence that level 4 vehicles can operate as expected under all conditions (Bilger 2013).

Implementation Projections

Autonomous vehicle implementation can be predicted based on the pattern of previous vehicle technologies, and vehicle fleet turnover rates.

- *Automatic Transmissions* (Healey 2012). First developed in the 1930s. Took until the 1980s to become reliable and affordable. Now standard on most U.S. medium and high-priced vehicles, although some models have manual mode. When optional they typically cost $1,000 to $2,000. Currently 90-95% new vehicle market share in North America and about 50% in Europe and Asia.
- *Air Bags* (Dirksen 1997). First introduced in 1973. Initially an expensive and sometimes dangerous option (they could cause injuries and deaths), they became cheaper and safer, were standard on some models starting in 1988, and mandated by U.S. federal regulation in 1998.
- *Hybrid Vehicles* (Berman 2011). Became commercially available in 1997, but prices were high and performance poor. Their performance and usability has improved, but typically add about $5,000 to vehicle prices. In 2012 they represented about 3.3% of total vehicle sales.
- *Subscription Vehicle Services*. Navigation, remote lock/unlock, diagnostics and emergency services. OnStar became available in 1997, TomTom in 2002. They typically cost $200-400 annually. About 2% of U.S. motorists subscribe to the largest service, OnStar.
- *Vehicle Navigation Systems* (Lendion 2012). Vehicle navigation systems became available as expensive accessories in the mid-1980s. In the mid-1990s factory-installed systems became available on some models, for about $2,000. Performance and usability have since improved, and prices have declined to about $500 for factory-installed systems, and under $200 for portable systems. They are standard in many higher-priced models.

Table 5 summarizes the deployment cycles, from first commercial availability to market saturation, for these technologies. Most new technologies require decades of technical development and market growth to saturate their potential markets, and in many cases never become universal. Airbags had the shortest cycle and the most complete market share, due to federal mandates. Automatic transmissions required more than five decades for prices to decline and quality to improve, and are still not universal. Hybrid vehicles are still developing after 15 years on the market, have substantial price premiums and modest market share. This suggests that new vehicle technologies generally require two to five decades from commercial availability to market saturation, and without government mandates will not be universal.

Table 5 **Vehicle Technology Deployment Summary**

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

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

Modern vehicles are durable, resulting in slow fleet turnover. Median operating lives increased from 11.5 years for the 1970 model year, to 12.5 years for the 1980 model year, and 16.9 years for the 1990 model year (ORNL 2012, Table 3.12), suggesting that current vehicles may have 20 year or longer average lifespans. As a result, new vehicle technologies normally require three to five decades to be implemented in 90% of operating vehicles. 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 as vehicles age. For example, 2001 vehicles averaged approximately 15,000 miles their first year, 10,000 miles their 10^{th} year and 5,000 miles their 15^{th} year, so vehicles older than ten years represent about 50% of the vehicle fleet but only about 20% of vehicle mileage (ORNL 2012, Table 3.8).

As previously described, autonomous driving capability will probably increase vehicle purchase prices by thousands of dollars, and may require hundreds of dollars in annual subscription fees for special navigation and mapping services. Although self-driving vehicles may provide large benefits to some users (high-income non-drivers, long-distance automobile commuters, and commercial drivers), it is unclear what portion of motorists will consider the benefits worth the additional costs. It will probably follow the pattern of automatic transmissions, which took nearly five decades to reach market saturation, and a portion of motorists continue to choose manual transmissions due to preference of cost savings.

Table 6 summarizes projected autonomous vehicle implementation rates based on previous vehicle technology deployment. This assumes that fully-autonomous vehicles are available for sale and legal to drive on public roads around 2020, but, as with previous vehicle technologies, are initially imperfect (poor reliability and performance, and difficult to operate) and costly (tens of thousands of dollars price premiums), and so represent a small portion of total vehicle sales, with market share increasing during subsequent decades as their performance improves, prices decline, and their benefits are demonstrated. Over time they will increase as a share of total vehicle fleets. Since newer vehicles are driven more than average annual miles their share of vehicle travel is proportionately large.

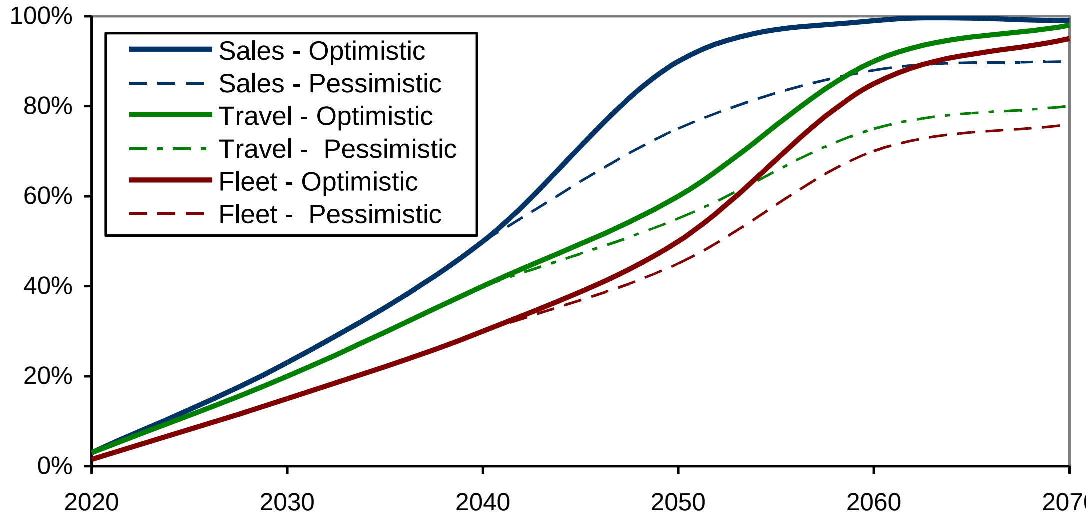
Table 6 **Autonomous Vehicle Implementation Projections**

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

Autonomous vehicle implementation will probably take several decades.

Figure 1 illustrates the deployment rates from Table 6. If accurate, in the 2040s autonomous vehicles will represent approximately 50% of vehicle sales, 30% of vehicles, and 40% of all vehicle travel. Only in the 2050s would most vehicles be capable of automated driving.

Figure 1 **Autonomous Vehicle Sales, Fleet and Travel Projections** (Based on Table 6)



If autonomous vehicle implementation follows the patterns of other vehicle technologies it will take one to three decades to dominate vehicle sales, plus one or two more decades to dominate vehicle travel, and even at market saturation it is possible that a significant portion of vehicles and vehicle travel will continue to be self-driven, indicated by the dashed lines.

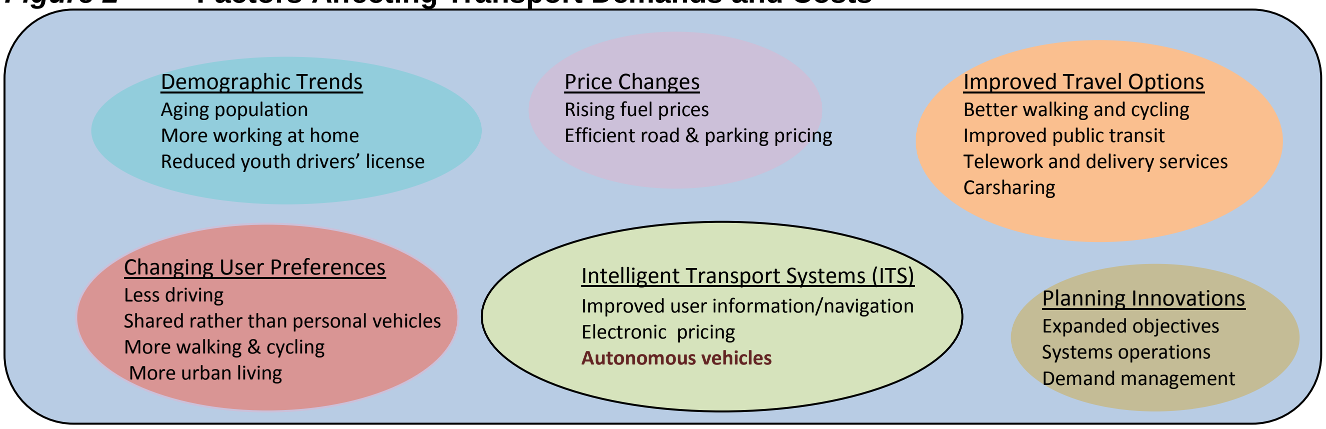
Autonomous vehicles implementation could be slower and less complete than optimistic predictions. Technical challenges may be more difficult to solve than expected, so fully self-driving vehicles may not be commercially available until the 2030s or 2040s. They may have higher than expected production costs and retail prices, their benefits may be smaller and problems greater than predicted, and technical constraints, privacy concerns or personal preference may reduce consumer acceptance, resulting in a significant portion of vehicle travel remaining human-driven even after market saturation, indicated in the graph by dashed lines.

Significantly faster implementation would require much faster development and deployment than previous vehicle technologies. For example, for the majority of vehicle travel to be autonomous by 2035, most new vehicles purchased after 2025 would need to be autonomous, and new vehicle purchase rates would need to triple, so the fleet turnover process that normally takes three decades can occur in one. This would require most low- and middle-income motorists, who normally purchase cheaper new models or older used vehicles, to spend two to four times more in order to purchase a new automobile with self-driving capability, and many otherwise functional vehicles are scrapped just because they lack self-driving capability.

Planning Implications

Autonomous vehicle implementation is just one of several factors likely to affect transportation demands and costs during the next half-century, as illustrated in Figure 2. Demographic trends, changing consumer preferences, price changes, improving transport options, improved user information, and various planning innovations will also influence how and how much people drive. These may have greater impacts on transport planning than autonomous vehicles, at least until the 2040s.

Figure 2 **Factors Affecting Transport Demands and Costs**



Autonomous vehicles are one of many factors that will affect transport demands and costs in the next few decades, and not necessarily the most important.

Table 7 (next page) summarizes the functional requirements and planning implications of various autonomous vehicle impacts, and their expected time period based on Table 5 projections. This suggests that during the 2020s and 30s transport planners and engineers will primarily be concerned with defining autonomous vehicle performance, testing and reporting requirements for operation on public roadways. If several years of testing demonstrate autonomous vehicle benefits, transport professionals may support policies that encourage or require self-driving capability in new vehicles.

One potential impact during the 2030s or 40's may result from autonomous vehicles' ability to provide convenient and inexpensive taxi and carsharing services, reducing the need for conventional public transit services and allowing more households to rely on such services and reduce their vehicle ownership, which could reduce parking requirements.

Some benefits (higher traffic speeds, reduced congestion and automated intersections) require dedicated autonomous vehicle lanes. This will raise debates about fairness and cost efficiency, and human drivers may be tempted to use such lanes, for example, following a platoon of self-driving vehicles, introducing new risks, regulations and enforcement requirements, probably starting in the 2030s.

Table 7 **Autonomous Vehicle Planning Impacts By Time Period**

Impact	Functional Requirements	Planning Impacts	Time Period
Become legal	Demonstrated functionality and safety	Define performance standards testing and data collection requirements for automated driving on public roads.	2015-25
Increase traffic density by vehicle coordination	Road lanes dedicated to vehicles with coordinated platooning capability	Evaluate impacts. Define requirements. Identify lanes to be dedicated to vehicles capable of coordinated operation.	2020-40
Independent mobility for non-drivers	Fully autonomous vehicles available for sale	Allows affluent non-drivers to enjoy independent mobility.	2020-30s
Automated carsharing/taxi	Moderate price premium. Successful business model.	May provide demand response services in affluent areas. Supports carsharing.	2030-40s
Independent mobility for lower-income	Affordable autonomous vehicles for sale	Reduced need for conventional public transit services in some areas.	2040-50s
Reduced parking demand	Major share of vehicles are autonomous	Reduced parking requirements.	2040-50s
Reduced traffic congestion	Major share of urban peak vehicle travel is autonomous.	Reduced road supply.	2050-60s
Increased safety	Major share of vehicle travel is autonomous	Reduced traffic risk. Possibly increased walking and cycling activity.	2040-60s
Energy conservation and emission reductions	Major share of vehicle travel is autonomous. Walking and cycling become safer.	Supports energy conservation and emission reduction efforts.	2040-60s
Improved vehicle control	Most or all vehicles are autonomous	Allows narrower lanes and interactive traffic controls.	2050-70s
Need to plan for mixed traffic	Major share of vehicles are autonomous.	More complex traffic. May justify restrictions on human-driven vehicles.	2040-60s
Mandated autonomous vehicles	Most vehicles are autonomous and large benefits are proven.	Allows advanced traffic management.	2060-80s

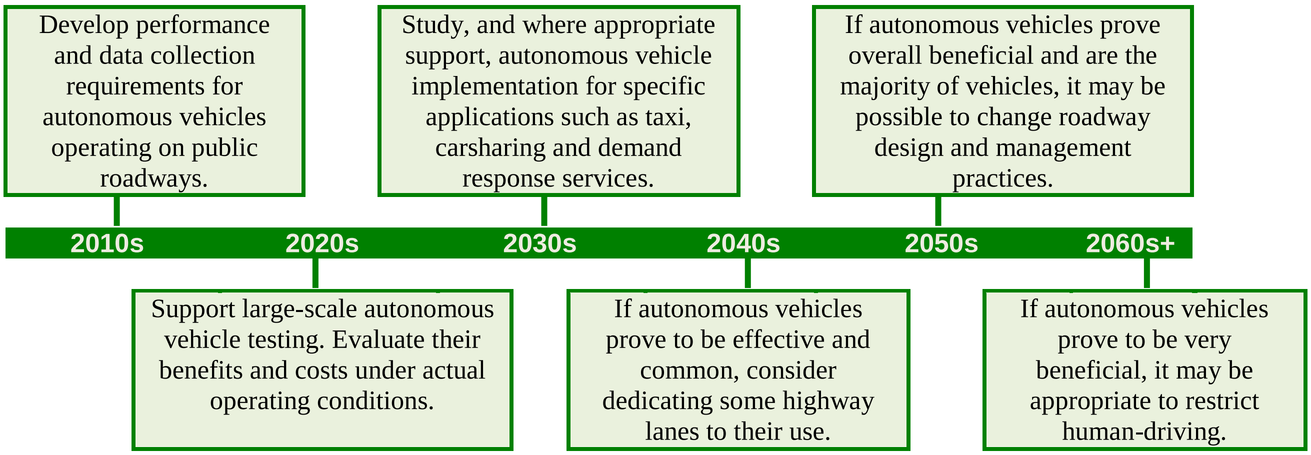
Autonomous vehicles will have various impacts on transportation planning.

When autonomous vehicles become a major share of total vehicle travel they may significantly reduce traffic risk, traffic congestion, parking problems, and provide some energy savings and emission reductions. Transportation professionals will be involved in technical analyses to determine their actual benefits, and policy debates concerning whether public policies should encourage or require autonomous vehicles.

These impacts may vary geographically, with more rapid implementation in areas that are more affluent (residents can more quickly afford autonomous vehicles), more congested (potential benefits are greater) and have more public support.

The timeline below summarizes autonomous vehicle planning impact projections.

Figure 3 **Autonomous Vehicle Planning Impacts Time-Line**



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

An Analogy: Automated Banking Services

As an analogy, consider automated banking service trends. Personal computers first became available for purchase during the 1970s, the Internet became public during the 1980s, automated teller machines (ATMs) became common in the 1990s, most households were using the Internet for personal business activities by the 2000s, and for decades banks have encouraged customers to use central call centers rather than local offices to answer questions, yet these technologies have not eliminated the need for local banks with human tellers.

Automated banking can reduce the number of branch offices and employees, but customers often need to interact with human tellers due to personal preferences, and because it is often faster and less frustrating, and therefore more productive, than automated, Internet or telephone options. Automation has had evolutionary rather than revolutionary impacts on bank activities. Other trends – new banking services, changing regulations and new management practices – have equal or greater impacts on bank infrastructure planning.

Autonomous vehicle implementation will probably follow similar patterns: deployment will take several decades, is unlikely to totally displace current technology, will have costs as well as benefits, and will only marginally affect infrastructure planning for the foreseeable future. It is one of several current trends that may marginally reduce road and parking supply requirements and affect roadway designs, but these changes will probably occur gradually over several decades, and autonomous vehicles will be just one, and not necessarily the most important, of many factors that affect road and parking planning practices.

Conclusions

Recent announcements that autonomous vehicles have safely driven hundreds of thousands of miles, and major manufactures aspire to sell such vehicles within a few years, have raised hopes that this technology will soon be widely available and solve transport problems such as traffic and parking congestion, accidents, and the need to provide mobility for non-drivers. However, the analysis in this report suggests that autonomous vehicles will have only modest impacts on transportation planning factors such as road and parking supply, and public transit demand for the next few decades.

There is considerable uncertainty concerning autonomous vehicle benefits, costs and travel impacts. Advocates claim that within a few years self-driving vehicles will be reliable and affordable, providing user savings that offset costs, and they will significantly reduce congestion and parking congestion, roadway infrastructure costs, accidents and pollution emissions which justify policies that encourage their implementation. However, autonomous vehicles will require additional equipment, services and maintenance that will probably increase user costs by hundreds or thousands of dollars per vehicle-year, and their benefits are unproven.

Autonomous vehicles may allow shared vehicles to replace personal vehicles in some situations. Their costs are likely to be between carshare ($0.60-1.00 per mile) and human-driven taxis ($2.00-3.00 per mile), depending on their additional cleaning costs, which will make them a cost effective alternative to owning a vehicle driven less than 2,500 to 6,000 annual miles, depending on their actual cost profiles.

Advocates may exaggerate net benefits by ignoring new costs and risks, *offsetting behavior* (the tendency of road users to take additional risks when they feel safer), *rebound effects* (increased vehicle travel caused by faster travel or reduced operating costs, which may increase external costs), and harms to people who do not to use the technology, such as reduced public transit service. Benefits are sometimes double-counted, for example, by summing increased safety, traffic speeds and facility savings, although there are trade-offs between them.

Current automated vehicles can only self-drive under limited conditions: significant technical and economic obstacles must be overcome before typical households can rely on them for daily travel. Operating a vehicle on public roads is more complex than flying an airplane since there are more and closer interactions with often unpredictable objects including other vehicles, pedestrians, animals, buildings, trash and potholes. If they follow previous vehicle technology development and deployment patterns, autonomous vehicles will initially be costly and imperfect. During the 2020s and perhaps the 2030s, autonomous vehicles are likely to be expensive novelties with limited abilities, requiring licensed drivers at the wheel ready to intervene if required. It will probably be the 2040s or 2050s before middle-income families can afford to purchase autonomous vehicles that can safely chauffeur non-drivers, and longer before such vehicles are affordable to lower-income households. It is possible that a significant portion of motorists will prefer to drive their vehicles, just as many motorists prefer manual transmissions, so traffic will mixed, creating new roadway management problems.

Vehicle innovations tend to be implemented more slowly than for other technological change due to their high costs, strict safety requirements, and slow fleet turnover. Automobiles typically cost fifty times and last ten times as long as personal computers and mobile phones, so consumers seldom purchase new vehicles just to obtain a new technology. Large increases in new vehicle purchase, expenditure and scrappage rates would be required for most vehicles to be autonomous before 2050.

Transportation professionals (planners, engineers and policy analysts) have important roles to play in minimizing autonomous vehicles risks and maximizing benefits. We can help support their development and testing, and establish performance standards they must meet to legally operate on public roads. If such vehicles perform successfully and become common they may affect planning decisions such as the supply, design and operation of roads, parking and public transit. To be prudent, such infrastructure changes should only occur after autonomous vehicle benefits, affordability and public acceptance are fully demonstrated. This may vary: autonomous vehicles may affect some roadways and communities more than others.

A critical question is whether autonomous vehicles increase or reduce total vehicle travel and associated external costs. It could go either way. By increasing travel convenience and comfort, and allowing vehicle travel by non-drivers, they could increase total vehicle mileage, but they may also facilitate carsharing, which allows households to reduce vehicle ownership and therefore total driving, and reduce some vehicle travel such as cruising for parking spaces.

Another critical issue is the degree potential benefits can be achieved when only a portion of vehicle travel is autonomous. Some benefits, such as improved mobility for affluent non-drivers and more convenient taxi and carsharing services, may occur when autonomous vehicles are relatively uncommon and costly, but many potential benefits require that most or all vehicles on a road operate autonomously. For example, it seems unlikely that traffic densities can significantly increase, parking requirements be significantly reduced, traffic lanes be narrowed, or traffic signals be eliminated until most vehicle on affected roads self-drive.

A key public policy issue is the degree that this technology may harm people who do not use such vehicles, for example, if increased traffic volumes and speeds degrade walking and cycling conditions, conventional public transit service declines, or human-operated vehicles are restricted. Some strategies, such as platooning, may require special lanes dedicated to autonomous vehicles to maximize potential benefits. There will probably be considerable debate over the merits and fairness of such policies.

Autonomous vehicle implementation is just one of many trends expected to affect future transport demands and costs, and therefore planning decisions, and not necessarily the most important. Its ultimate impacts depend on how it interacts with other trends, such as shifts from private to shared vehicles. It is probably not a “game changer” during most of our professional lives, and is certainly not a “paradigm shift” since it does not fundamentally change how we define transport problems; rather, it tends to reinforce the existing automobile-oriented planning paradigm.

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