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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 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 (Polzin 2016). Advocates predict that consumers will soon be able to purchase affordable self-driving vehicles that will greatly reduce traffic and parking costs, accidents and pollution emissions, and chauffeur non-drivers, 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; Gomes 2014). *The Economist* sponsored a debate concerning the near-term feasibility of self-driving cars (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 (APA 2016; Fagnant and Kockelman 2013; Grush 2016; Guerra 2015; ITIF 2013; Levinson 2015; Narla 2013), and factors that affect implementation (Preston and Waterson 2015). 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)

*This section summarizes expected benefits and costs resulting from autonomous vehicles.*

### *Potential Benefits*

Advocates predict that autonomous vehicles will provide significant user convenience, safety, congestion reductions, fuel savings, and pollution reduction benefits. Such claims many be overstated. For example, advocates argue that because driver error contributes to more than 90% of traffic accidents, self-driving cars will reduce crashes 90% (KPMG 2012; Fagnant and Kockelman 2013), including system failures ("death by computer"), cyberterrorism (Bilger 2013), *offsetting behavior* (road users' tendency 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; Fung 2015; Kockelman, et al. 2016; Lin 2013; Ohnsman 2014). If they feel safer, vehicle occupants may reduce seatbelt use, other road users may become less cautious, vehicles may operate faster and closer together, and human drivers may be tempted to join autonomous vehicle platoons, which will introduce new risks and enforcement requirements. Millard-Ball (2016) suggests that pedestrians to become less cautious and responsible around autonomous vehicles. Detailed analysis by Sivak and Schoettle (2015a) concluded that autonomous vehicles may be no safer than an average driver and may increase total crashes when self- and human-driven vehicles mix.

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) and drive more annual miles. Self-driving taxis and self-parking cars will require empty backhauls. 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 human-driven vehicles may increase congestion on surface streets. Autonomous vehicles may reduce public transit travel demand, leading to reduced service, and stimulate more sprawled development patterns which reduce transport options and increase total vehicle travel.

### *Potential Costs*

The incremental costs of making autonomous vehicles are uncertain. They require a variety of special 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 special navigation and mapping service subscriptions (this explains the Google Corporation's interest in this technology). Other, simpler technologies add hundreds of dollars to vehicle retail prices. For example, GPS and telecommunications systems, review cameras, and automatic transmissions typically cost $500 to $2,000. Navigation and security services such as OnStar and TomTom have $200 to $350 annual 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 sensors and controls.

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 service costs, adding $1,000 to $3,000 to annual vehicle costs. These incremental costs may be partly offset by fuel and insurance savings. These 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 annual savings will total about $500, which will not fully offset predicted incremental annual costs.

Autonomous vehicles can be programed to optimize occupant comfort. Le Vine, Zolfaghari and Polak (2015) argue that because vehicle passengers tend to be more sensitive to acceleration than drivers, and occupants use travel time to work or rest (autonomous vehicle illustrations often show occupants playing cards or sleeping) it is plausible that for comfort sake users will program their vehicle for lower acceleration/deceleration characteristics than human-powered vehicles, leading to reductions in total urban roadway capacity.

### *Shared Vehicles*
Some advocates claim that self-driving capability will result in more vehicle sharing, including self-driving taxis and more sharing of private vehicles (Fagnant and Kockelman 2013; ITF 2014; Schonberger and Gutmann 2013). Sivak and Schoettle (2015b) estimate that, by allowing household vehicles to serve multiple residents, for example, taking a commuter to work and then transporting other household member for errands, they could reduce vehicle ownership up to 43%, and increase travel per vehicle by up to 75%. However, these impacts are difficult to predict. There are many reasons that motorists may prefer a personal rather than shared vehicle, for status, because they frequently keep tools or carry dirty loads in their vehicles, because they drive high annual miles, or because they need assistance provided by human drivers.

Shared autonomous vehicle cost profiles are likely to range between carsharing ($0.60- $1.00 per vehicle-mile, including ownership, operation and administrative costs) and human-operated taxis ($2.00-3.00 per vehicle-mile including ownership, operation, administration and labor costs). 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.* Taxis and public transit vehicles require frequent cleaning when passengers litter, smoke, spill food and drinks, spit or bring pets, and repairs when vehicles are vandalized. To minimize these risks self-driving taxis will need hardened surfaces, durable fabrics, minimal moving parts, electronic surveillance, 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 services.* Drivers often help passengers (particularly those with disabilities) in and out of taxies, carry luggage, ensure passengers safely reach destinations, and offer guidance to visitors.
- *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 use conventional taxis ($2.00-3.00 per mile) rather than own a personal vehicle driven less than about 2,500 annual miles, or rely on carsharing services ($0.60-1.00 per mile) rather than own a 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. Table 1 summarizes trip types most suitable for self-driving taxis, a minority of total vehicle travel. 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.

***Table 1*** **Likely Uses of Self-Driving Taxis**

| Suitable Uses | Unsuited Uses |
|---|---|
| Trips currently made by taxi or carshare vehicles.<br>Utilitarian trips currently made by a private vehicle driven less than 6,000 annual miles. | Motorists who take pride in vehicles or value extra comfort.<br>Motorists who drive more than 6,000 annual miles.<br>Motorists who require special accessories in their vehicles.<br>Motorists who often carry tools or dirty loads.<br>Passengers who want assistance getting in and out of taxies.<br>Passengers who place high values on privacy. |

*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.*

### *Impacts on Total Vehicle Travel*

Table 2 lists various ways that autonomous vehicles can affect total vehicle travel (*vehicle miles travelled* or *VMT*). Although it is difficult to predict how these factors will interact, many studies suggest that, by making vehicle travel more convenient, autonomous vehicles are likely to increase total vehicle travel unless specific demand management strategies are implemented, such as higher road user fees (Smith 2012).

***Table 2*** **Autonomous Vehicle Impacts on Total Vehicle Travel**

| Increases Vehicle Travel | Reduces Vehicle Travel |
|---|---|
| More convenient and productive travel (passengers can rest and work) will reduce travel time costs, stimulating more vehicle travel. | |
| Provides convenient vehicle travel to non-drivers (people too young, old, disabled, impaired, or otherwise lacking a drivers' license. Sivak and Schoettle (2015c) estimate that, accommodating non-drivers' latent travel demands could increase total vehicle by up to 11%. | More convenient shared vehicles allows households to reduce total vehicle ownership and use.<br>Increases vehicle ownership and operating costs, further reducing private vehicle ownership. |
| Self-driving taxis will travel more for empty backhauls. | Self-driving transit vehicles improve transit services. |
| Can make sprawled, automobile-dependent locations more attractive. | Reduced pedestrian risks and parking demands makes urban living more attractive. |
| Reduces traffic congestion and vehicle operating costs, which induces additional vehicle travel. | Reduce some vehicle travel, such as cruising for parking spaces. |

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

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 purchases an autonomous vehicle instead of shifting to walking, transit and taxies.
*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 homes, 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, accident, 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.*

This analysis suggests that effects which increase motor vehicle travel are more numerous and significant than those that reduce vehicle travel, so self-driving vehicles are likely to increase total vehicle travel, although these impacts are difficult to predict and will depend on specific autonomous vehicle implementation, such as their actual performance and user costs, and other factors that affect vehicle travel such as fuel and road prices. Increases in total vehicle travel may be somewhat offset by reductions in per-mile costs of this incremental travel; for example, self-driving cars may impose less traffic congestion, parking costs, accident risk and air pollution costs than human-operated vehicles per mile travelled, so the increased vehicle travel will impose little or no extra external costs, but the net effects are uncertain.

### *Summary of Benefits and Costs*

Table 4 summarizes expected autonomous vehicle benefits and costs.

***Table 4*** **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.<br><br>*Reduced driver costs.* Reduce costs of paid drivers for taxis and commercial transport.<br><br>*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.<br><br>*Increased safety.* May reduce many common accident risks and therefore crash costs and insurance premiums. May reduce high-risk driving, such as when impaired.<br><br>*Increased road capacity, reduced costs.* May allow platooning (vehicle groups traveling close together), narrower lanes, and reduced intersection stops, reducing congestion and roadway costs.<br><br>*More efficient parking, reduced costs.* Can drop off passengers and find a parking space, increasing motorist convenience and reducing total parking costs.<br><br>*Increase fuel efficiency and reduce pollution.* May increase fuel efficiency and reduce pollution emissions.<br><br>*Supports shared vehicles.* Could facilitate carsharing (vehicle rental services that substitute for personal vehicle ownership), which can provide various savings. | *Increases costs.* Requires additional vehicle equipment, services and maintenance, and possibly roadway infrastructure.<br><br>*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).<br><br>*Security and Privacy concerns.* May be used for criminal and terrorist activities (such as bomb delivery), vulnerable to information abuse (hacking), and features such as GPS tracking and data sharing may raise privacy concerns.<br><br>*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.<br><br>*Social equity concerns.* May have unfair impacts, for example, by reducing other modes' convenience and safety.<br><br>*Reduced employment and business activity.* Jobs for drivers should decline, and there may be less demand for vehicle repairs due to reduced crash rates.<br><br>*Misplaced planning emphasis.* Focusing on autonomous vehicle 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. |

*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, 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.

## Development and Deployment

Table 5 summarizes likely stages of autonomous vehicle development and deployment.

***Table 5*** **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 (2016), many new vehicles have some level 1 automation features such as cruise control, obstruction warning, and parallel parking. Some manufactures, such as Tesla, now 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 achieve unrestricted level 4 operation (Simonite 2016). 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 be required before regulators and potential users gain confidence that level 4 vehicles can operate as expected under all conditions (Bilger 2013; Schoettle and Sivak 2015).

## 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. It 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. Current new vehicle market shares are about 90% in North America and 50% in Europe and Asia.
- *Air Bags* (Dirksen 1997). First introduced in 1973. Initially an expensive and sometimes dangerous option (they could cause injuries and deaths), they became cheaper and safer, were standard on some models starting in 1988, and mandated by U.S. federal regulation in 1998.
- *Hybrid Vehicles* (Berman 2011). Became commercially available in 1997, but 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 6 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 6*** **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. A recent consumer survey found general support for the concept, but also significant concerns about privacy and safety, and relatively low willingness to pay extra for self-driving capability features (Schoettle and Sivak 2014).

Table 7 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. Without mandates, deployment 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 personal preferences and cost savings.

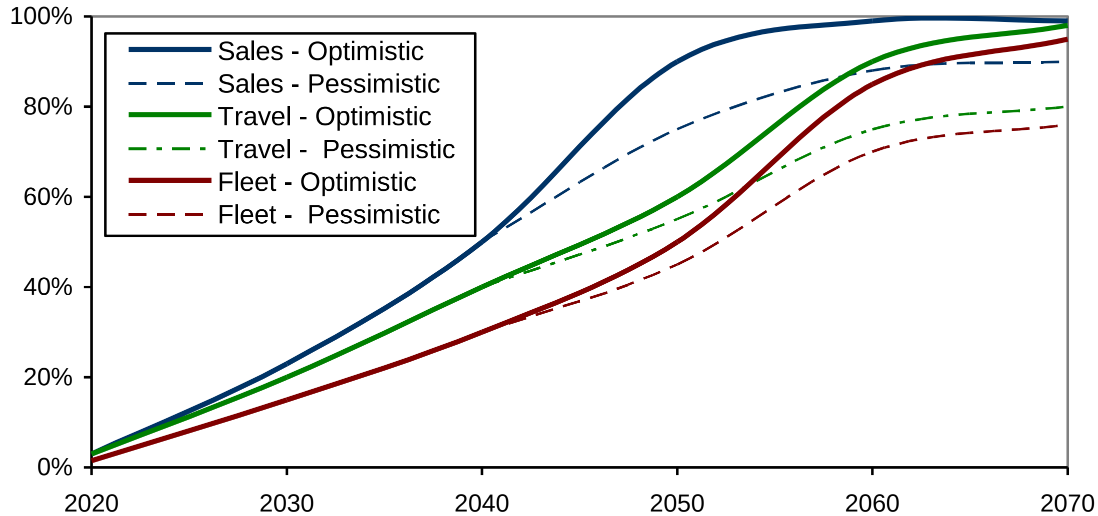
***Table 7*** **Autonomous Vehicle Implementation Projections**

| 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.*

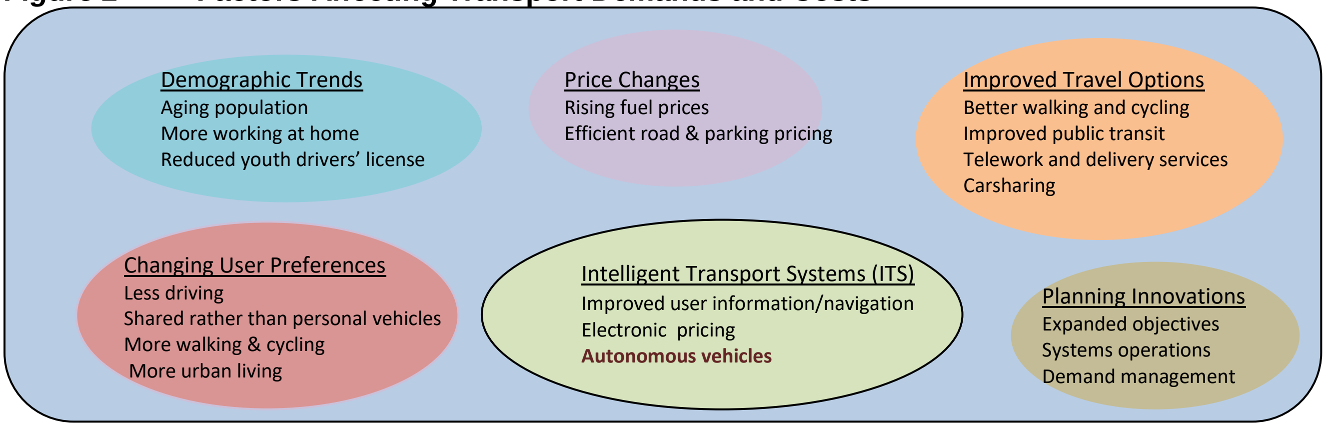
Autonomous vehicle implementation could be even slower and less complete than these predictions. Technical challenges may be more difficult to solve than expected, so fully self-driving vehicles may not be commercially available until the 2030s or 2040s. They may have higher than expected production 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, deployment and fleet turnover 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 used vehicles or cheaper new models to spend significantly more in order to purchase a new automobile with self-driving capability, and many otherwise functional vehicles be scrapped just because they lack self-driving capability.

## Planning Implications

Autonomous vehicle implementation is just one of several factors likely to affect future transport demands and costs, as illustrated in Figure 2. Demographic trends, changing consumer preferences, price changes, improving transport options, improved user information, and other planning innovations will also influence how and how much people drive. These may have greater planning impacts 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 8 (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. However, modeling by the International Transport Forum indicates that self-driving taxis and public transit services are complements rather than substitutes, since transit is more efficient at serving many peak-period urban trips and so significantly reduces the self-driving taxi fleet size and costs.

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 8*** **Autonomous Vehicle Planning Impacts By Time Period**

| Impact | Functional Requirements | Planning Impacts | Time Period |
|---|---|---|---|
| Become legal | Demonstrated functionality and safety | Define performance, 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 |

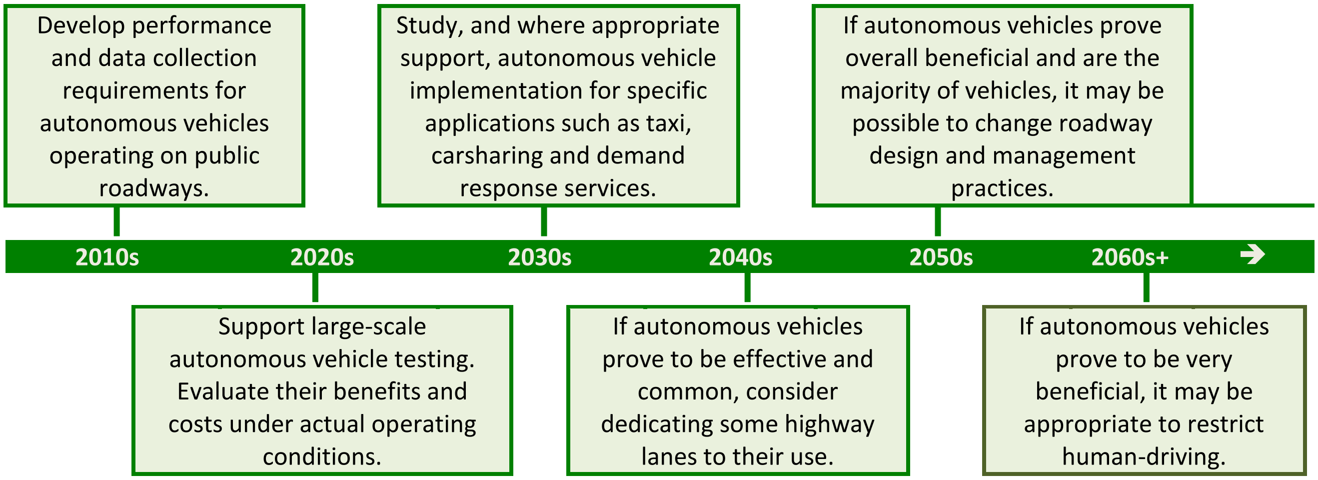
*Autonomous vehicles will have various impacts on transportation planning.*

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 likely to affect road, parking and transit demands, and these changes will probably occur gradually over several decades.

## Conclusions

Recent announcements that autonomous vehicles have safely driven hundreds of thousands of miles and major manufactures aspire to soon sell such vehicles, and optimistic predictions of their benefits, have raised hopes that this technology will soon be widely available and solve many transportation problems. However, there are good reasons to be cautious when predicting their future role.

There is considerable uncertainty concerning autonomous vehicle benefits, costs and travel impacts. Advocates claim that they will provide large benefits that offset costs, but they will require additional equipment, services and maintenance costs that will probably total hundreds or thousands of dollars per vehicle-year, and many of their benefits are unproven.

Current automated vehicles can only self-drive under limited conditions: significant technical and economic obstacles must be overcome before most households can rely on them for daily travel. Operating a vehicle on public roads is more complex than flying an airplane due to the frequency and proximity of interactions with often-unpredictable objects including other vehicles, pedestrians, animals, buildings, trash and potholes. If they follow previous vehicle technology deployment patterns, autonomous vehicles will initially be costly and imperfect. During the 2020s and perhaps the 2030s, autonomous vehicles are likely to be expensive novelties with limited abilities, such as restrictions on the road conditions in which they may operate. It will probably be the 2040s or 2050s before middle-income families can afford to own self-driving vehicles that safely operate in all conditions, and longer before used autonomous vehicles become affordable to lower-income households. A significant portion of motorists may resist such vehicles, just as some motorists prefer manual transmissions, resulting in mixed traffic that creates new roadway management problems.

Vehicle innovations tend to be implemented more slowly than other technological changes due to their high costs, slow fleet turnover and strict safety requirements. Automobiles typically cost fifty times and last ten times as long as mobile phones and personal computers, so consumers seldom purchase new vehicles just to obtain a new technology. Autonomous vehicles will probably have relatively costly equipment and service standards, similar to airplanes, which may discourage some users. Large increases in new vehicle purchase and scrappage rates would be required for most vehicles to be autonomous before 2050.

Self-driving taxi costs are likely to range between carsharing ($0.60-1.00 per mile) and human-driven taxis ($2.00-3.00 per mile), depending on factors such as their cleaning costs. This will make them a cost effective alternative to owning lower (5,000 annual miles) vehicles. However, many motorists are likely to prefer owning personal vehicles for prestige and convenience sake. As a result, shared autonomous vehicles are likely to reduce vehicle ownership mostly in compact, multi-modal urban areas, and will have little effect in exurban and rural areas.

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.

Transportation professionals (planners, engineers and policy analysts) have important roles to play in autonomous vehicle development and deployment. 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 roadways, 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. This review suggests that they will probably increase total vehicle travel unless implemented with offsetting policies such as efficient road and parking pricing.

Another critical issue is the degree potential benefits can be achieved when only a portion of vehicle travel is autonomous. Some benefits, such as improved mobility for affluent non-drivers, may occur when autonomous vehicles are uncommon and costly, but many potential benefits require that most or all vehicles on a road operate autonomously. For example, it seems unlikely that traffic densities can significantly increase, traffic lanes be narrowed, parking supply be significantly reduced, 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-driven vehicles are restricted. Some strategies, such as platooning, may require special autonomous vehicle lanes to achieve benefits. These issues will probably generate considerable debate over their merit and fairness.

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

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