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Future Highways - Automated Vehicles

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COURSE DESCRIPTION:

It has been approximately 100 years since the motorized vehicle replaced the horse and buggy. The future of highway transportation is now undergoing another major revolution as engineers across numerous disciplines (transportation, automotive, technology, etc.) work towards moving the responsibility of driving the automobile from human to machine, see Figure 1. The development of cars driven completely without aid by a human driver (i.e., driverless cars), commonly referred to as ‘automated’ vehicles, will certainly give more appropriate meaning to the term ‘auto’-mobile.

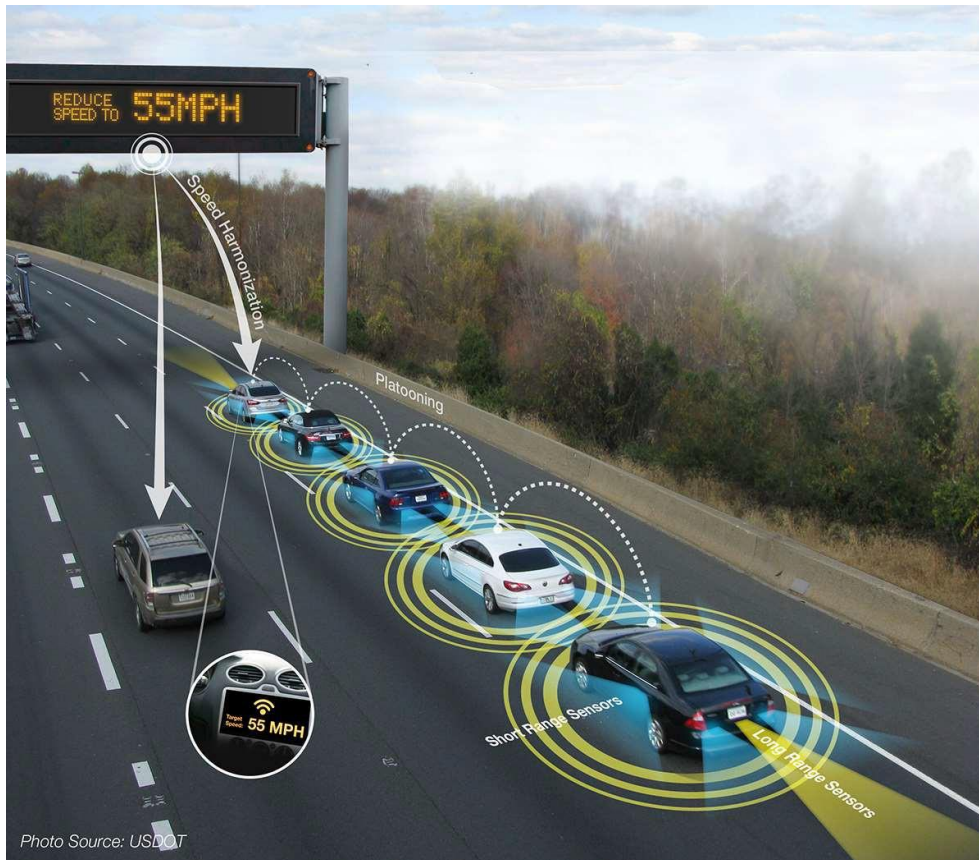


Figure 1. Example of a future highway
Source: USDOT

In this course, you will learn about:

- the terminology being used in the field of automated highway vehicles
- examples of government legislation being implemented to facilitate the future of automated vehicles
- the technologies being used in automated vehicles
- automated vehicle engineering research and standards under development
- potential impacts of automated vehicles on traffic flow and roadway design

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INTRODUCTION

Transportation affects just about every facet of our lives—work, social, recreational, etc. Society depends on transportation networks to facilitate the movement of people and goods on a daily basis. The health of our country’s economy is strongly correlated to the health of our transportation system. (1) Highway transportation is by far the dominant mode of travel for both people and goods in the U.S. (relative to air, sea, and rail modes). Consequently, the efficiency and safety of our highway transportation system has a very significant impact on our quality of life. For the last 25+ years, the increase in demand for personal and freight travel has outpaced the expansion of our highway system, which has led to severe congestion in urban areas. Congestion leads to reduced levels of societal productivity, increased energy consumption, and increased emissions output. Congestion, such as that shown in Figure 2, is a regular occurrence in urban areas.

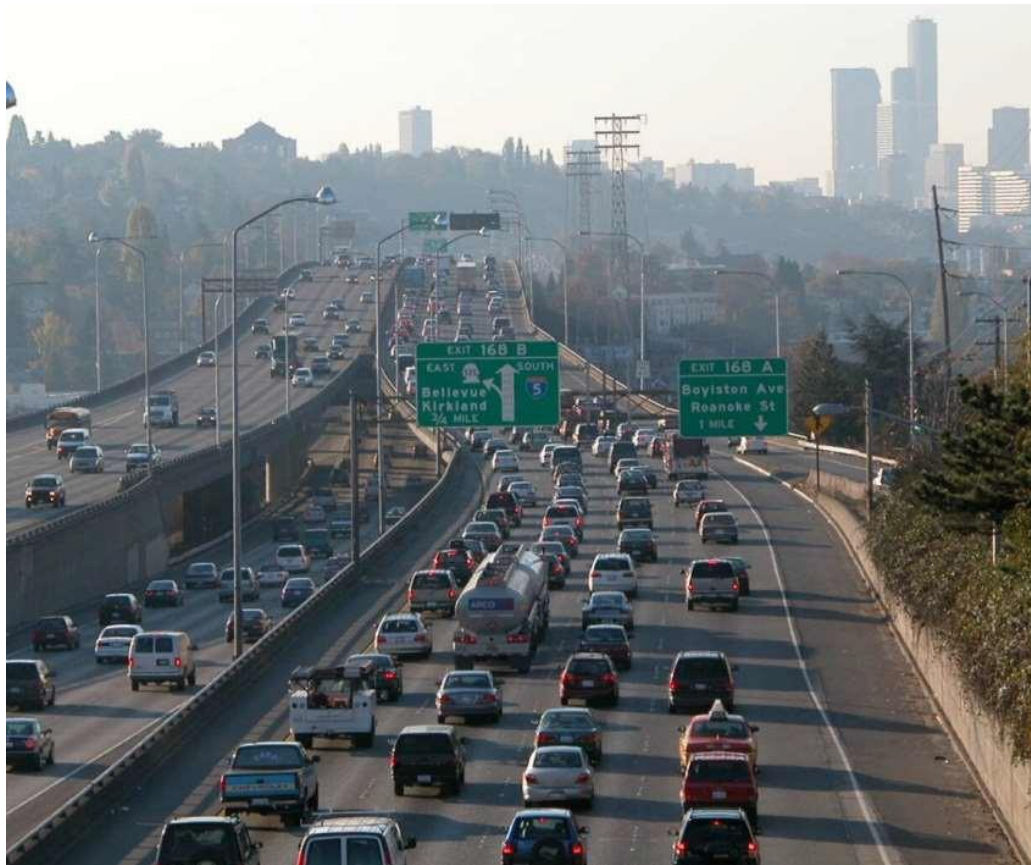


Figure 2. Congestion example in Seattle WA
Source: Washington State Transportation Center (TRAC)

The U.S. Interstate Highway System is comprised of over 45,000 miles of highway, with almost 4 million total miles of roadway in the U.S., and 4.6 trillion passenger-miles of travel are accumulated annually in the U.S. (2) According to the 2019 Texas Transportation Institute Urban

Mobility Report (3), Americans spent 8.8 billion more hours (approximately 54 hours per traveler) due to congestion in 2017 and needed to allow an additional 34 minutes to arrive at their destination for a trip that takes 20 minutes in light traffic. The effect of congestion on freight truck operations cost the economy \$20 billion, which was likely passed along to the consumers in the price of the goods being transported. Freight trucks contribute nearly 11 percent to urban congestion, yet only account for 7 percent of the miles traveled in urban areas. (3)

Due to congestion, commuters spent an additional \$166 billion in time and fuel. (3) Congestion caused U.S. travelers to waste 3.3 billion gallons of fuel (approximately 21 gallons per traveler) in 2017. (3) According to the Environmental Protection Agency (EPA), transportation contributed 29 percent of the U.S. greenhouse gas emissions in 2019, caused by the burning of fossil fuel for cars, trucks, ships, trains, and airplanes. Passenger cars and light-duty trucks, such as sport utility vehicles, pickup trucks and minivans, account for over half of the 29 percent gas emissions due to transportation. (4) Figure 3 illustrates the primary sources of greenhouse gas emissions in the United States.

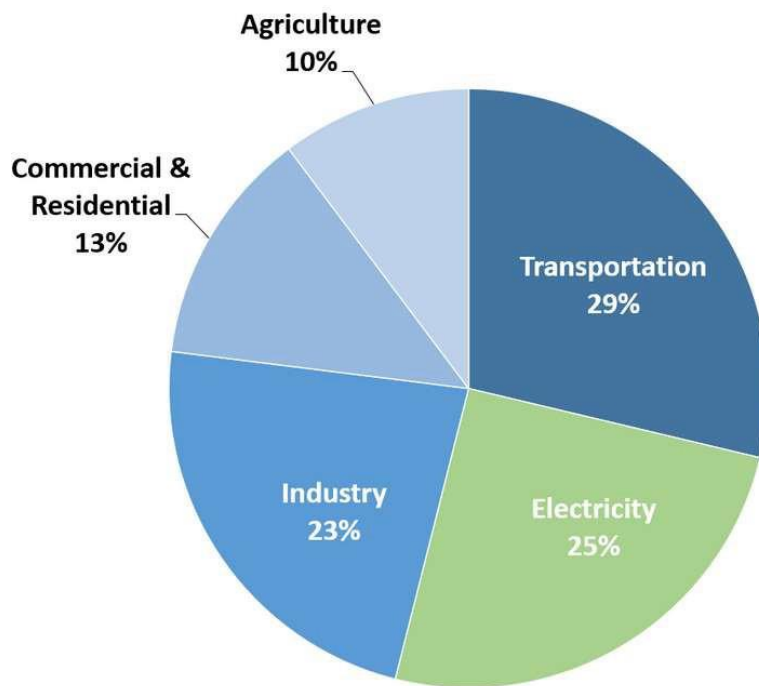


Figure 3. Primary sources of greenhouse gas emissions in the United States (as of 2/4/2022)
Source: EPA (4)

Furthermore, with all the demand for travel, there is a corresponding high number of vehicle crashes that occur on our roadways. According to the National Highway Traffic Safety Administration (NHTSA), there were 6.76 million crashes and 2.74 million injuries in the U.S. in 2019. There were 36,096 fatalities from vehicle crashes in 2019. (5) While modest improvements in safety have come from advances in vehicle technology, such as air bags and anti-lock brakes,

by far the biggest contributor to automobile crashes is human error. Aside from the direct and emotional costs of crashes, they often compound the congestion problem as well, particularly in urban areas. Figure 4 is an example of a common scene on urban freeways.



Figure 4. A vehicle crash and resulting impact on congestion
Source: Washington State Transportation Center (TRAC)

The Future—Automated Vehicles

Clearly, reducing congestion and the frequency and severity of crashes on our highway system will significantly increase the effectiveness of the highway system and the societal benefits we receive from it. Technology is an integral part of society and is advancing at a remarkable rate with computers, cell phones, and much more. Now the future of highway transportation will be transformed by technology with automated vehicles, which will benefit transportation mobility, energy consumption, environmental impacts, and safety.

Current technology has begun to give drivers critical information to avoid potential crashes and save lives (see Figure 5). The role of highways in the 21st century continues to evolve, and technology has the potential to change the paradigm of designing vehicles from sustaining a crash to preventing a crash. Eventually, the automobile will be able to completely take over the task of driving from the human.



Figure 5. Future crash alert technology

Source: USDOT

The future advances of automated vehicles, according to NHTSA research, could prevent 80 percent of crashes involving non-impaired vehicles. (6) Future highways with automated vehicles, especially those that are under complete computer control, could eventually result in a near-zero rate of crashes, minimum levels of energy consumption and vehicle emissions, and reduced travel times. Vehicles that can drive themselves will also lead to increased mobility for persons with disabilities and the elderly.

The remainder of this document will provide a primer on automated vehicle technologies and their potential impacts on future highway transportation. Before commencing with the overview of the two major technology areas of automated vehicles, namely autonomous vehicles and connected vehicles, an introduction to the common terminology that is used in this field is provided.

Terminology

Autonomous Vehicles

“Autonomous” is the term generally used when referring to vehicles that can perform all the necessary driving functions. However, to be more precise, a distinction is typically made between vehicles that require zero input from a human to drive (and may not contain a steering wheel, accelerator/brake pedals, and the like) and vehicles in which a human is expected to monitor the driving functions and be able to take control in emergency situations. The former is referred to as a “driverless” vehicle and the latter is referred to as a “self-driving vehicle.” Autonomous vehicles do not require any communications to other vehicles or roadside infrastructure. (7)

Connected Vehicles

Connected vehicles use wireless communication technology to communicate with other vehicles and highway infrastructure. Connected vehicles can receive information that will allow a human or computer driver to operate the vehicle more efficiently and/or avoid a potential collision. For example, a connected vehicle can receive information from a traffic signal ahead, which might indicate that if the vehicle maintains its current speed, it will not have to stop at the signal. Likewise, a connected vehicle could receive information from vehicles much further ahead that they are slowing due to congestion and the driver/vehicle could revise its travel route accordingly.

Automated Vehicles

“Automated vehicles are those in which at least some aspect of a safety-critical control function (e.g., steering, throttle, or braking) occurs without direct driver input. Automated vehicles may be autonomous (i.e., use only vehicle sensors) or may be connected (i.e., use communications systems such as connected vehicle technology, in which cars and roadside infrastructure communicate wirelessly).” (7) It should be noted that not all sources use the term “automated vehicles” consistently. Some sources do not include connected vehicles in the definition of automated vehicles; that is, they consider automated vehicles to be just those that fit within the NHTSA-defined levels of automation (as described later in this document). For the purposes of this document, we are using the definition of automated vehicles as provided by the USDOT (the source of the quote above), which includes both autonomous and connected vehicles. Figure 6 illustrates an example of an automated vehicle that includes connected vehicle technology and speed and lane position automation.



Figure 6. Example of an automated vehicle
Source USDOT

Vehicle-to-Vehicle (V2V)

Vehicle-to-vehicle communication technology refers to communication technology that is used to provide vehicles the ability to share speed, position, and other operational data with one another.

Vehicle-to-Infrastructure (V2I)

Vehicle-to-infrastructure communication technology refers to communication technology that is used to share operational data for both vehicles and traffic control devices (e.g., traffic signals) between both entities.

Vehicle-to-Vehicle and Vehicle-to-Infrastructure (V2X)

V2X is a more general term to refer to both V2V and V2I communication technologies.

Automated Highway System (AHS)

An Automated Highway System refers to a highway that has automated vehicles operating on it.

*"Vehicle-to-vehicle technology represents the next generation of auto safety improvements, building on the life-saving achievements we've already seen with safety belts and air bags," said former U.S. Transportation Secretary Anthony Foxx. "By helping drivers avoid crashes, this technology will play a key role in improving the way people get where they need to go while ensuring that the U.S. remains the leader in the global automotive industry."
(8)*

AUTONOMOUS VEHICLE TECHNOLOGY

Technologies to assist the human with the vehicle driving task started appearing in the 1980's, such as cruise control and anti-lock brakes. Current and near-future technology provide stability and traction control, adaptive cruise control, self-parking, and accident-prevention systems. Varying levels of driving automation may be present in a vehicle, and NHTSA and the Society of Automotive Engineers (SAE) has defined six categories for such automation, as follows: (9)

No-Automation (Level 0): The human driver does all the driving.

Driver Assistance (Level 1): An advanced driver assistance system (ADAS) on the vehicle can sometimes assist the human driver with either steering or braking/accelerating, but not both simultaneously.

Partial Automation (Level 2): An advanced driver assistance system (ADAS) on the vehicle can itself actually control both steering and braking/accelerating simultaneously under some circumstances. The human driver must continue to pay full attention (“monitor the driving environment”) at all times and perform the rest of the driving task

Conditional Automation (Level 3): An Automated Driving System (ADS) on the vehicle can itself perform all aspects of the driving task under some circumstances. In those circumstances, the human driver must be ready to take back control at any time when the ADS requests the human driver to do so. In all other circumstances, the human driver performs the driving task.

High Automation (Level 4): An Automated Driving System (ADS) on the vehicle can itself perform all driving tasks and monitor the driving environment – essentially, do all the driving – in certain circumstances. The human do not need to pay attention in those circumstances.

Full Automation (Level 5): An Automated Driving System (ADS) on the vehicle can do all the driving in all circumstances. The human occupants are just passengers and need never be involved in driving.

Figure 7. NHTSA-defined vehicle automation levels

Vehicles labeled as “autonomous”, such as that in Figure 8, are considered to meet NHTSA’s definition of automation level 4.



Figure 8. An example of an autonomous vehicle (in development by Nissan)

Source: Wikimedia Commons

Vehicle Cybersecurity

Autonomous vehicle technology depends on many electronic components that have vulnerabilities to someone accessing the vehicle via Bluetooth, Wi-Fi, USB or through the vehicle diagnostic port. (10) NHTSA’s goal is to stay ahead of potential cybersecurity with research and industry partnerships that encourage independent steps in prevention. A “Cybersecurity Best Practices for Modern Vehicles” guide was released in 2016. (11)

The discussion in the remainder of this section is specific to vehicles that meet the definition for NHTSA level 4 and 5 automation.

How Does it Work?

Currently, autonomous vehicles utilize a combination of internal sensors, video cameras, GPS, and advanced software. These technologies are coordinated such that the vehicle can be driven without

any human input to steering, throttle, and braking systems. Autonomous vehicles (i.e., NHTSA automation levels 4 and 5) must be able to map its surroundings and the vehicle's relative position in the mapped area in order to navigate and avoid obstacles. Autonomous vehicle technology is developing and evolving quickly, with a large variety of automobile manufactures, researchers, and other interested parties developing systems independently. Therefore, there is not a single design model or blueprint that demonstrates an autonomous vehicle. Furthermore, those involved with designing autonomous vehicles tend to not be forthcoming with the specifics of their designs, due to intellectual property concerns. Thus, a more general overview of the components that are known to be involved in some autonomous vehicle designs are provided here.

- **Actuators** – The brake, throttle, steering actuators take signals from sensors and adjust vehicle mechanics accordingly.
- **Ultrasonic Sensor** – Used to detect obstacles in front and behind the vehicle by using high-frequency sounds waves (inaudible to humans) that reflect off objects.
- **Global Positioning System (GPS)** – The GPS satellite network is used to continuously determine vehicle position (latitude and longitude coordinates) and speed. The GPS coordinates are also used with mapping software to provide route navigation functionality.
- **Laser Range Finder (LIDAR)** – Laser Range Finder (LIDAR) – Used to continuously measure horizontal distance from the vehicle to surrounding objects by illuminating such objects with a 360-degree rotating laser and analyzing the reflected light. Autonomous vehicles use LIDAR technology to detect obstacles to navigation by generating a 3-dimensional (3D) map of its environment. It also provides the information needed by the algorithms to identify traffic control devices and valid travel paths.
- **Video Cameras** – Used with image processing software to detect roadway lanes (through striping), road signs, stop lights, and other objects.
- **Radar Sensors** – Used to detect traffic signs and signals, and other obstacles by transmitting microwave signals. Utilizing the radar sensors on the front of the vehicle, the computer system can determine the speed and distance of the vehicle in front of it (in the same lane) and automatically adjust the speed to maintain a desired distance from such vehicle.

Autonomous Vehicle Research and Testing

Several companies such as Google, Tesla, and Uber have been frontrunners in autonomous vehicle development and testing. In 2012, Google tested a fleet of driverless vehicles (including six Toyota Priuses fitted with equipment for their autonomous vehicle design) and logged more than 190,000 miles. These miles were logged on city streets and highways, but further details on traffic conditions such as range of vehicle operating speeds and level of congestion, as well as roadway, lighting, and weather conditions are not available. All these miles of testing were without any

incidents due to the autonomous systems. One of Google’s more current autonomous vehicle designs is built on the Lexus SUV platform (see Figure 9). The LIDAR unit (again, used for creating a 3D map of surrounding objects) is shown mounted on the roof of the vehicle. The Google vehicle also has four radar sensors mounted to the front and rear bumpers, a video camera, GPS, inertial measurement unit and wheel sensors. The Google vehicle is also purportedly capable of following traffic laws. (12)

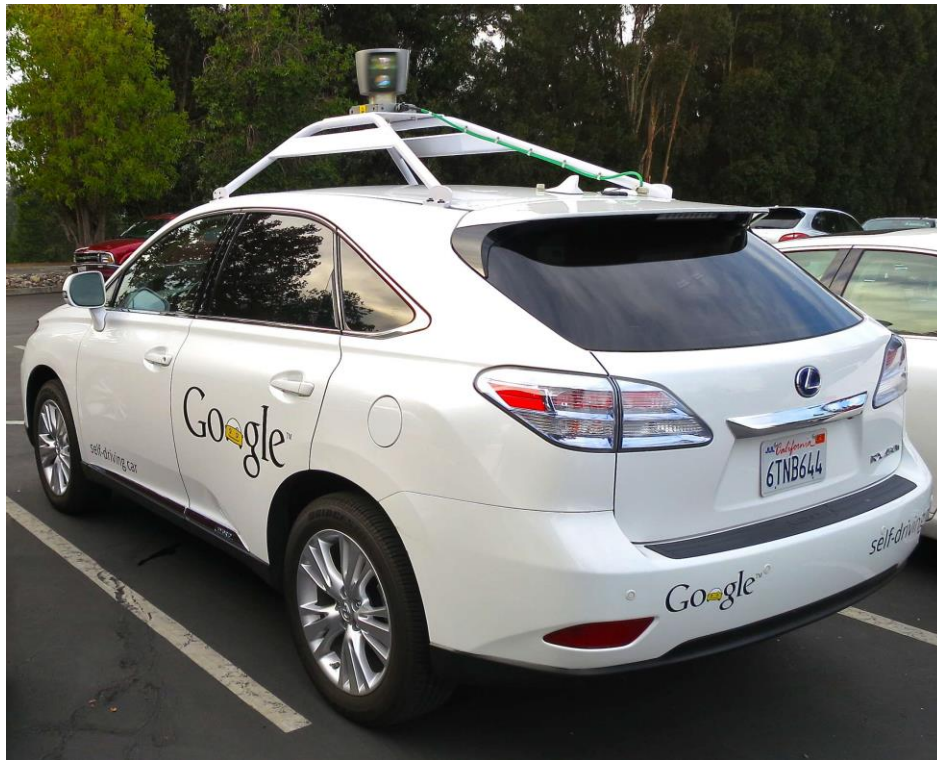


Figure 9. A Google autonomous vehicle on a city street
Source: Wikimedia Commons

More recently, many of the major vehicle manufacturing companies have initiated autonomous vehicle development efforts.

The University of Michigan Transportation Research Institute (UMTRI) developed a 32-acre Mobility Test Facility with a four-lane highway, design to simulate dangerous traffic events and road conditions. The facility “simulates the broad range of complexities vehicles encounter in urban and suburban environments. It includes approximately three lane-miles of roads with intersections, traffic signs and signals, sidewalks, benches, simulated buildings, streetlights, and obstacles such as construction barriers.” (13)

Potential Advantages and Disadvantages of Autonomous Vehicles

Potential Advantages

Autonomous vehicles are dependent on the equipment housed within the vehicle and functions independent of any outside infrastructure.

- *Improved safety*
By removing the biggest contributor to crashes (i.e., the human) from the driving function, autonomous vehicles will potentially save thousands of lives and prevent tens of thousands of injuries per year in the U.S.
- *Reduced traffic congestion - increasing roadway capacity and decreasing travel time*
Roadway capacity is generally considered to be the maximum number of vehicles that can move past a point on the roadway. Vehicle crashes typically cause significant reductions in capacity, either through directly blocking lanes and/or through driver distraction (i.e., rubbernecking). By reducing vehicle crashes, the congestion on roadways will be greatly reduced. With less time waiting for traffic crashes to clear and backups due to roads being over capacity, travel times will decrease. Travelers will be able to enjoy taking less time to get to their destination.
- *Improved air quality and reduced fuel demand*
With less traffic congestion, vehicles will be sitting idle for significantly shorter periods of time, reducing fuel demands and improving air quality from vehicle emissions. Additionally, computer-controlled cars will be capable of setting acceleration and deceleration rates in a more optimal manner than humans to conserve fuel and reduce emissions.
- *Vehicle sharing*
Autonomous vehicles can reduce the number of household vehicles. Since autonomous vehicles (level 5) will not need a human driver, a single vehicle can serve more transportation demands than non-autonomous vehicles. For example, an autonomous vehicle could take one household member to a destination and then return home to take another family member to another destination, and so on. Likewise, there would be more flexibility with car-sharing services because a vehicle can drive itself between various pick-up/drop-off locations.
- *Space needed for parking would be reduced*
With more people sharing vehicles, the need for parking spaces will be reduced.
- *Increased mobility for financially disadvantaged persons*
Those individuals that rely on public transportation for financial reasons will have improved mobility options through autonomous vehicle car-sharing capabilities.
- *Increased mobility for disabled and elderly persons*
Without the need to operate the vehicle, those with physical limitations could utilize an autonomous vehicle.

- *Passenger productivity*
Without the need to be in control of the vehicle, passengers will be free to make use of vehicle travel time for other purposes (rest, work, etc.).
- *Money saved from crashes - car repairs, insurance, and medical bills*
Billions of dollars each year are spent on car repairs because of crashes. With fewer crashes, car insurance claims will decrease, which should reduce premiums. Medical bills, loss of wages, and pain and suffering will also be greatly reduced as a result of fewer crashes.
- *Reduce the need for traffic law enforcement*
With autonomous vehicles, there will be much less need for police to stop vehicles and write citations for things like red-light running, speeding, impaired driving, and so on. This will allow police to spend more time focusing on other law enforcement activities.

Potential Disadvantages

- *Loss of jobs*
Jobs related to crashes, such as collision repair, injury lawyers, medical personnel, auto insurance, and traffic law enforcement will be greatly reduced.
- *Resistance to giving up control of driving function*
Some people like to drive and may be resistant to letting a computer do the driving for them. Going from the “ultimate driving machine” to the “ultimate riding machine” may be perceived as a reduction in the quality of life for some.
- *Reduced privacy*
Although controls will certainly be put in place to protect personal privacy to the extent reasonable, travel information will potentially be more open to inspection with autonomous vehicles.
- *Software reliability and security*
Autonomous vehicles will be even more dependent on computer software than traditional vehicles. Such software will contain millions of lines of code. “Bugs” in the software could result in very negative consequences. Furthermore, securing the software of autonomous vehicles from malicious attacks (i.e., “hacking”) will be critical.

CONNECTED VEHICLE TECHNOLOGY

Connected vehicle technology, whether in autonomous vehicles or human-driven vehicles, has the potential to make significant improvements to the effectiveness of our highway transportation system. V2X communications will provide for a high level of cooperation between vehicles and traffic control devices with a certain proximity to one another. With highway vehicles, and even trains that intersect highways, communicating with one another, considerable reductions in crashes and congestion can be achieved.

Safety

V2X technology can provide timely warnings to a driver of potentially hazardous situations, such as:

- a vehicle in blind spot when changing lanes
- sudden braking ahead
- a disabled vehicle in the lane ahead
- an active construction zone ahead
- a school zone ahead
- upcoming traffic lights are about to change

Implementation of a V2X warning message is illustrated in Figure 10.

Most crashes occur at intersections and when changing lanes; thus, current and future technology is focused on communication in these areas. NHTSA has estimated that connected vehicle technology could reduce the number of non-impaired driver crashes by 80% and prevent most typical crash scenarios such as those at intersections. (14) Figure 11 illustrates intersection communication with V2X technology.

"Vehicle to vehicle crash avoidance technology has game-changing potential to significantly reduce the number of crashes, injuries and deaths on our nation's roads," said NHTSA Acting Administrator David Friedman.

"Decades from now, it's likely we'll look back at this time period as one in which the historical arc of transportation safety considerably changed for the better, similar to the introduction of standards for seat belts, airbags, and electronic stability control technology."



Figure 10. Implementation of driver warning message
Source: USDOT



Figure 11. Intersection connected vehicles can improve safety at busy intersections
Source: USDOT

Congestion

With the potential for V2X technology to reduce crashes, congestion will be reduced as well. In addition, with a vehicle's ability to send up-to-the second data on its location and speed, drivers can avoid downstream congestion by using alternative routes. The V2X communications can provide information such as a recommended speed to be able to move through several successive traffic signals without getting stopped; thus, reducing delay, fuel consumption, and emissions output. V2X could utilize real time vehicle data to automatically determine if there is a vehicle disabled and dispatch emergency vehicles, as well as let drivers know to move aside for approaching emergency vehicles.

V2X technology could also potentially connect travelers via their cell phones to communicate traffic conditions and schedule/location information for buses, trains, and other forms of public transit to make trips more efficient. Figure 12 and Figure 13 illustrate additional examples of connected vehicle technology.



Figure 12. Connected vehicle technology will help to reduce crashes between light and heavy vehicles

Source: USDOT



Figure 13. V2V communication on freeways will help to prevent crashes

Source: USDOT

How Does it Work?

As previously mentioned, vehicles can be autonomous, connected, or both. The following discussion focuses on the technology used to facilitate V2X communications, which is central to the connected vehicle concept, and independent of whether the vehicle also contains technology for various levels of automated driving. Figure 14 and Figure 15 show a Federal Highway Administration (FHWA) Test Connected Vehicle.

Communications Technologies

Initially, the transportation industry was planning to use two-way short-to-medium-range wireless communication channels, utilizing a protocol like WiFi on a dedicated frequency spectrum of 5.85-5.925 GHz. This specific communication protocol was referred to as dedicated short-range communications (DSRC). Recently, the Federal Communications Commission (FCC) opened 45 MHz of the originally reserved 75 MHz (5.85 – 5.895 GHz), leaving just the range from 5.895 – 5.925 GHz, a band of 30 MHz, dedicated to transportation communication applications. (15)

There is concern within the industry that the dedicated 30 MHz band is insufficient to serve all the imminent transportation communication needs. Thus, other alternatives are being considered. A leading candidate at this moment is cellular 5G technology. While the range of frequencies for 5G varies by cellular carrier, and can vary within carrier depending on the application, transportation communication applications would likely utilize a very high frequency range, such as the “millimeter band” (approximately 30 – 300 GHz). (16) These very high frequencies offer the potential for very high data transmission rates, but a significant concern with the use of cellular-based communications is the lack of spectrum exclusivity for transportation applications; thus, more potential for interference and cyber-hacking. (17)



Figure 14. FHWA connected vehicle with equipment attached to the roof
Source: Scott Washburn



Figure 15. FHWA connected vehicle on-board equipment
Source: Scott Washburn

Communication Messaging

Connected vehicle/infrastructure relies on the exchange of messages between vehicles and road-side equipment/devices. SAE defines the standards for formatting and content of such messages.

(18) The messages are grouped into several different categories, based on general functional area. Some commonly used message categories are:

- Basic Safety Message (BSM): Contains information on vehicle state (position, velocity, braking status, steering wheel angle, etc.)
- Signal Phase and Timing Data (SPaT): Contains information on active signal phase, lanes served by phase, time until green, etc.
- Map Data (MAP): Contains information on lane positions, crosswalk positions, allowed vehicular movements for each lane, etc.

The frequency of message communication can vary, but the most essential (safety-related) messages, such as those in the BSM category are typically transmitted at a rate of 10 Hz (i.e., 10 times per second).

Potential Advantages and Disadvantages of Connected Vehicles

Potential Advantages

The advantages of connected vehicles are much the same as for autonomous vehicles, but with the potential to provide additional improvements to safety, traffic efficiency, mobility, fuel use, and emissions output as well as socioeconomic benefits. These additional benefits would be achieved through the additional information obtained from wireless communications providing operational data on all vehicles and traffic control devices within a certain vicinity (example illustration in Figure 16).



Figure 16. V2V and V2I technology between all modes of transportation

Source: USDOT

Potential Disadvantages

Beyond the disadvantages discussed previously for autonomous vehicles, connected vehicles are dependent on the infrastructure around them and require more software and equipment. This increases the costs and the complexity of the system. Even less privacy is likely under a connected vehicle system.

Connected Vehicle Research and Testing

“The U.S. Department of Transportation (USDOT) Intelligent Transportation Systems Joint Program Office (ITS JPO), Federal Highway Administration (FHWA), Federal Transit Administration (FTA), Federal Motor Carrier Safety Administration (FMCSA), and the National Highway Traffic Safety Administration (NHTSA) are collaborating to research and spur the deployment of connected vehicle technology. (19)

NHTSA issued guidance in September 2017 (19) on automated vehicle development, providing guidance and recommendations for passing laws to assist states to permit testing on emerging vehicle technology and how to ensure safety as new technology is tested on roadways. NHTSA will work with its public and private partners to establish policy and standards for connected vehicle technology to improve Americans’ way of life, focusing on making surface transportation safer and greener.

The Intelligent Transportation Systems Joint Program Office (ITS JPO) released “*The ITS Strategic Plan 2015-2019*” to provide a framework for research, development. The plan’s priorities are for deployment of connected vehicle implementation and automation. (21)

Automated vehicles and highways could significantly change driving in the future, but how and when we achieve this change will depend on current and

future research as well as standards developed to implement V2X technology. In 2015, the USDOT sponsored a study to assess safety, mobility, and environmental impacts of connected vehicles. The study is a combination of four research programs; Vehicle-to-Infrastructure (V2I) Safety, Dynamic Mobility Applications, Applications for the Environment: Real-Time Information Synthesis, and Road-Weather Management. As many as 50 V2I applications have been developed as a result of these programs. (21)

A 2015 study by the Intelligent Transportation Society (ITS) of America evaluated potential socioeconomic benefits to connected vehicles focused on left turn assist, forward collision warning, and lane change warning. The study found connected vehicle applications could result in \$178.8 billion dollars of annual savings in the United States to medical care costs and productivity loss if all vehicles were equipped with the technology. (19)

A summary of the USDOT sponsored study findings on safety, mobility, and environmental impacts of connected vehicles is as follows (19):

Safety Benefits: *Combinations of V2I safety and road weather applications are effective in reducing crashes:*

Red Light Violation Warning and Pedestrian in Signalized Crosswalk Warning applications together have the potential to address more than 250,000 crashes and 2,000 fatalities each year.

The Curve Speed Warning application has the potential to address more than 169,000 crashes and 5,000 fatal crashes per year.

Traffic management applications on freeways can reduce the number of crash-related incidents by 25 percent during winter weather conditions

Mobility Benefits: *Combinations of V2I applications are effective in prioritizing signal timing and reducing travel time and overall delay:*

Combinations of signal control applications (Intelligent Traffic Signal System, Freight Signal Priority, and Transit Signal Priority and Freight Signal Priority) reduced travel time by up to 27 percent.

The Incident Scene Pre-Arrival Staging Guidance for Emergency Responders application can potentially reduce travel time for emergency vehicles by up to 23 percent and their number of stops by up to 15 percent.

When cooperative adaptive cruise control and speed harmonization applications are optimized for the environment, they can potentially reduce travel time on freeways by up to 42 percent.

Environmental Benefits: *V2I applications have potential congestion and lane management capabilities and can reduce fuel consumption and emissions:*

When signal operations and freeway lane management applications are optimized for the environment, they could yield fuel savings of up to 22 percent.

The Low Emissions Zone application resulted in a 20-percent reduction in vehicle-miles traveled.

Three coordinating eco-signal operations applications (Eco-Approach and Departure, Eco-Signal Timing, and Eco-Signal Priority) resulted in an 11-percent reduction in carbon dioxide emissions and fuel consumption.

GOVERNMENT LEGISLATION

States that have passed legislation specific to automated vehicles on roadways are Alabama, Arkansas, California, Colorado, Connecticut, Florida, Georgia, Illinois, Indiana, Kentucky, Louisiana, Maine, Michigan, Mississippi, Nebraska, New York, Nevada, North Carolina, North Dakota, Oregon, Pennsylvania, South Carolina, Tennessee, Texas, Utah, Virginia, Vermont, Washington, Wisconsin, and Washington D.C. In 2017, 33 states had introduced legislation and 18 states enacted bills in 2018. The governors of Arizona, Delaware, Hawaii, Idaho, Massachusetts, Maine, Minnesota, Ohio, Washington, and Wisconsin have issued executive orders for autonomous vehicles. States develop their own policies and continue to change. A brief summary of each state legislation related to autonomous vehicles can be found at *The National Conference of State Legislatures* website. (22)

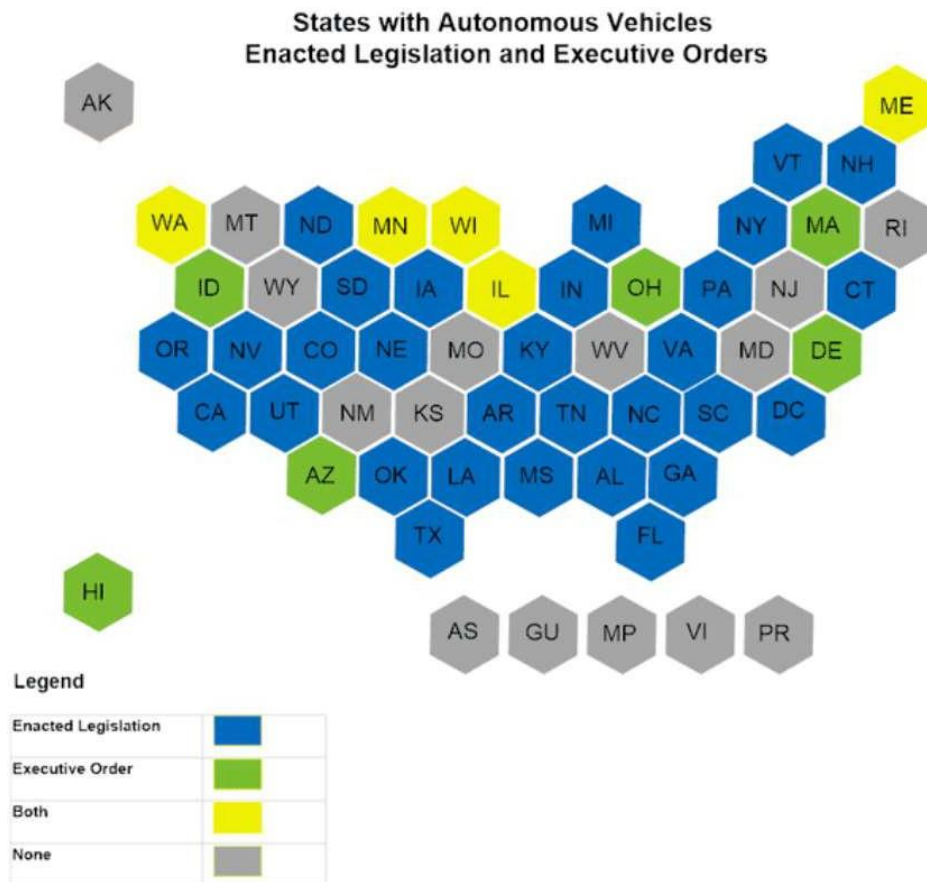


Figure 17. States with Enacted Autonomous Vehicle Legislation (as of 2/4/2022)

Source: National Conference of State Legislatures

More detail and current information are provided at The Insurance Institute for Highway Safety (IIHS) website (23) and summarized in the table below.

State	What type of driving automation on public roads does the law/provision permit?	Does the driving automation law/provision...		
		Require an operator to be licensed?	Require an operator to be in the vehicle?	Require liability insurance?
Alabama	deployment — commercial motor vehicles only	no	No	yes; \$2,000,000
Arizona	deployment	yes	depends on level of vehicle automation ¹	yes
Arkansas	deployment - commercial purposes	yes	depends on level of vehicle automation ²	yes ³
California	deployment	not addressed	no	yes; \$5,000,000
Colorado	deployment	no	not addressed	no
Connecticut	testing	yes	yes	yes; \$5,000,000
District of Columbia	deployment	yes	yes	no
Florida	deployment	depends on level of vehicle automation ⁴	depends on level of vehicle automation ⁵	yes
Georgia	deployment	depends on level of vehicle automation ⁶	depends on level of vehicle automation ⁷	yes
Hawaii	testing	not addressed	yes	not addressed
Illinois	testing	yes	yes	yes
Iowa	deployment	yes	depends on level of vehicle automation ⁹	yes
Louisiana	deployment — commercial motor vehicles only	no	no	yes; \$2,000,000
Maine	testing	not addressed	not addressed	yes
Massachusetts	testing	no	yes	no
Michigan	depends on vehicle ¹⁰	yes	no	yes

Figure 18. Autonomous Vehicle Laws by State (as of 2/4/2022)

Source: Insurance Institute for Highway Safety

POTENTIAL IMPACTS OF AUTOMATED VEHICLES ON TRANSPORTATION ENGINEERING

There are many areas across transportation engineering that will potentially be affected by automated vehicles. In this course, we will discuss the potential impacts of automated vehicles on traffic flow and geometric design and some of the considerations that must be made in determining the extent of the influence that can be expected in these respective areas.

Traffic Flow

Uninterrupted Flow Facilities

Uninterrupted-flow facilities are considered to be roadways in which external controls, such as traffic signals, stop signs, etc., are not present. Freeways, multilane highways, and two-lane highways generally fall into this category. Operations on such roadways are often characterized by the relationship between traffic volume and the resulting average speed for such volume. Figure 19 shows an example speed-flow relationship for freeway facilities, which is generally consistent with that given by the Highway Capacity Manual (HCM). (24)

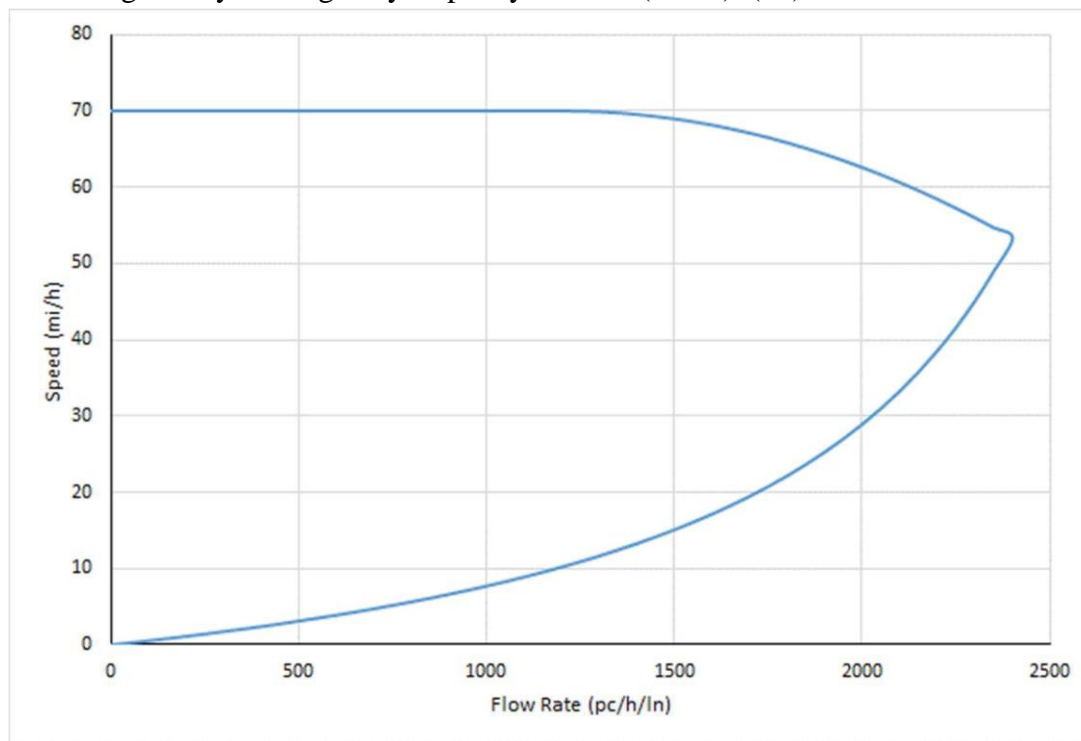


Figure 19. Speed-flow relationship for freeways

Source: Scott Washburn

In this figure, the upper curve illustrates the speed-flow relationship for under-saturated conditions—that is, traffic flow operations prior to a breakdown and the subsequent onset of stop-and-go conditions. The lower curve illustrates the approximate speed-flow relationship of the

traffic stream once stop-and-go (i.e., saturated) conditions have set in. It can be observed from this figure that the maximum number of passenger cars (pc) we can expect to move on a freeway lane (commonly referred to as ‘capacity’) is about 2400 (the “apex” point in this figure).

The speed-flow relationship in Figure 19 is largely predicated upon vehicle size and human driving behavior. The capacity value of 2400 pc/h/ln translates to an average headway (i.e., the time elapsed between the passage of two consecutive vehicles at a given point on the roadway) of 1.5 seconds (3600 s/h divided by 2400 pc/h/ln). With a traffic consisting completely of autonomous vehicles (i.e., one without any human drivers), will it be possible, or feasible, to increase freeway capacity and even eliminate the lower curve in Figure 19? In other words, can we achieve a speed-flow relationship that looks more like the one illustrated in Figure 20?

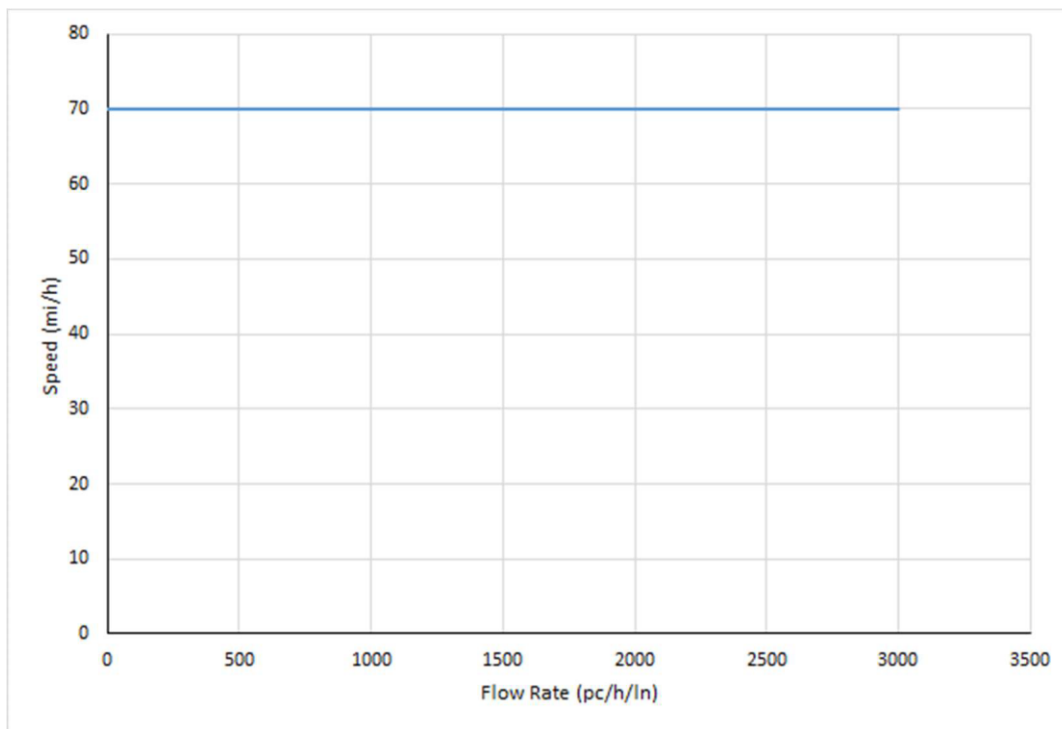


Figure 20. Possible speed-flow relationship for freeways with a traffic stream of 100% autonomous vehicles

Source: Scott Washburn

Figure 20 shows a capacity value of 3000 pc/h/ln. To achieve this flow rate, the average headway between vehicles would need to be reduced to 1.2 seconds (3600/3000). The corresponding spacing between consecutive vehicles for this headway would be:

$$70 \frac{\text{mi}}{\text{h}} \times \frac{5280 \text{ ft}}{1 \text{ mi}} \times \frac{1 \text{ h}}{3600 \text{ s}} \times 1.2 \frac{\text{s}}{\text{veh}} = 123.2 \frac{\text{ft}}{\text{veh}} \quad (1)$$

Note that this spacing is measured from a common point on the consecutive vehicles, typically front bumper to front bumper. Thus, the spacing includes the length of the lead vehicle. With a traffic stream of entirely autonomous vehicles, and assuming vehicle lengths similar to current passenger car vehicle lengths, it is certainly possible to program the vehicle computer to drive 70 mi/h at a spacing of 123.2 ft.

However, before deciding on a target capacity value (with corresponding vehicle speeds and spacing) for which to design the automated freeway (i.e., a freeway with a 100% autonomous vehicles), we also need to consider the design emergency stopping condition. For example, we could choose to design for the situation where a lead vehicle comes to a sudden stop, such as might happen with the collapse of a vehicle or pedestrian overpass onto the freeway. In this case, for the given vehicle speeds and spacing (assuming a capacity flow rate), will it be possible to bring all the trailing vehicles to a stop without any rear-end collisions? The following numerical example will examine this question.

For a traffic stream traveling at 70 mi/h with inter-vehicle spacing of 123 ft, the required average deceleration rate is calculated with equation 2.

$$a = \frac{v^2}{2d} \quad (2)$$

where

V = initial vehicle speed in ft/s,

a = acceleration (negative for deceleration) in ft/s², and

d = deceleration distance in ft.

This equation assumes level grade and that the vehicle comes to a complete stop (i.e., final velocity equals 0 mi/h).

$$d = 123 \text{ ft} - 16 \text{ ft (assumed lead vehicle length)} = 107 \text{ ft}$$

$$V = 70 \text{ mi/h} \times 5280 \text{ ft/mi} \div 3600 \text{ sec/h} = 102.67 \text{ ft/s}$$

$$a = \frac{102.67^2}{2(107)} = 49.3 \text{ ft/s/s}$$

This required deceleration rate, however, is not feasible. For the foreseeable future, autonomous vehicles will still be using rubber tires on asphalt or concrete pavements. Consequently, the maximum theoretical deceleration rate is 32.2 ft/s^2 (i.e., $1g$), which is based on a maximum rubber/pavement coefficient of road adhesion of 1.0. However, even with modern braking systems, a deceleration rate as high as $1g$ is still very optimistic. The stopping deceleration rate assumed for roadway design (25) is 11.2 ft/s^2 . Rearranging equation 2 to solve for the deceleration distance assuming a deceleration rate of 11.2 ft/s^2 yields a value of 471 ft. Even using a realistic emergency deceleration rate of 20 ft/s^2 yields a deceleration distance of 264 ft, which is still more than double the 107 ft available stopping distance. It is worth noting that under the current speed-flow relationship (i.e., for a traffic stream of all human drivers), the 1.5 second average headway for a capacity flow rate of 2400 pc/h/ln gives an average spacing of 154 ft. This spacing is also too short to avoid a rear-end collision, assuming a sudden stop by the lead vehicle, under realistic deceleration rates. However, it is well known that human drivers do not maintain sufficient following distances to avoid a rear-end collision in the case of a sudden stop by the lead vehicle. The other factor not considered in the calculations presented here is reaction time. This value can be significant for human drivers, but likely would be extremely small for autonomous vehicles.

A decision would need to be made on the design capacity level. If we design for a capacity level that will allow all cars to stop without hitting the car in front if it stops instantly due to a catastrophic collision condition, then an increase in roadway capacity over the current condition is unlikely. In fact, it would probably be lower. However, if we allow for following distances and speeds that would lead to a “chain-reaction” rear-end pile up in the case of a sudden vehicle stop, we could achieve higher capacities than currently realized. While situations that might lead to a near instantaneous stop by a vehicle on the roadway might be rare, they do happen, such as when overpasses collapse (e.g., the collapse of a pedestrian bridge onto the roadway below in Detroit (26)).

As for congestion, can it be avoided altogether with automated vehicle highways? This remains to be seen but will certainly be impacted by roadway lane configurations issues (e.g., areas with a lane drop and ramp merge areas) and vehicle cooperation capabilities. To make the most efficient use of roadway capacity, particularly under high traffic demand situations, it will be essential to develop algorithms for cooperative vehicle movements. For example, when a vehicle is attempting to merge onto the freeway from an on-ramp, and the freeway is running at a near-capacity condition, the freeway vehicles near the on-ramp and the merging vehicle will have to coordinate as smooth of a merge operation as possible to minimize the potential disruptions to the rest of the traffic stream on the freeway. This task will likely be more easily accomplished for autonomous vehicles that also have V2X capabilities.

Interrupted Flow Facilities

In contrast to uninterrupted-flow facilities, interrupted-flow facilities are considered to be roadways in which external controls, such as traffic signals, stop signs, etc., are present. These

controls generally have very significant impacts on the traffic operations.

Signalized Intersections

Two factors influence the capacity of traffic movement at a signalized intersection—the relative amount of green time given to the movement and queue discharge rate (also referred to as the saturation flow rate). The queue discharge rate refers to the rate (vehicles per unit time) at which vehicles discharge through the intersection from a standing queue once the traffic signal turns from red to green. Before reaching an equilibrium discharge rate, time is lost when the signal indication initially turns from red to green through driver reaction to the signal change and initial vehicle motion. This “startup lost time” usually applies to the first several vehicles in the queue before the equilibrium discharge rate is reached. Figure 21 illustrates a typical pattern of queue discharge headways at a signalized intersection.

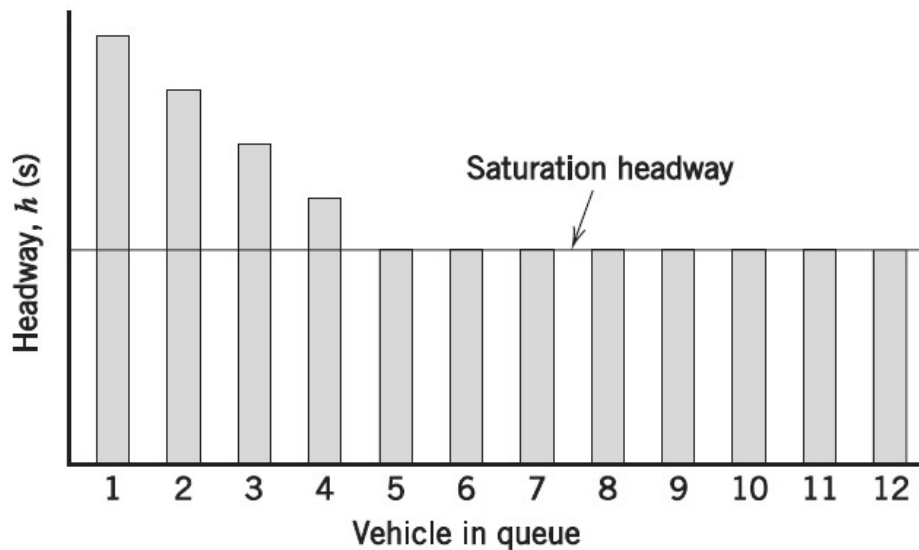


Figure 21. Illustration of queue discharge headways at a signalized intersection with human drivers

Source: Scott Washburn

Although the above figure illustrates an equilibrium discharge headway value for vehicles 5 to the end of the queue, driver inattentiveness (e.g., using a cell phone instead of paying attention to the traffic signal) often disrupts this equilibrium queue discharge rate and leads to further inefficiencies of the movement of vehicles through the intersection.

For a queue of autonomous vehicles at a signalized intersection, it is likely that startup lost time will be nearly eliminated since reaction will be negligible. There may still be very small amount of start-up lost time due to the initial vehicle movements at the start of the green time. With the more precise control of acceleration and inter-vehicle spacing possible with autonomous vehicles, the equilibrium discharge headway will also be less likely than what it currently is with human drivers. Furthermore, driver inattentiveness will be a non-factor. Figure 22 is an example

illustration of queue discharge headways at a signalized intersection with a stream of autonomous vehicles.

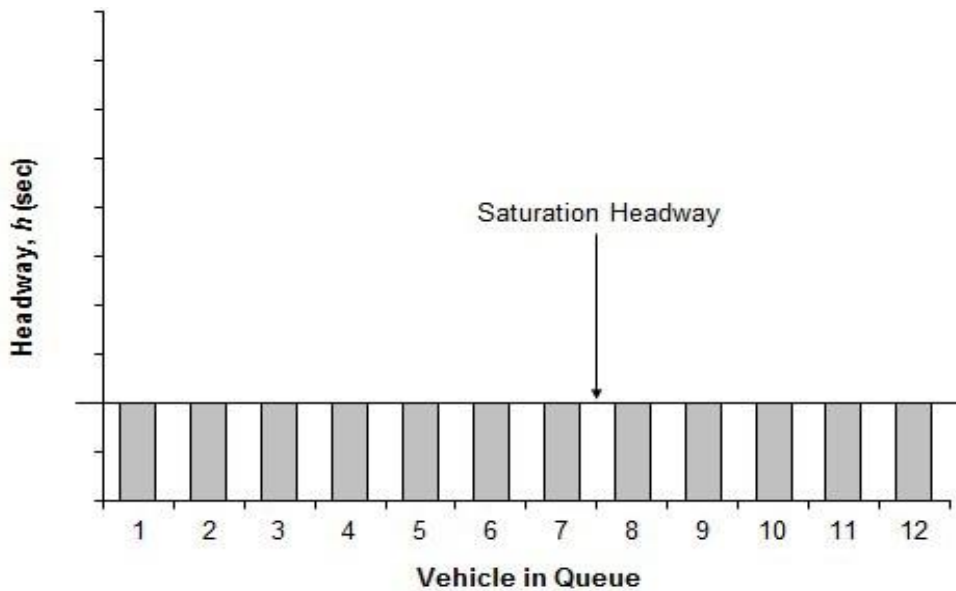


Figure 22. Illustration of queue discharge headways at a signalized intersection with autonomous vehicles

Source: Scott Washburn

Unsignalized Intersections

At unsignalized intersections, those that regulate the control of traffic with stop and/or yield signs, the efficiency of movements is a function of priority rules and gap acceptance behavior. Gap acceptance refers to the process by which a driver, without the right-of-way, assesses when they have a sufficient gap in traffic to safely move into. Figure 23 is a picture of a roundabout, which is one form of an unsignalized intersection.



Figure 23. Unsignalized intersection—roundabout
Source: Scott Washburn

Major roundabout intersections in the U.S. use yield signs at each entry leg to the circular roadway. Thus, vehicles approaching the roundabout must yield to vehicles on the circular roadway and assesses when there is a gap in the circulating traffic of sufficient size for them to be able to safely enter the circular roadway. This gap acceptance process by drivers is a significant factor in how much traffic can move through the intersection (i.e., capacity). It is likely that autonomous vehicles will be more efficient than humans with the gap acceptance process, translating to higher capacities at unsignalized intersections.

Geometric Design

Geometric design refers to the physical design of a roadway configuration—for example, how sharp to make a curve (referred to as a horizontal curve), how much banking to use on the horizontal curve, and what rate of change in vertical slope to use on a roadway segment that connects to roadway segments with differing grades (referred to as a vertical curve). Geometric design is largely predicated on three factors: vehicle performance as a function of physics, sight distance (human) for safe stopping, and vehicle dimensions. The first two factors will be discussed in this document.

Vehicle Performance

Vehicle acceleration and deceleration rates factor into geometric design in several areas. Acceleration rates will impact the design of things such as the acceleration lanes for on-ramps and the steepness of upgrades. Deceleration rates will impact the design of things such as deceleration lanes for off-ramps or turning lanes, maximum steepness of downgrades, and the design of horizontal and vertical curves for stopping, as discussed further in the next section.

As mentioned previously, autonomous vehicles are likely to be using rubber tires on asphalt/concrete pavement for some time to come. The corresponding coefficients of road adhesion also affect geometric design, as it imposes limits on acceleration and deceleration rates (again, typically 1g) in a linear travel direction. The coefficient of road adhesion also imposes limits on the centripetal acceleration that a vehicle can maintain while negotiating a horizontal curve (see Figure 24). This, along with the degree of banking and curvature, limits a vehicle's speed through the turn.

Despite the limits in acceleration due to the rubber tire/pavement interface, current geometric design guidelines assume acceleration and deceleration values much lower than the maximum values to account for low performance vehicles (which are not capable of even 1g acceleration or deceleration rates) and poor pavement conditions. Even if future vehicles can achieve higher coefficients of road adhesion and improvements in powertrain and braking technologies lead to considerable improvements in acceleration and deceleration rates for even low-cost vehicles, acceleration rates used for roadway design will always need to consider limits in human tolerance to such rates. Furthermore, energy consumption and emissions output concerns may also factor into maximum acceleration rates used in autonomous vehicles.

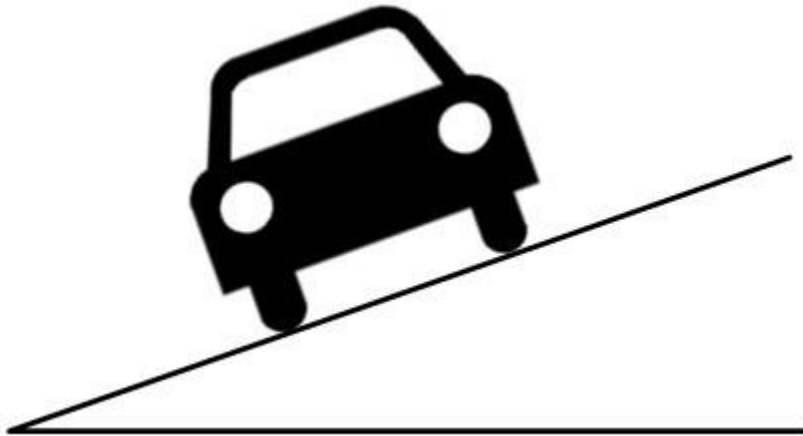


Figure 24. Illustration of vehicle negotiating banked horizontal curve

Source: Scott Washburn

Based on vehicle performance considerations, it is unlikely that autonomous vehicles will impact geometric design standards in an appreciably different manner than non-autonomous vehicles.

Sight Distance

Sight distance generally refers to the issue of how far in advance (units of distance) a vehicle driver can detect a potential obstacle in the roadway. This distance needs to be considered, along with the desired speed for the roadway and human reaction time, when determining the design characteristics of horizontal and vertical curves.

With a fully autonomous vehicle, where “machine vision” has replaced human vision, what kind of impacts can we expect to see on the standards and guidelines used for geometric design? This will certainly be a function of the capabilities of the technology used in the vehicle, which are constantly evolving. Under good weather conditions, LIDAR and vision sensors (cameras) have proven to be at least as effective as humans in obstacle detection. Vision sensors are subject to the same limitations as human sight in darkness and adverse weather conditions. While darkness is not an issue for LIDAR, this technology has thus far shown only limited success in situations with heavy rain or snow. Thus, the current technologies used on autonomous vehicles do not overcome one of the major limitations with human sight—that is, line-of-sight. For example, at this point, it is not reasonable to assume that an autonomous vehicle could detect an obstacle in the roadway (such as fallen boulders) around the bend of the curve shown in Figure 25 any sooner than a human could.



Figure 25. Horizontal curve with limited sight distance

Source: Scott Washburn

This sight distance concept is illustrated more generically in Figure 26.

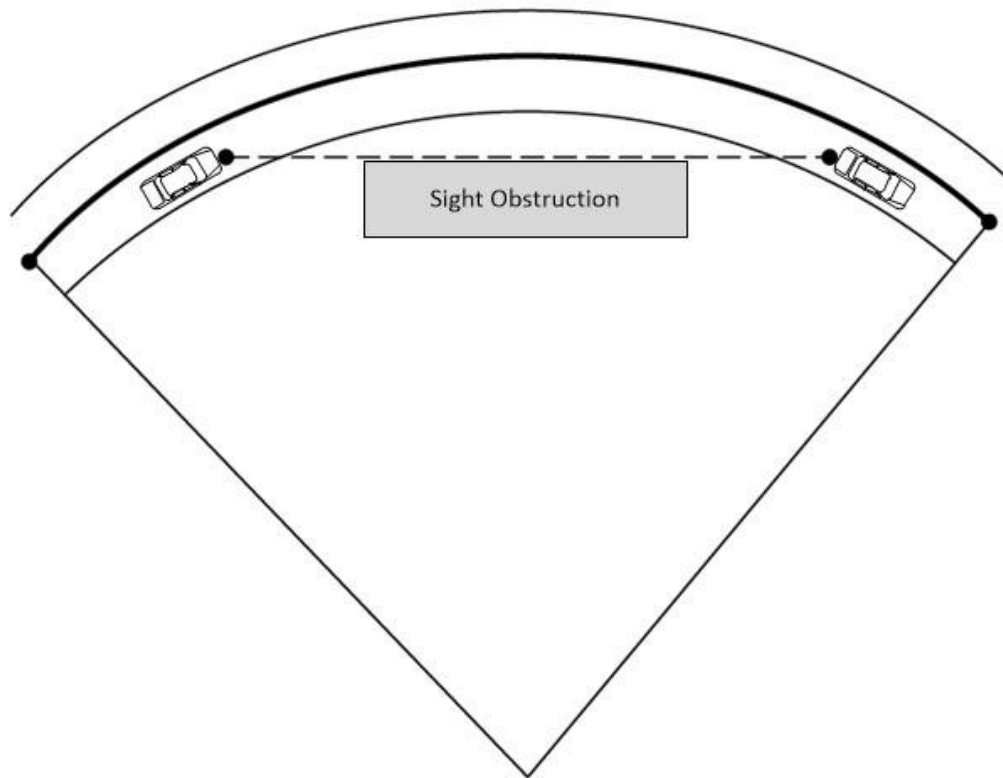


Figure 26. Illustration of impact of obstruction in line-of-sight on horizontal curve sight distance
Source: Scott Washburn

Likewise, sight distance is a critical factor in designing the rate of change of slope for a vertical curve, as illustrated in Figure 27. If the autonomous vehicle obstacle detection technology is able to “see” through the crest of the vertical curve, then the rate of change of slope along the curve could be greater for the same design speed, as illustrated in Figure 28.



Figure 27. Illustration of line-of-sight on vertical curve sight distance

Source: Scott Washburn

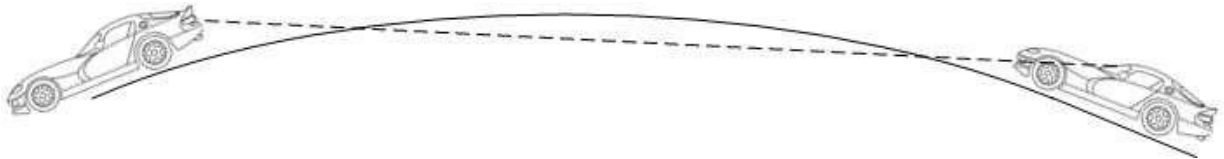


Figure 28. Illustration of “sight” distance through crest of vertical curve

Source: Scott Washburn

Sight distance also factors into the issue of gap acceptance (discussed in the previous section). Figure 29 illustrates a two-way stop-controlled intersection (stop control on the minor road approaches). The line of sight between a vehicle stopped on a minor road approach and vehicles on the major road is demonstrated by the shaded triangles (i.e., sight triangles). The larger the triangles (i.e., length of triangle leg along major roadway), the more time drivers on the minor road have to make a decision and potentially enter the intersection. Thus, larger sight triangles will result in a higher capacity for the minor road movements.

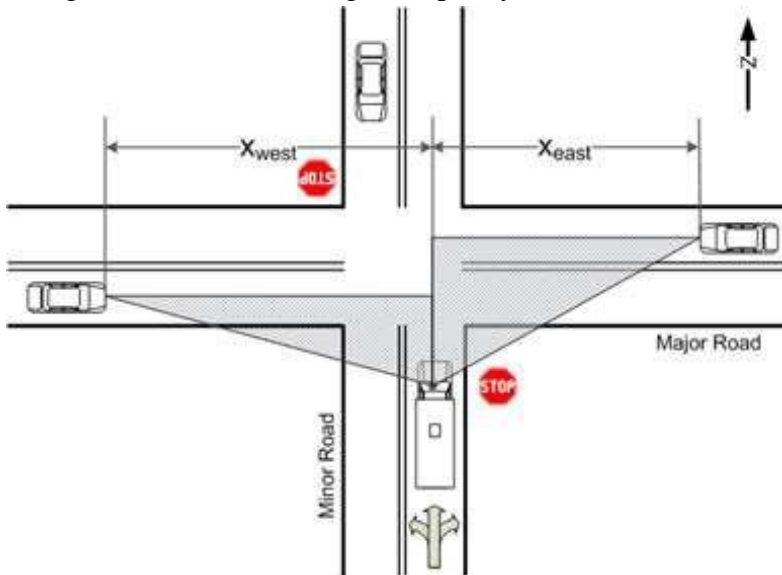


Figure 29. Illustration of sight triangles at two-way stop-controlled intersection

Source: Scott Washburn

Although significant changes to roadway design standards due to differences in sight distance between human and machine are not likely based on current technology, the process of reacting/responding to a roadway obstacle once it is detected, in the form of applying the vehicle brakes, would likely be faster for the autonomous vehicle and could lead to modest increases in design speed, all other factors being the same.

Thus far, the discussion was specific to autonomous vehicles without V2X capabilities. For vehicles with V2X capabilities, they would potentially be capable of knowing the position of other comparably equipped vehicles in their vicinity, even those it could not “see”. However, they would likely not know about obstacles such as fallen boulders in the roadway, or even disabled vehicles in which the V2X communications systems are no longer operational.

SUMMARY

In this course we have introduced the topic of automated vehicles (autonomous and connected). More specifically, we have covered the terminology being used in the field of automated highway vehicles, examples of government legislation being implemented to facilitate the future of automated vehicles, the technologies being used in automated vehicles, automated vehicle engineering research and standards under development, and potential impacts of automated vehicles on traffic flow and roadway design. Two of the biggest issues that adversely impact the efficiency and societal benefit of the U.S. highway system are congestion and safety. Automated vehicle technology appears to hold great promise for making significant improvements in these two areas in the future.

REFERENCES

1. Mannering, Fred L. and Washburn, Scott S. *Principles of Highway Engineering and Traffic Analysis*, 7th Edition. John Wiley and Sons, Hoboken, NJ, 2020.
2. <https://www.bts.gov/topics/national-transportation-statistics>
3. <https://static.tti.tamu.edu/tti.tamu.edu/documents/umr/archive/mobility-report-2019.pdf>
4. <https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions#transportation>
5. <https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/813060>
6. <https://www.nhtsa.gov/technology-innovation/vehicle-vehicle-communications>
7. <http://www.its.dot.gov/factsheets/pdf/AutomationUSDOT.pdf>
8. <http://thehill.com/policy/transportation/197265-dot-clears-the-road-for-smart-cars>
9. <https://www.nhtsa.gov/technology-innovation/automated-vehicles-safety>
10. <https://www.nhtsa.gov/technology-innovation/vehicle-cybersecurity>
11. National Highway Traffic Safety Administration. (2016, October). *Cybersecurity best practices for modern vehicles*. (Report No. DOT HS 812 333). Washington, DC: Author.
12. <http://spectrum.ieee.org/automaton/robotics/artificial-intelligence/how-google-self-driving-car-works>
13. <https://mcity.umich.edu/our-work/mcity-test-facility/>
14. https://www.its.dot.gov/factsheets/pdf/PlanningFutureTransportation_FactSheet.pdf
15. <https://www.federalregister.gov/documents/2021/05/03/2021-08802/use-of-the-5850-5925-ghz-band>
16. <https://www.lifewire.com/5g-spectrum-frequencies-4579825>
17. <https://www.automotiveworld.com/articles/v2x-is-close-heres-what-still-needs-to-happen/>
18. https://saemobilus.sae.org/content/J2735_202007?_ga=2.78172690.703479548.1644849275-1188803566.1643827379

19. <https://www.its.dot.gov/factsheets/pdf/ConnectedVehicleBenefits.pdf>
20. https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/documents/13069a-ads2.0_090617_v9a_tag.pdf
21. https://www.its.dot.gov/research_areas/strategicplan2015.htm
22. <http://www.ncsl.org/research/transportation/autonomous-vehicles-self-driving-vehicles-enacted-legislation.aspx>
23. <https://www.iihs.org/topics/advanced-driver-assistance/autonomous-vehicle-laws>
24. National Academies of Sciences, Engineering, and Medicine. 2022. *Highway Capacity Manual 7th Edition: A Guide for Multimodal Mobility Analysis*. Washington, DC: The National Academies Press. <https://doi.org/10.17226/26432>.
25. AASHTO (American Association of State Highway and Transportation Officials). *A Policy on Geometric Design of Highways and Streets*, 6th Edition. Washington, DC, 2011.
26. <http://www.cbsnews.com/news/truck-driver-dies-after-detroit-pedestrian-bridge-collapse/>