Autonomous Vehicles

Autonomous vehicles (AVs) use technology to partially or entirely replace the human driver in navigating a vehicle from an origin to a destination while avoiding road hazards and responding to traffic conditions. Given the broad spectrum of AVs, the National Highway Traffic Safety Administration (NHTSA) has developed a five-level classification scheme based on vehicle capabilities.[1] The Society of Automotive Engineers (SAE) has developed a similar classification with six levels based on human intervention, separating Level 4 NHTSA into two levels.[2]

Levels of Automation

The National Highway Traffic Safety Administration classifies AVs by level of automation:[3]

Level 0	Vehicles equipped with no automated features, requiring the driver to be in complete control of the vehicle.
Level 1	Vehicles equipped with one or more primary automated features such as cruise control.
Level 2	Vehicles equipped with two or more primary features, such as adaptive cruise control and lane-keeping, that work together to relieve the driver from controlling those functions.
Level 3	Vehicles equipped with features that allow the driver to relinquish control of the vehicle's safety-critical functions depending on traffic and environmental conditions. The driver is expected to take over control of the vehicle given the constraints of the automated features after an appropriately timed transition period. Google's experimental Lexus RX450h has level 3 automation.
Level 4	Fully autonomous vehicles that monitor roadway conditions and perform safety-critical tasks throughout the duration of the trip with or without a driver present. This level of automation is appropriate for occupied and unoccupied trips.

Development of Autonomous Vehicles

AV research started in the 1980s when universities began working on two types of AVs: one that required roadway infrastructure and one that did not.[1] The U.S. Defense Advanced Research Projects Agency (DARPA) has held "grand challenges" testing the performance of AVs on a 150-mile off-road course.[1] No vehicles successfully finished the 2004 Grand Challenge, but five completed the course in 2005.[1] In 2007, six teams finished the third DARPA challenge, which consisted of a 60-mile course navigating an urban environment obeying normal traffic laws.[1]

Autonomous Vehicle Technologies

AVs use combinations of technologies and sensors to sense the roadway, other vehicles, and objects on and along the roadway.[4] The key technologies and sensors are described in the figure to the right. Currently, there are no U.S. AV standards requiring specific technologies to be in place.[5]

Autonomous Vehicle Technologies[1,6,7,8]

Global Positioning Systems (GPS): Locate the vehicle by using satellites to triangulate its position. Although GPS has improved since the 2000s, it is only accurate within several meters.

Ultrasonic sensors: Provide short distance data that are typically used in parking assistance systems and backup warning systems.

Light Detection and Ranging (LIDAR): A 360-degree sensor that uses light beams to determine the distance between obstacles and the sensor.

Cameras: Frequently used inexpensive technology, however, complex algorithms are necessary to interpret the image data collected.

Radio Detection and Ranging (RADAR): A sensor that uses radio waves to determine the distance between obstacles and the sensor.

Prebuilt Maps: Sometimes utilized to correct inaccurate positioning due to errors that can occur when using GPS and INS. Given the constraints of mapping every road and drivable surface, relying on maps limits the routes an AV can take.

Dedicated Short-Range Communication (DSRC): Used in Vehicle to Vehicle (V2V) and Vehicle to Infrastructure (V2I) systems to send and receive critical data such as road conditions, congestion, crashes, and possible rerouting. DSRC enables platooning, a train of vehicles that collectively travel together.

Inertial Navigation Systems (INS): Typically used in combination with GPS to improve accuracy. INS uses gyroscopes and accelerometers to determine vehicle position, orientation, and velocity.

Infrared Sensors: Allow for the detection of lane markings, pedestrians, and bicycles that are hard for other sensors to detect in low lighting and certain environmental conditions.

Current and Projected Market

Market Leaders

- Google's 24 Lexus RX450h SUVs (Level 3 NHTSA) and 34 prototype vehicles (Level 4 NHTSA) have driven in autonomous mode over 1.7 million miles since 2009 in Kirkland, WA; Mountain View, CA; Phoenix, AZ; and Austin, TX.[9]
- Tesla's Model S and X (Level 2 NHTSA) have accumulated over 130 million miles in Autopilot mode since Oct. 2015.[10,11]
- Other major contributors include Audi, BMW, Daimler, GM, Nissan, Volvo, Bosch, Continental, Delphi Automotive, Mobileye, Valeo, Velodyne, Nvidia, Ford, as well as many other OEMs and technology companies.[5,12]

Regulations, Liability, and Projected Timeline

- Regulation will directly impact the adoption of AVs. Currently, there are no national standards or guidelines for AVs, allowing states to determine their own.[13] As of April 2016, 8 states (CA, FL, LA, MI, NV, ND, TN, UT) and D.C. have enacted AV legislation regarding the definition of AVs, permissible use, and liability.[14]
- Product liability laws need to assign liability properly when AV crashes occur, as highlighted by the May 2016 Tesla Model S fatality. Liability will depend on multiple factors, especially whether the vehicle was being operated according to its level of automation.[10,15]
- Although many researchers, OEMs, and industry experts have different projected timelines for AV market penetration and full adoption, the majority predict NHTSA level 4 AVs around 2030.[16,17]
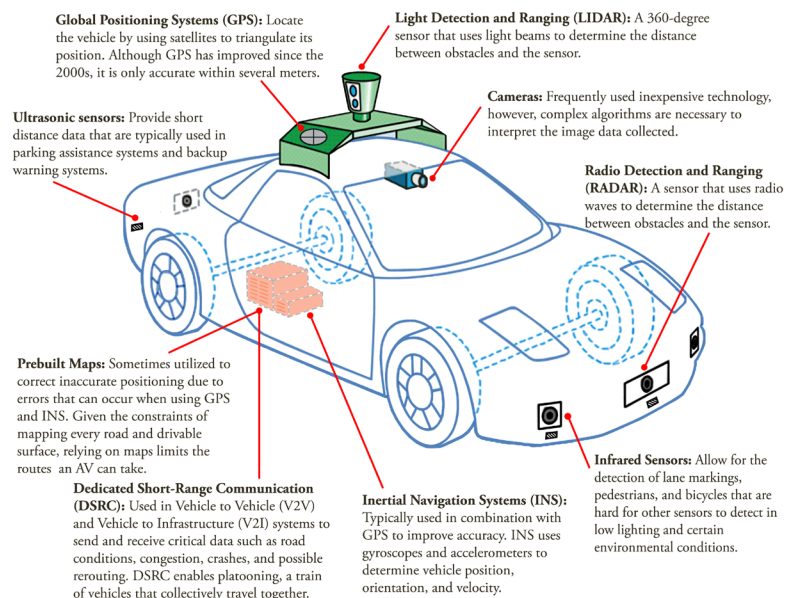
Current Limitations and Barriers

- There are several limitations and barriers that could impede adoption of AVs, including: the need for sufficient consumer demand, assurance of data security, protection against cyberattacks, regulations compatible with driverless operation, resolved liability laws, societal attitude and behavior change regarding distrust and subsequent resistance to AV use, and the development of economically viable AV technologies.[5]
- Weather can adversely affect sensor performance on AVs, potentially impeding adoption. Ford recognized this barrier and started conducting AV testing in the snow in 2016 at the University of Michigan's Mcity testing facility, utilizing technologies suited for poor weather conditions.[12]

Impacts, Solutions, and Sustainability

Although AVs alone are unlikely to have significant direct impacts on energy consumption and GHG emissions, when AVs are effectively paired with other technologies and new transportation models, significant indirect and synergistic effects on economics, the environment, and society are possible.[18,19] Although there is a lack of empirical research, many research efforts have focused on the following metrics to evaluate AV performance.

Metrics and Associated Impacts

- **Congestion**: Congestion is predicted to decrease, reducing fuel consumption by 0%-4%. However, decreased congestion is likely to lead to increased vehicle-miles traveled (VMT), limiting the fuel consumption benefit.[18]
- **Eco-Driving**: Eco-Driving, practices that typically reduce fuel consumption, is predicted to reduce energy consumption by up to 25%.[18] However, if AV algorithms do not prioritize efficiency, fuel economy may decrease by 3%.[20]
- **Platooning:** Platooning, a train of detached vehicles that collectively travel closely together, is expected to reduce energy consumption between 3%-25% depending on the number of vehicles, their separation, and characteristics.[18]
- **De-emphasized Performance**: Vehicle performance, such as fast acceleration, is likely to become de-emphasized when comfort and productivity become travel priorities, potentially leading to a 5%-23% reduction in fuel consumption.[18]
- **Improved Crash Avoidance**: Due to the increased safety features of AVs, crashes are less likely to occur, allowing for the reduction of vehicle weight and size, decreasing fuel consumption between 5%-23%.[18]
- **Vehicle Right-Sizing**: The ability to match the utility of a vehicle to a given need. Vehicle right-sizing has the potential to decrease energy consumption between 21%-45%, though the full benefits are only likely when paired with a ride-sharing on-demand model.[18]
- **Higher Highway Speeds**: Increased highway speeds are likely due to improved safety, increasing fuel consumption by 7%-30%.[18,21]
- **Travel Cost Reduction**: AVs are predicted to reduce the cost of traveling due to decreased insurance cost and cost of time due to improvements in productivity and driving comfort. These benefits could result in increased travel potentially increasing energy consumption by 4% to 60%.[18]
- **New User Groups**: AVs are likely to increase VMT, especially for elderly and disabled users. Fuel consumption is anticipated to increase between 2%-10% from new user groups.[18]
- **Changed Mobility Services**: Ride-sharing on-demand business models are likely to utilize AVs due to the significant reduction of labor costs.[22] The adoption of a ride-sharing model is estimated to reduce energy consumption by 0%-20%.[18]
- Although an accurate assessment of these interconnected impacts cannot currently be made, several scenarios have been projected. One study evaluated the potential impacts of four scenarios, each with unknown likelihoods. The most optimistic scenario projected a 40% decrease in total road transport energy and the most pessimistic scenario projected a 105% increase in total road transport energy.[18]

Projected Fuel Consumption Impact Ranges[18,21]

(Chart categories, top to bottom: Congestion, Eco-Driving, Platooning, De-emphasized Performance, Improved Crash Avoidance, Vehicle Right-Sizing, Higher Highway Speeds, Travel Cost Reduction, New User Groups, Changed Transportation Services. X-axis: % Change in Energy Consumption, -50% to 50%.)
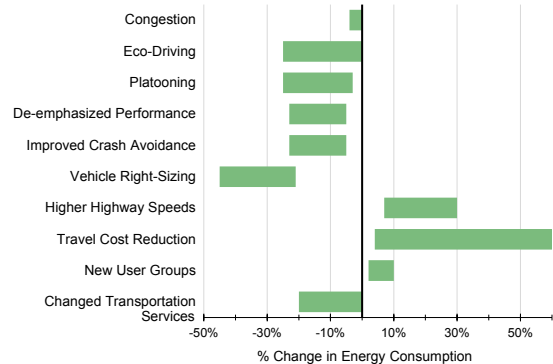
Potential Benefits and Costs

- U.S. annual vehicular fatality rate is 32,000; 93% of crashes are due to human error. AVs have the potential to remove/reduce human error and decrease deaths.[23] Depending on adoption and vehicle characteristics, AVs have the potential to reduce crashes by 90%, potentially saving approximately $190 billion per year.[24]
- Potential benefits include improvements in safety and public health; increased productivity, quality of life, mobility, accessibility, and travel, especially for disabled and elderly; reduction of energy use, environmental impacts, congestion, and public and private costs associated with transportation; and increased adoption of car sharing.[1,13,25,26]
- Potential costs include increased congestion, VMT, urban sprawl, total time spent traveling, and upfront costs of private car ownership leading to social equity issues; usage impact on other modes of transportation; and increased concern with security, safety, and public health.[1,13,21,26]

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