ERDC/CERL SR-24-2

Construction Engineering
Research Laboratory

Autonomous Transport Innovation

Autonomous Vehicle Testing

A Survey of Commercial Test Sites and Features

Julie L. Webster, Emma L. Smith, Annette L. Stumpf, and
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US Army Engineer Research and Development Center (ERDC)
Construction Engineering Research Laboratory (CERL)
2902 Newmark Drive
Champaign, IL 61824

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Abstract

Connected and autonomous technologies are valuable to the Army because of their recognized potential to reduce the number of personnel exposed to threats in forward operations. The successful integration of such technologies has the potential to reduce Soldier deaths and injuries. Automation of routine tasks can also allow warfighters to focus their time on more strategic efforts. Furthermore, a reduction in manpower is expected to proportionally reduce energy use and material supply and resupply demands while bolstering resilience. To achieve these benefits, the reliability, safety, and utility of connected and autonomous systems must be successfully demonstrated in a variety of conditions before widespread adoption. Therefore, the Army needs a realistic testing environment to develop, test, and evaluate emerging technologies. This environment and its supporting infrastructure should provide a variety of terrain, functional areas, and power scenarios and should be able to demonstrate the viability of connected and autonomous technologies on an operational scale. The primary objective of this research was to survey US commercial facilities associated with autonomous vehicle development, testing, and evaluation.

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Preface

This study was conducted for Headquarters, US Army Corps of Engineers (HQUSACE), under Program Element No. 0603728A, Project No. 03F.

The work was performed by the Engineering Processes Branch of the Facilities Division, US Army Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL). At the time of publication, Mr. James Allen was chief, Engineering Processes Branch; Ms. Giselle Rodriguez was chief, Facilities Division; and Mr. Kurt Kinnevan was the technical director for Installations. The deputy director of ERDC-CERL was Ms. Michelle Hanson, and the director was Dr. Andrew Nelson.

Assistance provided by Ms. Ellen Hartman, Land and Heritage Conservation Branch, was greatly appreciated. Ellen provided valuable technical support in a timely manner that ensured this report was complete and properly formatted.

COL Christian Patterson was commander of ERDC, and Dr. David W. Pittman was the director.

1 Introduction

1.1 Background

Connected and autonomous technologies are valuable to the Army because of their potential to reduce the number of personnel exposed to threats in forward operations. Specifically, the successful integration of such technologies has the potential to reduce Soldier deaths and injuries. Automation of routine tasks can also allow warfighters to focus their time on more strategic efforts. Furthermore, a reduction in manpower is expected to proportionally reduce energy use and material supply and resupply demands while bolstering resilience. These reductions can be realized in both forward operations overseas and in US-based cantonment activities.

To achieve these benefits, the reliability, safety, and utility of connected and autonomous systems must be successfully demonstrated in a variety of conditions before widespread adoption. Therefore, the Army needs a realistic testing environment to develop, test, and evaluate emerging technologies. This environment and its supporting infrastructure should provide a variety of terrain, functional areas, and power scenarios and should be able to demonstrate the viability of connected and autonomous technologies on an operational scale.

The private sector plays a strong role in paving the future of autonomous technologies. The ability to test on well-developed proving grounds available across the US allows developers and manufacturers to uphold safety and spur innovation. For routine use, the military intends to exploit private sector advances made at their proving grounds. The military is also using autonomous technologies in unconventional ways that are relevant to warfare. These applications compel the development of a new type of proving ground with military-specific testing regimes.

1.2 Objectives

The primary objective of this research was to survey US commercial facilities associated with autonomous vehicle (AV) development, testing, and evaluation. Of particular interest were tenure and mission, natural site features and climate, testing infrastructure and facilities, equipment and technology, programs and customization, and organizational affiliations.

Using this initial survey of facilities, an additional objective was to analyze how individual features are useful for challenging AV functions.

Researchers studied these facilities to gain an understanding of the general structure and specific attributes used by the industry to effectively test AVs. This knowledge is expected to inform the Army's efforts to establish its own AV testing environment.

1.3 Approach

The initial work involved archival research; collected material was parsed by site. For each location, data were then reviewed and further grouped into overarching categories to obtain clarity on noteworthy elements. This information is presented in Chapter 2, which includes site surveys that broadly characterize each facility. Site features received an additional level of scrutiny and classification for the purposes of a comparative analysis across sites and the subsequent development of a features typology, which is presented in Chapter 3.* Once the typology was developed, additional study was required to better understand how individual site features were used to test overall AV performance and their component functions.

All archival research was conducted using information from publicly available sources. These sources included

- presentations,
- press releases and industry news,
- proposals,
- scholarly papers,
- university dissertations, and
- websites.

Due to the secretive and proprietary nature of AV development, any information not obtainable from publicly available sources was marked not applicable (NA) or was simply not covered in this report. Similarly, the coverage of sites and features in this report is not exhaustive due to the fast-changing landscape of AV development. Nonetheless, this document

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* Some features are found in both Chapters 2 and 3 but use different terminology. Those in Chapter 2 are presented using local nomenclature; those in Chapter 3 are in generalized terms for comparative purposes.

provides a foundation upon which to guide AV test-site development for the Army.

2 Survey of Commercial Autonomous Vehicle (AV) Test Sites

Chapter 2 provides an overview of known commercial AV testing locations in the United States. The sites are presented in alphabetical order. Known descriptive elements, including site name, location, setting, opening date, AV uses, and discrete features, are provided in textual and bullet-point formats. Noteworthy testing features are categorized by type (i.e., fixed physical features, technologies, movable obstacles, and support infrastructure). Where available, site-sponsored website URLs are provided for access to the latest information. Photographs, schematic diagrams, and conceptual renderings of test sites are provided for visual context.

2.1 Almono—Pittsburgh, Pennsylvania

Description: Almono is a closed-course test site that is owned and operated by Uber and is used to develop their self-driving capabilities.* The site opened in 2017 and is located on an old steel mill site along the Monongahela River in Pittsburgh's Hazelwood neighborhood (Muoio 2017). The 42 acre simulated city is used to test near-real-world conditions without putting any driver or pedestrian in true danger (Goldberg 2017). The testing and development at Almono aim to equip the vehicles for autonomous ride-hailing services in the public environment (Muoio 2017). Figure 1 shows aerial views of Almono.

URL: Not applicable (NA)

See for this section: Aupperlee (2017); Goldberg (2017); Muoio (2017); Nguyen (2017); Reinke (2017); Rosenblatt (2019); Wehner (2017)

Physical features: • four-lane intersections with complicated turning rules • large roundabout • narrow road with tight bends • road signs and operational traffic lights • various roadway configurations with lane markers • wide, freeway-like thoroughfare

Technologies: NA

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* Almono is named after the first syllables of Pittsburgh's three rivers: Allegheny, Monongahela, and Ohio. Uber's lease of the site expires in 2023, and the company plans to use the site as needed until the expiration date. Aptiv (another self-driving car company) will begin using the site as early as 2020 (Rosenblatt 2019).

Obstacles: • dynamic obstacles and mannequins • erratic road drivers on course • fake buildings constructed from shipping containers

Support infrastructure: NA

Figure 1. Aerial view of Almono showing trapezoidal and pyramidal landforms, an urban street grid, and stationary structures. (Map data: SIO, NOAA, NGA, GEBCO Landsat / Copernicus.)

2.2 American Center for Mobility (ACM)—Ypsilanti Township, Michigan

Description: The American Center for Mobility (ACM) is located on 500 acres of the former General Motors (GM) Willow Run Powertrain Plant (Avellan 2018). Since opening in 2016, ACM has been focused on testing, validating, and self-certifying connected and automated vehicles (CAVs) and other mobility technologies (Contech Engineered Solutions, n.d.). The site's owners were committed to designing their facility to meet the standards of the American Association of State Highway and Transportation Officials to ensure the availability of real-world infrastructure and driving scenarios. Figure 2 contains aerial views of ACM, and Figure 3 contains a map of the facility.

URL: https://www.acmwillowrun.org/

See for this section: Avellan (2018); Brugeman et al. (2018); Contech Engineered Solutions (n.d.); Lawrence (2017); Medina et al. (2018); Reid (2019); Teale (2018); Thibodeau (2018); Walsh (2020)

Physical features: ● two-lane roundabouts ● 2.5 mi[*] highway loop and six-lane highway ● 6 × 6 lane intersection that can be reconfigured to reflect varying geometries ● 700 ft tunnel in which to (1) control light and weather and (2) terminate location and positioning satellite and GPS technology so vehicle learns how to transfer from satellite to local sensors ● active public roadway running through site (i.e., the inner portion of US 12) ● asphalt and concrete roads built for 50 to 65 mph speeds ● bridge infrastructure ● inactive rail crossings ● low speed maneuvering areas ● overhead road signage ● rural, commercial, and urban driving environments ● series of building facades and seven-lane "Main Street" to mimic urban environment ● trilevel interchanges to test *z*-axis comprehension for AVs ● user defined area (8 acres that can be outfitted with temporary features fitting testing needs) ● varying road conditions (e.g., deterioration, potholes, and faded lane markings) ● varying road materials (e.g., dirt, gravel, asphalt, and concrete)

Technologies: ● ability to create desired weather conditions if they do not occur naturally (i.e., large on-site storage tanks repurposed to hold water to create wet or icy test areas and snowmaking machines) ● cameras inside tunnel to monitor performance ● future plans for AT&T to develop a cellular network at the site to test vehicle-to-vehicle (V2V) communications ● proposed National Automotive Cybersecurity Testing Laboratory to allow researchers to hack vehicles in controlled conditions, analyze security, and then test on the track

Obstacles: ● balloon cars and variable targets to represent objects AVs must learn to avoid

Support infrastructure: ● garages to support on-site testing activity ● technology park and headquarters building

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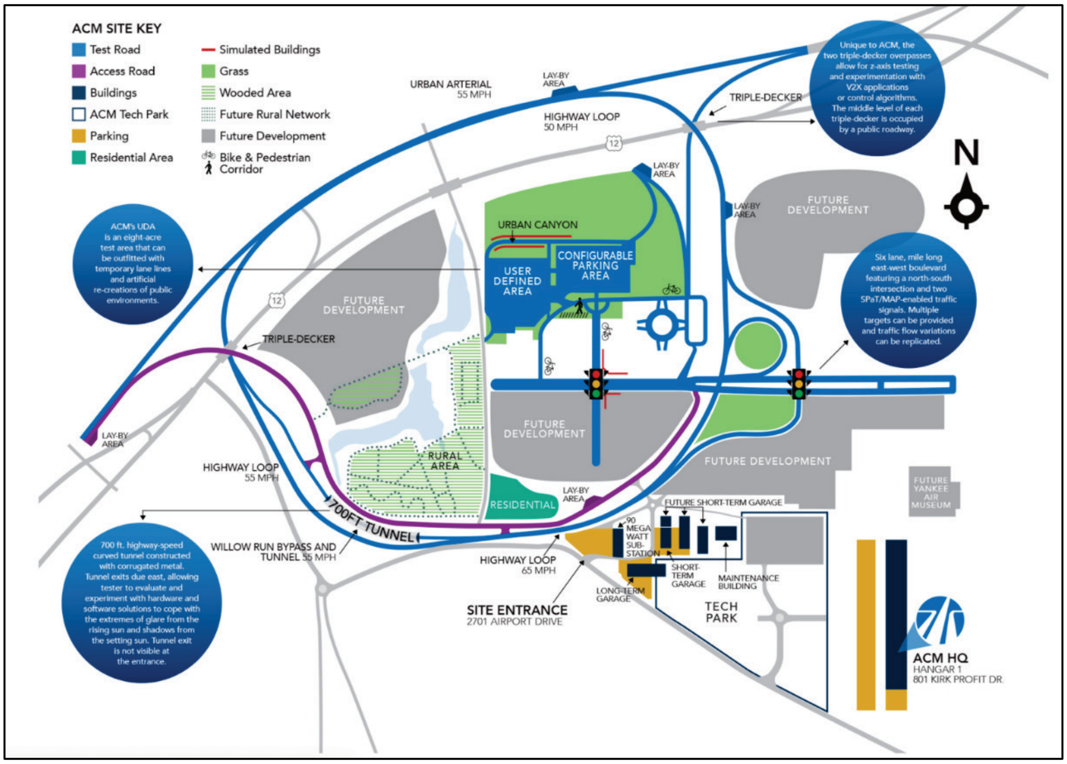
[*] For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office, 2016), 248–252, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

Figure 2. The American Center for Mobility (ACM) challenges autonomous vehicles (AVs) with varying road configurations, including a simulated highway environment. (Map data: Google Earth 2019.)

Figure 3. The ACM hosts a variety of research and development (R&D) facilities and physical testing tracks. Future development is planned for specific test scenarios and a cybersecurity center. (Image reproduced with permission from Walsh 2020.)



Unique to ACM, the two triple-decker overpasses allow for z-axis testing and experimentation with V2X applications or control algorithms. The middle level of each triple-decker is occupied by a public roadway.

ACM's UDA is an eight-acre test area that can be outfitted with temporary lane lines and artificial re-creations of public environments.

Six lane, mile long east-west boulevard featuring a north-south intersection and two SPaT/MAP-enabled traffic signals. Multiple targets can be provided and traffic flow variations can be replicated.

700 ft. highway-speed curved tunnel constructed with corrugated metal. Tunnel exits due east, allowing tester to evaluate and experiment with hardware and software solutions to cope with the extremes of glare from the rising sun and shadows from the setting sun. Tunnel exit is not visible at the entrance.

2.3 Automotive Enviro Testing (AET)—Baudette, Minnesota

Description: Automotive Enviro Testing's (AET's) facility, created in 1993, is situated on 750 acres of a former US Air Force radar base. Its location, which is 50 mi south of the Canadian border in northern Minnesota, is known for having reliable winter test conditions. These conditions are conducive to multidimensional and low temperature AV testing. The 23 winter courses support diverse aspects of winter automotive research and development (R&D). Figure 4 contains a map of AET.

URL: https://www.aettesting.com/

See for this section: AET (“Automotive,” n.d.; “Garages,” n.d.)

Physical features: ● 1.2 mi off-road course ● two packed snow ovals (55 ft × 1.8 mi and 1 mi) ● two packed snow vehicle dynamics areas (600 ft × 3,600 ft and 600 ft × 2,000 ft) ● nine lane hills ● all-wheel drive course (300 ft × 2,000 ft) ● asphalt vehicle dynamics area (48 ft × 2,050 ft with 330 ft diameter) ● camber course (i.e., packed snow handling lanes that transition to a multigrade vehicle dynamics area, producing various camber angles) ● driveway parking course with varying grades ● ice and snow circles ● ice vehicle dynamics area (164 ft × 3,000 ft) ● multiflex autocross (with configurable lane structure) ● potholes, sine, chatter ● slush pool (configurable sizes) ● split and alternating frictions

Technologies: ● five large −40°F cold cells

Obstacles: NA

Support infrastructure: ● 13 secure garages ● fueling stations ● secure storage

Figure 4. Automotive Enviro Testing (AET) offers multiple road configurations to challenge vehicle dynamics. (Image reproduced with permission from AET, “Automotive,” n.d.)

2.4 Castle—Atwater, California

Description: Castle is a highly restricted, closed course that sits on 91 acres two hours east of San Jose that formerly housed Castle Air Force Base. The site lease began in 2014. Castle is used to observe how Waymo’s self-driving cars perform on real road conditions. The road network allows flexibility in creating a variety of driving scenarios. Waymo uses the site to conduct “structured testing,” or repeatable tasks to hone the car’s skills with each test. Figures 5 and 6 contain aerial views of Castle. Figure 7 shows a street-level view of the facility.

URL: NA

See for this section: DeBord (2018); Halsey (2017); Madrigal (2017)

Physical features: • two-lane roundabout • automobile and bike lane road separation • cluster of old military dormitories mimics an urban street environment • concrete driveways, cul-de-sacs, and curbs mimic suburbia • intersections and traffic signals • parking lots and parallel parking • railroad tracks with a working railroad crossing • residential streets • variable road conditions (e.g., faded pavement markings, potholes, and disrepair) • variable roadway types (e.g., straight wide roadway, expressway-style streets, boulevards, and residential streets)

Technologies: NA

Obstacles: • employees drive cars, create traffic, act as pedestrians, ride bikes, and hold stop signs • foreign objects and debris for testing

Support infrastructure: NA

Figure 5. The Castle course showing that Castle makes use of existing roadways, marked open pavement (*left*), and newly poured concrete driveways and curbs (*right*) to test AVs. (Map data: Google Earth 2013.)

Figure 6. Satellite imagery of the Castle course shows that Castle uses a traffic circle, various intersection configurations, and large paved areas to run vehicles through their paces. (Map data: Google Earth 2013.)

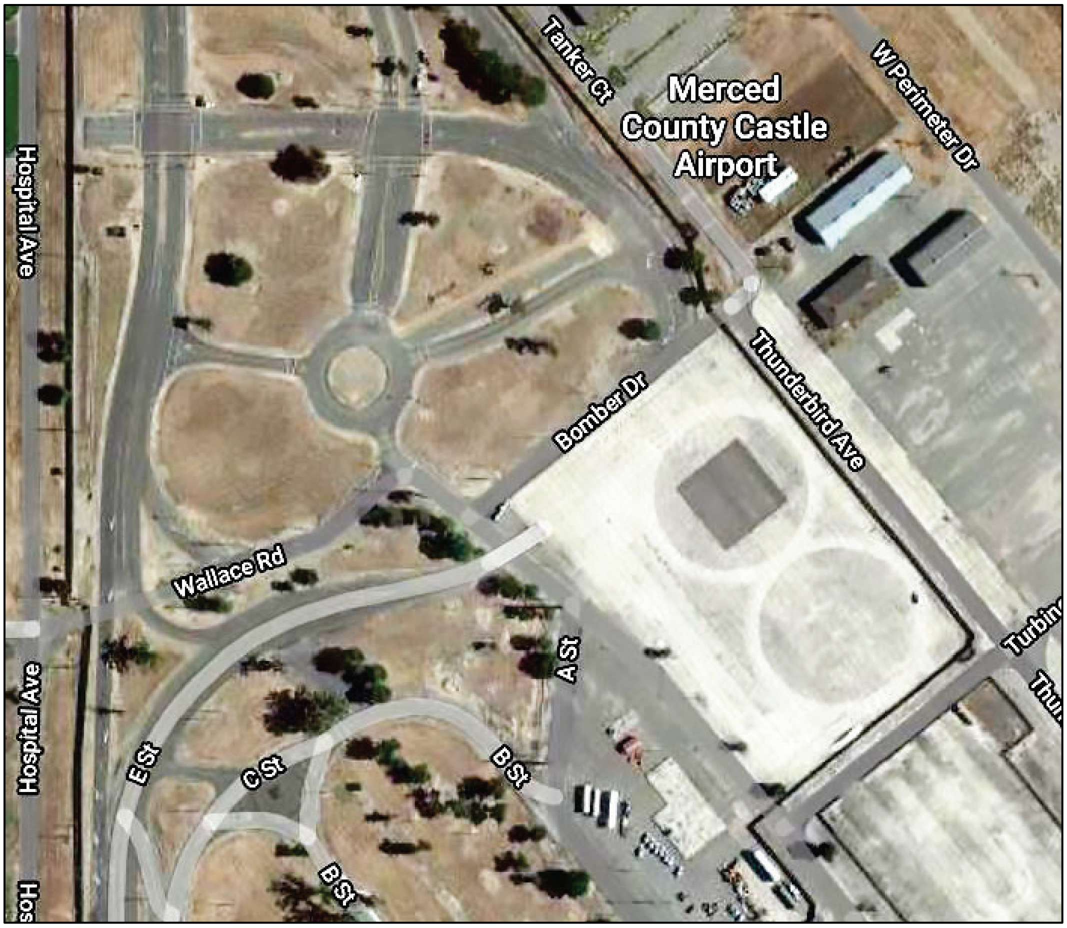


Figure 7. Castle features driveway infrastructure (*left*) and a roundabout feature (*right*) to further challenge vehicle competencies. (Images reproduced with permission from Madrigal 2017.)

2.5 Curiosity Lab—Peachtree Corners, Georgia

Description: Curiosity Lab is located in a 500 acre technology park north of Atlanta. It is a technology incubator open to smart city and mobility testing for land and air innovation. The lab opened in September 2019 to act as an intermediary between a closed testing environment and full-scale AV deployment. Curiosity Lab provides a real-world environment so AVs can be tested where people actively live, work, and play (Figures 8 and 9).

URL: https://www.curiositylabptc.com/

See for this section: City of Peachtree Corners, Georgia (n.d.); Frost (2019); Lee (2020); Business View Magazine (2019)

Physical features: ● 1.5 mi AV test track ● 13% grade on track that lends itself to experimentation with computer vision ● dedicated AV lanes ● shade trees that allow observation of changes in light patterns

Technologies: ● 4G LTE ● 5G wireless ● dedicated short-range communication (DSRC) ● networked traffic lights ● smart pole streetlights ● track mapping ● video surveillance

Obstacles: NA

Support infrastructure: ● 25,000 sf innovation center with control room ● no-cost testing and insurance for driverless vehicles, drones, cyber security, and data

Figure 8. The Curiosity Lab boasts modal separation and real-world interactions. (Image reproduced with permission from City of Peachtree Corners, Georgia, n.d.)

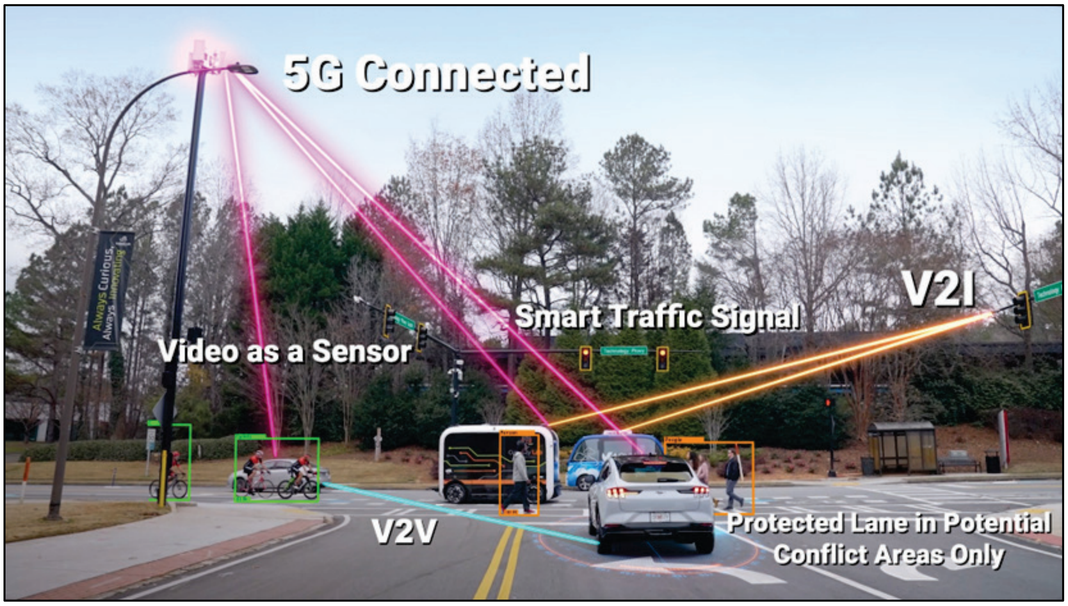


Figure 9. The Curiosity Lab has dedicated AV lanes and drone airspace for use by companies eager to test their innovative technology. (Image reproduced with permission from City of Peachtree Corners, Georgia, n.d.)

2.6 Fiat Chrysler Chelsea Proving Grounds—Chelsea, Michigan

Description: The Chelsea Proving Grounds is a private closed course on 4,000 acres 50 mi west of Detroit (Figures 10 and 11). The site opened in 1954, but in 2018, Fiat Chrysler invested $30 million for an autonomous-specific testing facility at the site. The AV facility was developed to allow for testing of various autonomy levels for Fiat Chrysler vehicles. The company aims to use the facility to test and advance autonomous safety technologies to offer their customers important features across their brand. Their autonomous highway speed track offers a range of challenging driving and sensor testing environments. The designated test pad provides a space for testing advanced driver-assistance systems (ADAS) technology, including automatic braking and parking.

URL: NA

See for this section: JR98 (2016); MCG (2013); Thornton (2018)

Physical features: ● 1.9 mi drag strip ● 4.7 mi high speed oval (35° banking) ● 7%, 15%, and 32% grade areas ● 35 acre safety-feature evaluation area ● dedicated autonomous highway speed track ● endurance road
● interstate exit and entrance configuration ● rough blacktop and gravel surfaces for endurance testing ● test circle ● tunnel features ● varying

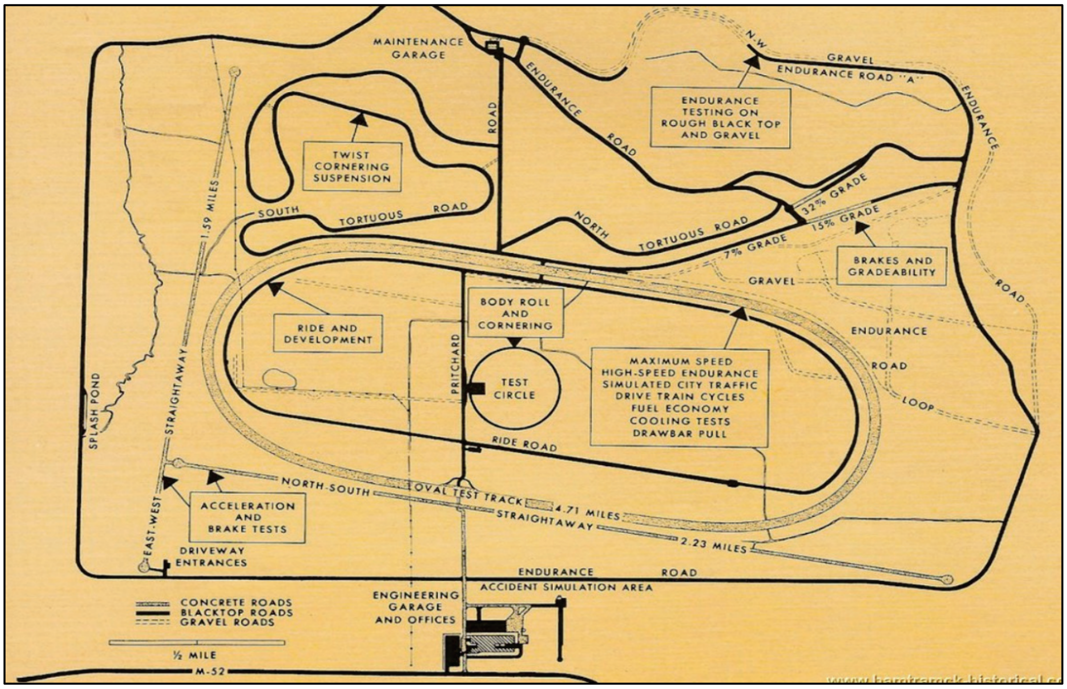
lighting conditions ● winding “Tortuous Road” for twist cornering suspension evaluation

Technologies: NA

Obstacles: various

Support infrastructure: ● 6,500 sf high-tech command center that includes vehicle-to-infrastructure (V2I) communication, facility control and monitoring, and test vehicle support

Figure 10. Chelsea Proving Grounds features a main roadway loop with associated challenge courses on the site’s perimeter. (Map reproduced from JR98 2016. Public domain)



Note: Featured map does not yet include the autonomous driving test facilities.

Figure 11. Trees and other natural features that exist within the course surroundings at Chelsea provide an extra dimension to challenge AVs. (Map data: Google Earth 2013.)

2.7 Ford Arizona Proving Ground—Wittman, Arizona

Description: The Ford Arizona Proving Ground is located on 1,498 acres near Phoenix. It opened for Volvo in 1985 and transitioned to Ford in 2009. Although it was originally developed for conventional automobile testing, Ford has continued to innovate and expand their capabilities to use the site for AV testing. Arizona provides a unique testing environment with year-round operations and extreme heat and sun. Outside parties can have vehicles tested by site personnel or can rent specific surfaces for their own staff. Figure 12 shows an aerial view of the facility.

URL: NA

See for this section: Center for Land Use Interpretation (n.d.); Test Professionals (2015); Turner Construction Company (n.d.)

Physical features: • 1.1 mi winding handling course (32 ft wide) • 2 mi straightaway (three lanes and 12 ft wide) • 2.2 mi oval • 12 acre wet pad • 22 acre vehicle dynamics area • 200 ft circle track • camel hump course • concrete surfaces at 7% and 30% grades • dirt track at 20%, 30%, 40%, and 50% grades • dust track • lane change dynamics area • tunnel feature

Technologies: NA

Obstacles: NA

Support infrastructure: • garage spaces with 35 bays

Figure 12. The Ford courses at Wittman come in a variety of configurations. (Image reproduced from Center for Land Use Interpretation, n.d., under a Creative Commons license [CC BY-NC-SA 4.0 Deed, https://creativecommons.org/licenses/by-nc-sa/4.0/].)

2.8 Ford (Dearborn) Development Center—Dearborn, Michigan

Description: The Dearborn Development Center is a closed course owned and operated by Ford. The 365 acre proving ground is adjacent to the Ford R&D laboratory and was revamped into the current test track in 2006. The site is multifaceted, allowing engineers to test future vehicles with precision and reliability (Figure 13).

URL: NA

See for this section: Charity Buzz (n.d.)

Physical features: • 0.8 mi straightaway • 2.5 mi of high-speed track • 2.6 mi of undulating low-speed pavement • 12 acre wet pad for testing how vehicles perform with less traction • 20 lanes of road surfaces from around the world • infield steering and handling course • 43 acre vehicle dynamics area • banked curves and curbs • brake hills • gravel surfaces • railroad crossings • vertigo-inducing brake hills

Technologies: NA

Obstacles: NA

Support infrastructure: NA

Figure 13. The Dearborn Development Center features a primary track loop with connected facilities to test diverse handling situations. (Map data: Google Earth 2019.)

2.9 Fowlerville Proving Ground—Fowlerville, Michigan

Description: The Fowlerville Proving Ground is an independent facility located on 950 secluded acres between Detroit and Lansing (Figure 14). It operates year-round as a center to test a range of automotive systems, including ADAS and automated vehicle technology. The recently constructed ADAS Pad and ADAS City supply the tester with real-world environments to properly challenge automated systems for future public use. Other facilities on the proving ground can be used to further test vehicle speed and stability in varied road conditions.

URL: https://www.ftt-a.com/track-facilities/

See for this section: Fowlerville Proving Ground ("Track and Facilities, n.d.; "Track Facilities," n.d.)

Physical features: ● 3 mi oval track (two 12 ft wide lanes and 7% curve grades) ● four-lane, 4,500 ft straightaway with fast and slow lanes and turnaround loops at the ends ● five-lane signaled intersection ● ADAS City multipurpose facility specializing in autonomous testing and designed for a variety of real-world settings (including two-lane, 100 ft diameter roundabout; highway entry and exit; pedestrian crosswalks; rural intersection; and tunnel and overpass) ● ADAS pad; 300 ft × 500 ft multipurpose dynamic pad with 2,300 ft straightaway approach (for testing ADAS and AV technology) ● brake hills (10%, 20%, and 30% grades) ● low friction road surfaces to mimic challenging road conditions using underground sprinklers to apply water (e.g., ceramic tile simulating ice, basalt tile simulating snow, and asphalt to simulate wet pavement) ● special surface roads (e.g., choppy concrete, manhole covers, and asphalt patches) ● vehicle dynamics pad (i.e., flat, level asphalt circle; 1,000 ft diameter; three separate approach or departure lanes; lane change configurations) ● wavy and gravel road pad

Technologies: ● ADAS City five-lane signaled intersection with configurable vehicle-to-everything (V2X) traffic signals

Obstacles: ● ADAS City pedestrian vulnerable road user platform ● ADAS City Strikeable Surrogate Vehicle (SSV) and tow behind test rig system for testing autonomous emergency braking (AEB) systems ● ADAS City supports 3D global vehicle platform and target (i.e., soft car obstacles)

Support infrastructure: ● 6,000 sf of garage space with vehicle operation and maintenance equipment available

Figure 14. Satellite imagery of the 950-acre Fowlerville Proving Ground, which features large driving loops and various infield facilities for additional testing. (Map data: Google Earth 2021.)

2.10 General Motors (GM) Mobility Research Center / Kettering University—Flint, Michigan

Description: The GM Mobility Research Center opened in 2016 on a 21-acre parcel of property at Kettering University, a former GM Chevrolet Division facility. The site includes outdoor lab space, closed course proving ground, and R&D facilities. It is open year-round for testing in diverse weather conditions for AV research, development, safety, and technology. It is also complemented by an additional focus on hybrid and electric vehicle technologies. The site benefits from the collaboration of Kettering University faculty, students, automakers, and suppliers. Figure 15 shows an aerial view of the facility.

URL: https://www.kettering.edu/mrc

See for this section: Kettering University (2017)

Physical features: ● 3.25 acre customizable test pad built to racetrack performance specifications; no breaks, seams, or drains on test pad surface; can be used in conjunction with road course ● 15 ft wide oval course ● consistent 1% slope across the entire length in one direction; no slope in the perpendicular direction, with ¼ in. tolerance over 10 ft in any direction
● elevation and surface changes ● S-curves (i.e., low-speed handling loops) ● site fully customizable to testing needs ● stadium-style lighting for use 24 hours per day ● straightaway distances of up to 500 ft ● year-round availability for testing in diverse weather conditions

Technologies: ● private 4G LTE Advanced cellular network infrastructure ● simulated flooding capability ● supports V2I testing ● supports V2V testing

Obstacles: NA

Support infrastructure: ● research annex that features labs, offices, and a garage with vehicle bays

Figure 15. Satellite imagery of the General Motors (GM) Mobility Research Center, which features a unique road structure that allows for extensive testing capabilities. (Map data: Google Earth 2019.)

2.11 GoMentum Station—Concord, California

Description: GoMentum Station is the nation's largest closed course facility and collaborative space dedicated to the safe development of automated vehicles. The 5,000-acre site is located 35 mi from San Francisco, at the former Concord Naval Weapons Depot. GoMentum opened in 2015 and features both human-made and natural features to challenge vehicles to adjust to plausible scenarios they may face in public deployment. Figures 16 and 17 show two different views of the facility.

URL: https://gomentumstation.net/

See for this section: Baker (2017); Brugeman et al. (2018); Cohen (2015); Cooley (2016); Craig (2019); Iwasaki (2018); Medina et al. (2018); GoMentum Station (n.d.)

Physical features: ● Two 1,400 ft long tunnels for sensor testing ● five intersections with advanced signaling ● 7 mi long spine road for testing high-speed driving ● 19.6 mi of variable paved roads ● building-like structures to mimic city environment ● grid road structure ● one-way, two-way, and merging lane types ● overpass and underpass ● railroad ● shared and separated bike lanes ● urban and rural settings ● worn pavement and road markings that reflect realistic driving environment and challenge vehicles

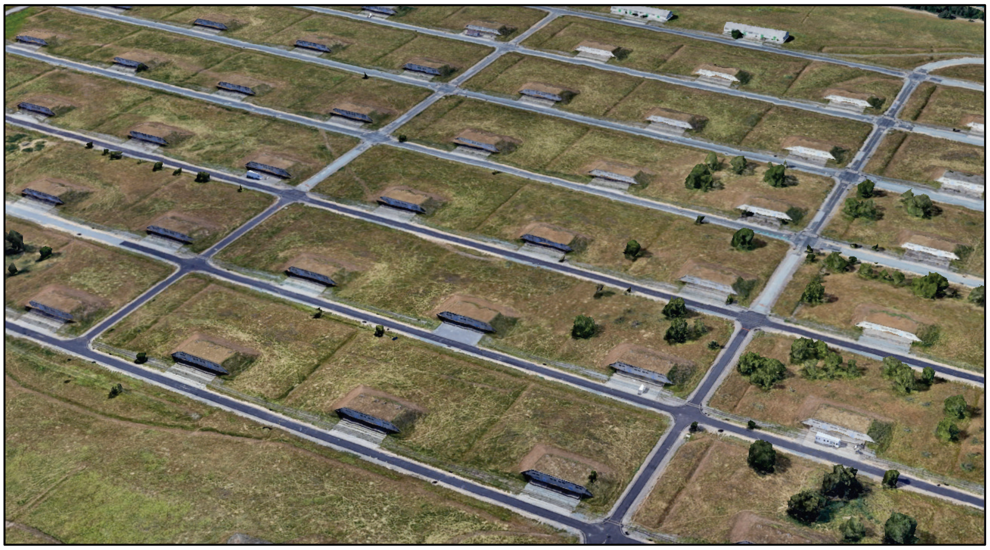
Technologies: ● 5G technology ● advanced Internet Protocol switches ● advanced traffic signaling equipment ● cellular V2X (CV2X) ● Digital twin simulator that allows test driving on GoMentum in a simulated environment (i.e., you can develop and test functions and script your own scenarios without physically being at the site) ● DSRC network ● real-time kinematic (RTK) corrected GPS service across the site ● traffic signal cabinets ● video vehicle detectors

Obstacles: NA

Support infrastructure: NA

Figure 16. Satellite imagery of GoMentum's road network, which provides extensive testing opportunities and replicates instances that may be found in a public setting. (Map data: Google Earth 2013.)

Figure 17. The former munition bunkers and connected streets at GoMentum mimic a traditional urban grid. (Map data: Google Earth 2013.)



2.12 Illinois–Automated and Connected Track (I-ACT)—Rantoul, Illinois

Description: The Illinois–Automated and Connected Track (I-ACT) will be a testing arena for connected and autonomous mobility on 400 acres of what was formerly Chanute Air Force Base. The environs will include nearby Interstate 57, an airport, a major rail corridor, a grid-system village, and surrounding agricultural lands. The I-ACT mission is to improve safety and mobility while reducing energy consumption and emissions for roadway, air, rail, water, and intermodal transportation systems. The opening date has yet to be determined, but the planning process has been a collaboration between academia, industry, and government partners who want to advance transportation technologies. Figures 18 and 19 and show some of I-ACT's planned features.

URL: http://stii.illinois.edu/

See for this section: Illinois Center for Transportation (2018); Yi (2020)

Physical features: • one-lane infinity loop • 2 one-lane circular loops • three-lane outer loop • autonomous agricultural technology testing area • autonomous multimodal transportation testing area • drone testing facility • dynamic test pad • energy harvesting • environmental test chamber • suburban test bed • urban test bed

Technologies: NA

Obstacles: NA

Support infrastructure: NA

Figure 18. The Illinois–Automated and Connected Track (I-ACT) site features eight primary thematic areas for research and testing. (Image reproduced with permission from Illinois Center for Transportation, n.d.)

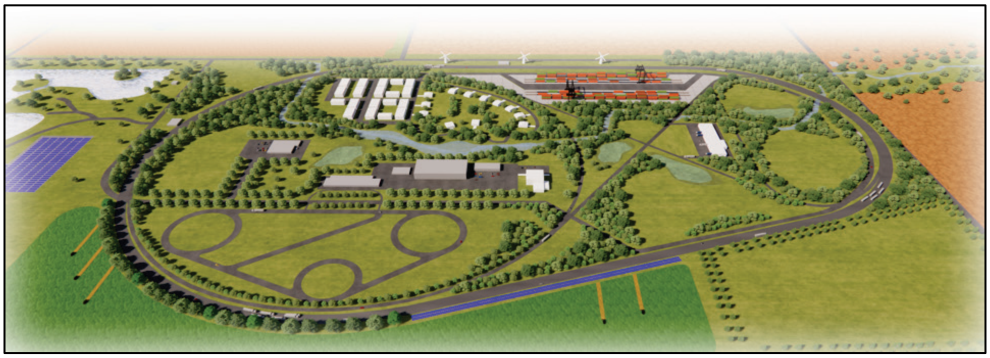


Figure 19. The I-ACT suburban test bed is centered around an intersection for testing AVs in environs with intermediate density. (Image reproduced with permission from Illinois Center for Transportation, n.d.)

I-ACT will include validation and deployment of autonomous and connected technology integration within nearby, grid-like village and roadway sections under county, village and state jurisdictions.

2.13 Infrastructure Automotive Technology Laboratory (iATL)—Alpharetta, Georgia

Description: The Infrastructure Automotive Technology Laboratory (iATL) opened in 2020 at 3000 Summit Place. The facility focuses on connected vehicle infrastructure and testing it in real traffic scenarios. The laboratory setting serves as an engineering technical facility for testing the functionality of connected vehicle technology between (a) transportation infrastructure and motor vehicles, (b) infrastructure and vulnerable road users, and (c) motor vehicles and vulnerable road users. While iATL lacks track facilities, the nearby transportation corridor allows innovators to test in a real-world streetscape with applicable interferences or obstructions. Figure 20 shows some of the tools used at iATL to test communication capabilities, and Figure 21 shows an aerial view of the facility.

URL: https://theiatl.com/

See for this section: Applied Information (2020); Frost (2020)

Physical features: NA

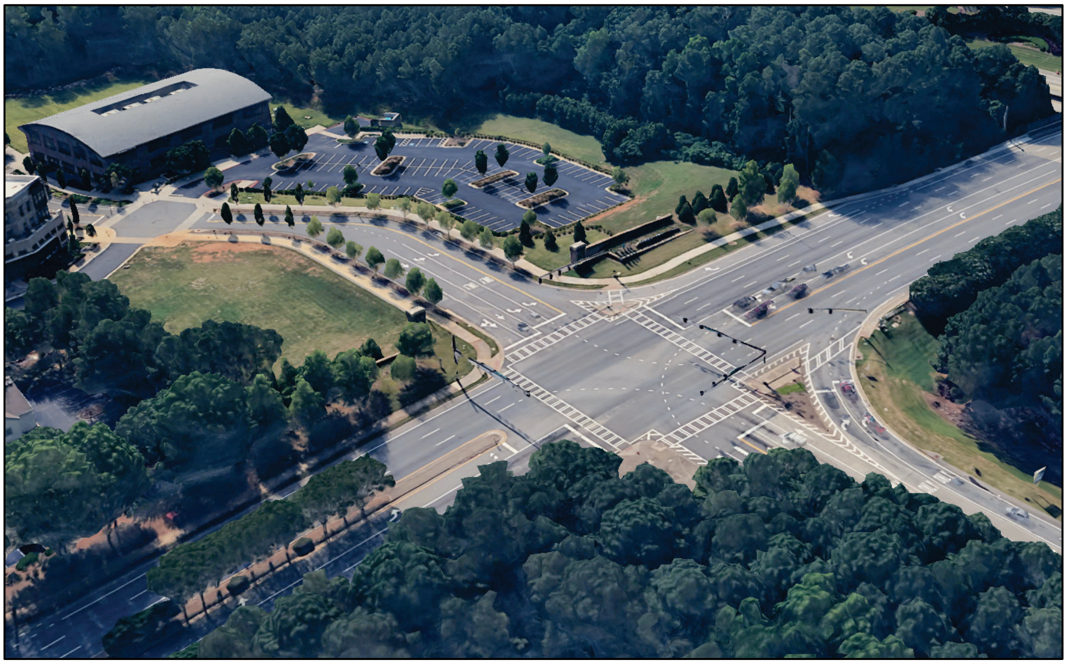
Technologies: • 4G LTE • 900 MHz radio • CV2X-based applications (i.e., for crosswalks, emergency response, intersections, school beacons, transit, and video cameras) • DSRC • traffic infrastructure (e.g., signals, signage, and controllers) to perform communication tests

Obstacles: NA

Support infrastructure: • 4,400 sf commercial building

Figure 20. The Infrastructure Automotive Technology Laboratory (iATL) facility features a variety of traffic signals and controllers to test communication capabilities. (Images reproduced with permission from iATL, n.d.)

Figure 21. Satellite image of iATL, which is located in the Fulton Community Improvement District that funded the large-scale deployment of connected vehicle technology. Its position off of a crucial corridor allows the facility to test its technology in a real-word intersection. (Map data: Google, SIO, NOAA, US Navy, NGA, GEBCO Landsat / Copernicus.)



2.14 International Transportation Innovation Center (ITIC)—Greenville, South Carolina

Description: The International Transportation Innovation Center (ITIC) is an independent, nonprofit proving ground providing a secure and confidential environment for testing and validating vehicles. The site opened in 2013 on approximately 300 acres at the S.C. Technology & Aviation Center on what was formerly Donaldson Air Force Base. The test track has a diversity of test elements to satisfy a wide variety of mobility testing needs, including transportation megatrends such as vehicle automation, connectivity, and electrification. Figure 22 shows the semi-virtual smart city intersections at ITIC, and Figure 23 shows an aerial view of the facility.

URL: http://www.itic-sc.com/

See for this section: Fayazi and Vahidi (2017); South Carolina Technology and Aviation Center (n.d.); Thornton (2016); Federal Highway Administration, Office of Operations (2017)

Physical features: ● 1 mi straightaway ● 1,700 ft durability track ● 10% and 20% slope hills with split-mu features ● 1,000 ft brake lane ● surface variations, including asphalt, concrete, and off-road ● 3 mi oval (opening 2024)

Technologies: Commercial-grade EV charging

Obstacles: NA

Support infrastructure: ● access to emergency services ● office and garage space ● transport vehicle parking

Figure 22. International Transportation Innovation Center (ITIC) was the site for autonomous vehicle-in-the-loop testing conducted by Clemson University for a Department of Energy grant in 2018. (Image reproduced with permission from ITIC, n.d.)

Figure 23. ITIC, located on what was Donaldson AFB, utilizes its extensive runway infrastructure as an avenue for vehicle testing. (Image reproduced from Wikimedia Commons under a Creative Commons license [CC BY-ND 4.0, https://creativecommons.org/licenses/by-nc-sa/4.0/].)

2.15 J. J. Pickle Research Campus / University of Texas—Austin, Texas

Description: The J. J. Pickle Research Campus, which was established in 1946, is located on 475 acres of the University of Texas at Austin. The site is involved with five key research areas in developing AVs: (1) highway, intersection, and rural road safety; (2) V2X sensing and communication; (3) vehicle and nonmotorized user interactions; (4) cybersecurity; and (5) policy and regulation. The center exploits research resources from the main University of Texas at Austin campus and uses the offsite J. J. Pickle Research Campus as a controlled testing environment. Figure 24 contains a map of the facility.

URL: https://www.utexas.edu/research/off-campus-research-sites

See for this section: Brown (2017); Texas Automated Vehicle Proving Ground Partnership (2016); NMRG (2000)

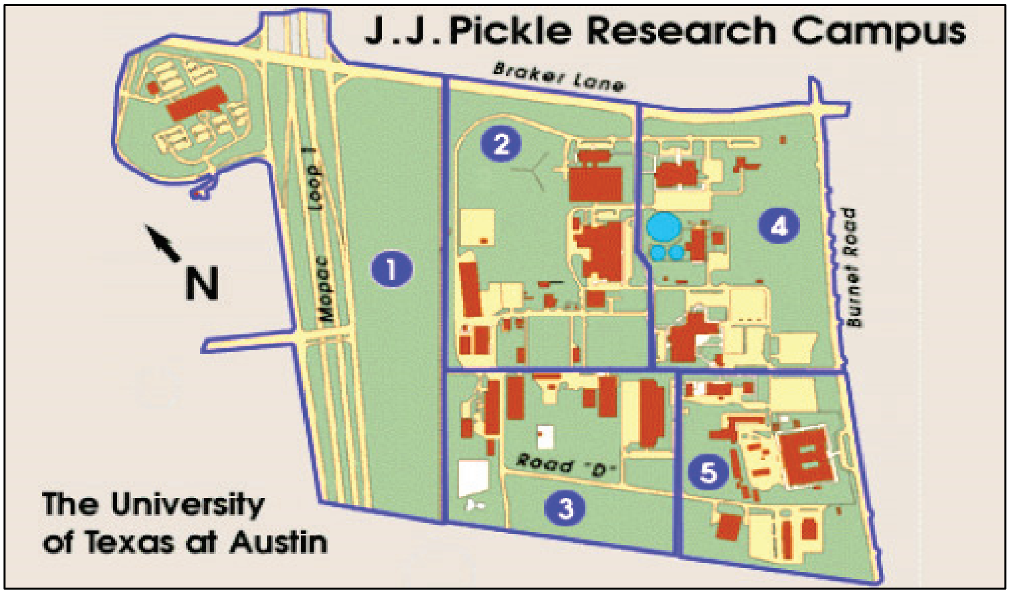
Physical features: ● internal roadways with restricted AV access ● use of streets and parking lot networks

Technologies: ● three test vehicles with various levels of AV and connected technologies to design and test roadside infrastructure ● millimeter wave (mmWave) communication system ● platform for testing different types of algorithms, giving hands-on experience at minimal risk ● signalized corridors to test V2I communications

Obstacles: NA

Support infrastructure: ● indoor 1:10 scaled vehicle test facility

Figure 24. The J. J. Pickle Campus provides an optimal road structure for AV testing. (Image reproduced from NMRG 2000. Public domain.)



2.16 Keweenaw Research Center (KRC) / Michigan Technological University—Calumet, Michigan

Description: Keweenaw Research Center (KRC) maintains more than 900 acres of proving grounds. Originally, the site was developed by the US Army as a field station for the evaluation of ground vehicle system performance in cold weather. That field station was named the Snow, Ice, and Permafrost Research Establishment (SIPRE), which was later consolidated with other facilities as a Cold Regions Research and Engineering Laboratory (CRREL) field site. Currently, Michigan Technological University operates the KRC, but it remains a major research and testing center for Detroit Arsenal and CRREL. Figure 25 shows a snow-covered road similar to that found on the test track at KRC, and Figure 26 contains a Google Earth view of the facility.

URL: https://www.mtu.edu/krc/

See for this section: KRC (n.d.); NATO (2018)

Physical features: • miles of prepared test tracks • ride and handling loops • circular track • ice rink • packed snow vehicle dynamics areas • off-road obstacle / 4WD course • customized test courses • 3,300 ft straightaway• stability test area •grooved ice • split friction surfaces with 15%, 20%, 25%, 30%, and 40% grades • slush pit • noise test area • packed snow slopes with 7%, 10%, 15%, 20%, 25%, and 30% grades

● variety of snow and soil conditions ● varying surface types (e.g., paved, gravel, dirt, grassy, snow, and ice)

Technologies: ● video and digital camera capability

Obstacles: NA

Support infrastructure: ● heated vehicle bays ● inspection pit ● cold test laboratory ● shop facility

Figure 25. A snow-covered road.

Figure 26. Satellite image of Keweenaw Research Center (KRC). (Map data: Google Earth 2022.)

2.17 Larson Transportation Institute (LTI)—Bellefonte, Pennsylvania

Description: Larson Transportation Institute (LTI) is located on the engineering campus of Penn State University, and its test track is in a rural setting near the university airport (Figure 27). In 2017, it was designated the testing location for the City of Pittsburgh's AV program. The site supports docking operations for heavy autonomous trucks, maintains the collection of vehicle platoon data for performance evaluations, and provides a staging area for teleoperated control of automated vehicles for highway testing. Originally constructed in 1972 for the university, the closed-loop test track is designed to accommodate a wide range of research activities.

URL: https://www.larson.psu.edu/about/test-track.aspx

See for this section: Korosec (2017); LTI ("Crash Safety," n.d.; "Test Track," n.d.); Medina et al. (2018); Michael Baker International (2018)

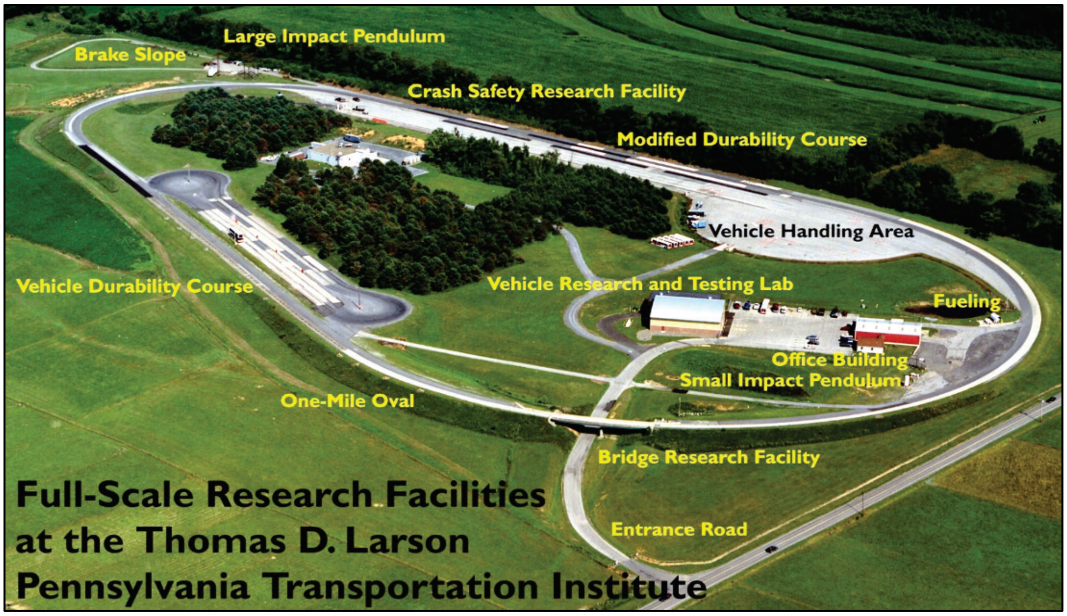
Physical features: ● 1 mi oval track ● traditional roadway infrastructure, including pavement markings, signage, and signal systems ● variable test surfaces area that can be installed on a temporary basis ● vehicle durability testing course ● vehicle handling area

Technologies: ● DSRC radio network ● electrification and charging systems ● mobile mapping vehicle (to host lidar) and camera systems with differential GPS (DGPS) ● on-site DGPS system

Obstacles: NA

Support infrastructure: ● crash safety research facility ● office building for supporting activities ● vehicle research and testing laboratory

Figure 27. Research and testing facilities for the test track at Larson Transportation Institute (LTI) were developed to challenge vehicle handling in a variety of on-road conditions. (Image reproduced with permission from LTI, "Test Track," n.d.)



2.18 Mcity/University of Michigan—Ann Arbor, Michigan

Description: Mcity is a 32 acre test site on the University of Michigan North Campus Research Complex (Figure 28). Since its opening in 2015, the goal of Mcity has been to advance transportation safety, sustainability, and accessibility. The site is designed to support rigorous and repeatable testing of automated vehicles before public use. Mcity is flexible, allowing researchers to simulate a variety of environments and providing necessary challenges for vehicles. The test track is developed on an "ABC" method for comprehensive testing: "accelerated evaluation covering the driving scenarios responsible for the most common motor vehicle crashes, behavior competence testing to ensure the automated vehicles demonstrate they can handle the majority of driving scenarios, and corner cases, or test situations that push the limits of these highly advanced automated vehicles" (Peng and McCarthy 2019, 2). Figure 29 shows building facades used to create an urban testing environment.

URL: https://mcity.umich.edu/

See for this section: Barth (2017); Medina et al. (2018); Peng and McCarthy (2019); Thompson (2015)

Physical features: ● 16+ mi of simple and complex roadway geometries ● 45-degree and parallel parking lines ● access to Michigan Traffic Laboratory (adjacent to Mcity) ● brick and gravel paving segments ● railroad crossings ● ramps ● signage, crosswalks, and sidewalks ● simulated highway overpass using a tunnel that blocks vehicles from wireless and satellite signals ● stationary and dynamic pedestrian mannequins ● variable size roundabouts and mobility circles ● varying road conditions (e.g., faded pavement and graffiti on road signs) ● wide straightaway

Technologies: ● connected vehicle wireless roadside equipment ● control network to collect data about traffic activity using wireless, fiber optics, Ethernet, and RTK positioning system ● internally developed software interface (OCTANE) that allows users to control facility infrastructure from phone, laptop, or vehicle computing platform ● lighting and traffic control devices ● open-source application programming interface (API) controls testing conditions throughout facility ● V2X communication throughout the facility and 5G connectivity

Obstacles: ● bicycles for obstacle avoidance testing and bicycle safety research ● faux cars and reconfigurable building facades ● repositionable obstacles

Support infrastructure: NA

Figure 28. Mcity hosts a diverse range of testing capabilities on its 32-acre site. (Image reproduced with permission from Mcity 2015.)

Figure 29. Mcity building facades provide an urban testing environment. The image on the *left* is a design rendering, and the physical implementation on site is shown on the *right*. (Image reproduced with permission from Mcity 2015.)

2.19 MGA Research Facility—Burlington, Wisconsin

Description: The MGA proving ground is a closed course located on 400 acre and is 65 mi northwest of Chicago (Figure 30).[*] The facility was established in 1988 for conventional automotive testing, but it has been a key partner of the Wisconsin AV Proving Grounds since 2016. Their primary focus in the AV environment is to aid in providing a gateway to public road capabilities. MGA contributes to this advancement of AV development and deployment by providing a diverse test environment.

URL: https://mgaresearch.com/locations-and-contacts/wisconsin/ and https://wiscav.org/

See for this section: BRC Online (n.d.); Traffic Operations and Safety Laboratory (n.d.); University of Wisconsin–Madison and MGA Research Corporation (2016)

Physical features: ● 15% grade ● 30% grade brake slope ● abuse test surfaces ● chassis course ● corrosion chambers ● crash and sled labs ● deep water fording ● gravel track ● main track ● north track (for ride and handling) ● off-road track ● powertrain course ● railroad crossings ● upper track (for durability) ● vehicle dynamics area (i.e., skid pad) ● water trough

Technologies: NA

Obstacles: NA

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[*] MGA is headquartered in Akron, New York.

Support infrastructure: ● main office containing vehicle prep, component test laboratory, and dummy and instrumentation calibration laboratory ● unleaded and diesel fueling

Figure 30. Satellite imagery of the MGA Research Facility, which features a main 1.2 mi outer loop with various infield tracks and facilities. (Map data: Google Earth 2011.)

2.20 Michigan Technical Resource Park (MITRP)—Ottawa Lake, Michigan

Description: Michigan Technical Resource Park (MITRP) is a 332 acre closed course on a site near the Michigan and Ohio border (Figure 31). MITRP is a privately owned testing facility with 140,000 sf of office, commercial, and industrial space within the site. Beyond testing conventional vehicles, MITRP uses their courses to test AVs. A primary focus for customers is to safely replicate edge case scenarios. The site offers a variety of on-road and off-road testing opportunities (Figure 32).

URL: https://www.mitrp.com/

See for this section: Krok (2018); MITRP (“Off-Road Courses,” n.d.; “On-Road Courses,” n.d.)

Physical features: ● 4 ft deep and 200 ft long twisting ditch ● 5 mi gravel course ● 20% and 30% hill grade ● 25 ft wide hill with 37% gradient slope ● 300 ft Burma Road ● chuckhole (i.e., cement pad with 3 in. deep bump) ● congested urban environments ● culvert course ● curb climbs (12 in., 15 in., and 18 in. heights) ● differing surface density area (e.g., gravel, asphalt grindings, limestone, sand, and silts) ● dirt course (150 ft long) ● dirt mounds (2 ft and 4 ft height) ● frame twist (i.e., one side is a flat riding surface, and the other is an 8–14 in. washboard surface) ● high speed capable 1.75 mi oval track with ½ mi straightaway ● mud pit (300 ft long and 20 ft wide) ● oval track with 6-degree, 15-minute track bank and 12-degree 30-minute suspended spirals ● railroad crossing and pothole simulation course ● railroad tie course ● ramp jump for suspension testing (20 ft long × 10 ft wide × 3.3 ft high) ● retaining pond and standing water area ● roller rise with 17% and 20% grades ● rough country course featuring washboard surfaces, bumps, and humps ● traction surfaces that mimic ice and snow ● water fording pit for EV testing (fall of 2023) ● environmental chamber with four-post vehicle shaker (spring of 2024)

Technologies: ● EV charging and fuel onsite

Obstacles: NA

Support infrastructure: ● technology room ● fuel ● garages ● machine shop ● material handling equipment ● scale ● test labs ● cafeteria and catering available onsite

Figure 31. Satellite imagery of the Michigan Technical Resource Park (MITRP), which hosts a large oval track as its primary feature and includes various research facilities for continuous development and innovation. (Map data: Google Earth 2011.)

Figure 32. Vehicles at MITRP have access to a series of road simulations, including hill grades to test braking and stability. (Image provided by MITRP and used with permission.)

2.21 National Advanced Driving Simulator (NADS) / University of Iowa—Iowa City, Iowa

Description: National Advanced Driving Simulator (NADS) is a building-based transportation safety research center. It uses a suite of driving simulators and on-road vehicles to conduct research tests for private and public entities. The first of three advanced technology simulators became operational in 2001. Simulation provides an optimal mechanism for research tactics that may be infeasible, too costly, or unsafe in a real-world environment. Their mission involves improving safety by researching the connection between drivers, motor vehicles, and road users. The expertise of the facility lies in a variety of features, including human factors, vehicle safety systems, driver impairment, driver distraction, connected vehicle technologies, automated vehicles, and on-road data collection technologies.

URL: https://www.nads-sc.uiowa.edu/

See for this section: Brown et al. (2010); University of Iowa (*NADS*, n.d.; “National Advanced,” n.d.)

Physical features: ● indoor facility

Technologies: ● three simulators, called *NADS-1*, *NADS-2*, and *MiniSim*

NADS-1 (Figure 33) includes the features that follow: ● 24 ft dome with actual vehicle cab ● 360-degree projected scenery and 40-degree vertical view with LED projectors ● custom software for optimal graphics and continuous image display utilizing a library of realistic driving environments (e.g., urban, suburban, rural, interstate, and day or night) ● audio system simulating real-world traffic features that are connected with vehicle behavior (e.g., wind, tires, engine, and tire blowout) ● simulation software features open architecture where systems communicate with each other using a published interface on a high-speed network ● flexible software architecture to allow for integration of third party systems ● realistic vibrations associated with driving on varied road surfaces ● yaw, roll, pitch, turning, and latitude and longitude cues to driver ● 13 degrees-of-freedom motion base

NADS-2 (Figure 34) includes the following features: ● fixed-base version of NADS-1 ● limited forward field of view ● high resolution projectors ● physical glare source to simulate headlights of oncoming vehicles ● interchangeable cabs ● ideal for simulations that do not require motion or wrap around visuals

MiniSim includes these features: ● portable, high performance driving simulator ● variety of hardware and software components to fit the testing needs of the client ● single 42 in. display ● steering, pedal, shift, and seat from real vehicle in quarter cab configuration ● surround sound audio ● liquid crystal display (LCD) instrument panel and touch screen operation console ● flexible configurations (i.e., multiple displays, floor gear selectors, center electronic console) ● urban, suburban, rural, interstate, day and night driving simulations ● varied driving conditions (e.g., dry, wet, and snowy) ● simulations complete with controlled and uncontrolled intersections, roundabouts, signs, and traffic lights ● non-US driving environments are available ● library of driving models (i.e., cars, trucks, vans, construction equipment, and utility vehicles) ● scenario packages designed to evaluate driver behavior ● Interactive Scenario Authoring Tool (ISAT); researchers can design their own scenarios based on needed testing

Obstacles: NA

Support infrastructure: NA

Figure 33. National Advanced Driving Simulator (NADS)-1 is a high-fidelity ground vehicle simulator with the largest motion range of any driving simulator in the United States. (Image reproduced with permission from University of Iowa, "National Advanced," n.d.)

Figure 34. NADS-2 offers features similar to those of NADS-1 in a fixed base. (Image reproduced with permission from University of Iowa, "National Advanced," n.d.)

2.22 Nevada Automotive Test Center (NATC)—Silver Springs, Nevada

Description: This 6,200-acre site is a privately owned, independent testing, evaluation, and engineering facility that was experimenting with AVs as early as 1996.[*] Nevada Automotive Test Center (NATC) is committed to developing systems that support autonomous operations. Site engineers can design unique testing events to challenge autonomous and connected vehicles. NATC recognizes the importance of testing new technology in a safe, controlled environment before it can be deployed on public roadways. NATC is also skilled in integrating intelligent systems into existing vehicle structure. Their cohesive environment allows development of controls to support autonomous operation. Figures 35 through 37 contain aerial views of the facility.

URL: https://natc-ht.com/

See for this section: Eskandarian et al. (1996)

Physical features: • 8 mi paved oval with banked turns • 500 ft radius skid pad • agricultural and off-highway vehicle road sharing • flooded paved roadway simulations using natural and manmade features • gravel and off-road course with varied elevations and slopes • lane change obstacle avoidance events • on and off ramps • sensor durability, corrosion, and contamination events • shock and vibration test infrastructure • signage and traffic directing • simulated dust or debris storm • simulated potholes and road hazards • simulated tree coverings • speed bumps and curbing and parking stalls • temporary traffic controls • tire blowout events • varied pavement conditions with degraded markings

Technologies: • electromagnetic interference technology • V2V capabilities • V2I capabilities

Obstacles: • dynamic obstacles

Support infrastructure: • customer workspaces • fabrication shop • maintenance facility • instrumentation facility • secure storage

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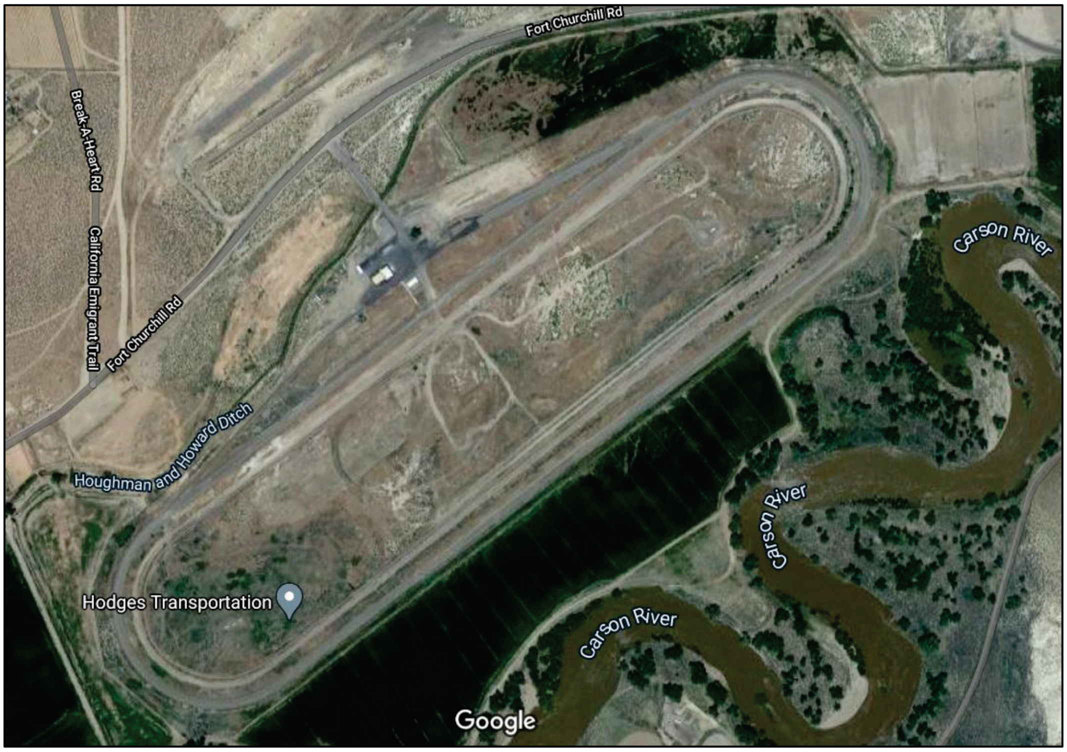
[*] NATC's first foray into autonomy was related to highway infrastructure rather than vehicles. In 1996, NATC rigged a test track so driverless trucks could load test sections of pavement 20 hours per day over two years (Eskandarian et al. 1996).

Figure 35. Satellite imagery of Nevada Automotive Test Center (NATC). NATC is unusual in that it accommodates off-road vehicle courses. (Map data: Google Earth 2019.)

Figure 36. Satellite imagery of the central portion of NATC, which features various pads and test areas. (Map data: Google Earth 2019.)

Figure 37. Satellite imagery of the 8 mi oval track at NATC, which features banked turns. (Map data: Google Earth 2019.)



2.23 Pennsylvania Safety Transportation and Research Track (PennSTART)—State College, Pennsylvania

Description: Pennsylvania Safety Transportation and Research Track (PennSTART) is to open in mid-2022 on a 110-acre site. It plans to operate in six key training, testing, and research areas: traffic incident management; tolling, intelligent transportation systems (ITS), and traffic signals; work zones; commercial vehicles; transit vehicles; and CAVs. The facility will be capable of testing over 75% of US DOT-approved connected vehicle applications. The track will allow for a controlled environment to test technology before deployment. It fulfills the Pennsylvania Department of Transportation's defined lead role to advance CAV technology in Pennsylvania. Figure 38 contains a map of the facility, and Figure 39 contains a rendering of its test track.

URL: https://www.pennstart.org/

See for this section: Aupperlee (2018); Michael Baker International (2018); PennSTART (2019); Pennsylvania Turnpike Commission (2018)

Physical features: • 1.5 mi high-speed oval track • four-point urban intersection • four-point roundabout • six-, four-, and two-lane highway sections • 80-acre infield for advanced testing and training environment • track length sufficient for highway speeds with return loop • rural and urban environs • signalized rural high-speed intersection • urban corners with small radii • on and off ramps • truck turnaround area and truck parking

Technologies: • bridge section with embankments • overhead active traffic management system • overhead toll gantry • railroad at-grade crossing • ramp meters and queue preemptor • roadway flooding area • signalized urban corridor • staging area with smart freight parking capabilities

Obstacles: NA

Support infrastructure: • academic buildings (e.g., classrooms and labs) • garage and parking • helipad

Figure 38. The proposal for Pennsylvania Safety Transportation and Research Track (PennSTART) features a variety of test environments to challenge vehicle technology and support R&D. (Map reproduced from Pennsylvania Turnpike Commission 2018. Public domain.)

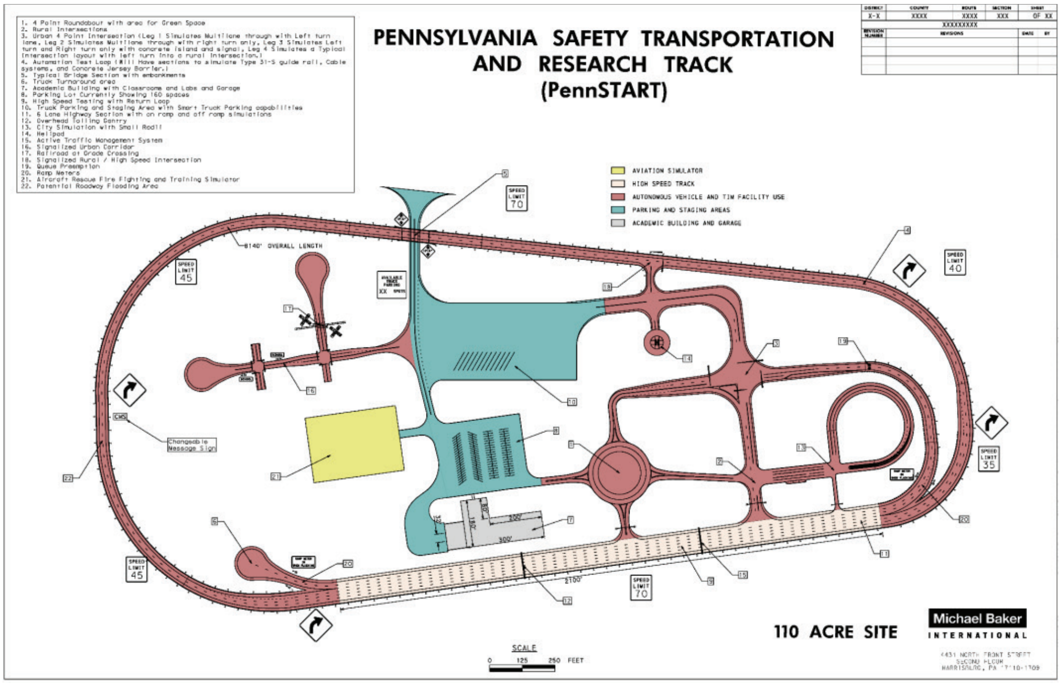


Figure 39. The PennSTART site features one large track loop with connected infield test environments and a technology laboratory. (Image reproduced with permission from the Commonwealth of Pennsylvania Department of Transportation 2019. Public domain.)

2.24 RELLIS Proving Grounds Research Facility / Texas A&M University—Bryan, Texas

Description: The RELLIS campus is part of the Texas AV Proving Ground Partnership for research on smart power grids, AV operations, and advanced manufacturing. The RELLIS AV operations opened in 2016 and take place on a 2,000-acre site. Focus areas include: (1) vehicle controls, robotics, and cybersecurity, (2) AV roadway infrastructure needs and V2I and, (3) truck platooning. Truck platooning is when two or more trucks closely follow each other as a group using connectivity technology and automated driving support systems to do so (ACEA 2017)Experiments range from virtual to full-scale testing. The primary goal of RELLIS AV operations is to further human–robot collaboration toward a future vision of full autonomy. Figure 40 contains an aerial view of the current RELLIS site.

URL: https://tti.tamu.edu/facilities/proving-grounds/

See for this section: Harms (2020); Texas A&M University System (2018)

Physical features: ● 1.2 mi straightaway ● 3 mi urban grid environment ● 3.5 mi test track simulating freeway conditions ● 6 mi of paved runways with aprons ● crash test proving ground with crash cushions and barrier systems ● friction pavement testing ● hydroplaning trough ● skid pads ● transportation pavement and signage and markings ● urban and rural conditions

Technologies: ● connected work zones ● instrumentation for truck platooning ● roadway safety test bed with roadside devices ● toll gantry test bed ● V2I capabilities

Obstacles: NA

Support infrastructure: ● indoor virtual simulation lab that can simulate fully autonomous, partially autonomous, and manual vehicles, all interacting with pedestrians and other users

Figure 40. Satellite view of the current RELLIS campus. (Maps data: Google Earth 2015.)

2.25 Road America—Elkhart Lake, Wisconsin

Description: Road America is a limited-access 640 acre motorsports facility that became a key element of the Wisconsin AV Proving Grounds in 2016 (Figure 41). The original facility opened in 1955 to provide a physical environment for conventional automotive testing. The site now contributes to the safe advancement of automated vehicles to pave the way for public road evaluation. The track has high availability during the winter and for night testing, and testing regimens include long distance, variable speed, freight, transit, and human-vehicle interaction.

URL: http://www.roadamerica.com/

See for this section: Road America (2015, 2018, n.d.); University of Wisconsin–Madison and MGA Research Corporation (2016); Wisconsin Automated Vehicle Proving Grounds (n.d.)

Physical features: • 1 mi go-kart track (i.e., an inside 4 mi road racing track) constructed into a hillside with combination paved and dirt surfaces, many twists and turns, and >50 ft of elevation change • 4 mi road circuit that offers high-speed straights, challenging turns, and elevation changes • 14 mi of paved access roads • 14 turns in course • 48 m elevation change • 6,604 m of course total • off-road course • several large, paved paddock areas • skid pad

Technologies: NA

Obstacles: NA

Support infrastructure: NA

Figure 41. Satellite imagery of Road America's large track, which allows for extensive testing capabilities. (Map data: Google Earth 2015.)

2.26 Smart Mobility Advanced Research and Test (SMART) Center—East Liberty, Ohio

Description: Smart Mobility Advanced Research and Test (SMART) Center is a state-of-the-art innovation hub designed to support a wide variety of AV/CAV testing in a safe, controlled, and repeatable environment (Figure 42). It is located on 540 acres of the 4,500 acre Transportation Research Center (TRC), a 501c3 nonprofit, independent organization with nearly 50 years of research and test experience. Also located at TRC is National Highway Traffic Safety Administration (NHTSA) Vehicle Research and Test Center (VRTC). The site pays particular attention to working with global AV safety consortia, driver practices for Society of Automotive Engineers (SAE) Level 3 autonomy, and the development of unmanned aerial vehicles. Level 3 autonomy means that the automated system performs the driving tasks, but the driver still can take over at any time (NHTSA, n.d.). Figure 43 contains a map of the facility.

URL: https://www.trcpg.com/tour/ohio/

See for this section: Drive Ohio (2019); Stanford (n.d.); TRC Ohio ("News," n.d.; "Virtual," n.d.); Visnic (2019)

Physical features: ● 1.2 mi straightaway ● six-lane signalized intersection (widest connected and signalized intersection in the industry) ● 18.5 lane-mi of pavement ● asphalt vehicle dynamics area ● circular vehicle dynamics area for low-speed testing of roundabouts and unique traffic situations ● neighborhood street network ● oblique intersection scenarios ● rural network, including wooded roads ● urban network of movable intersections ● 22 acre vehicle dynamic area

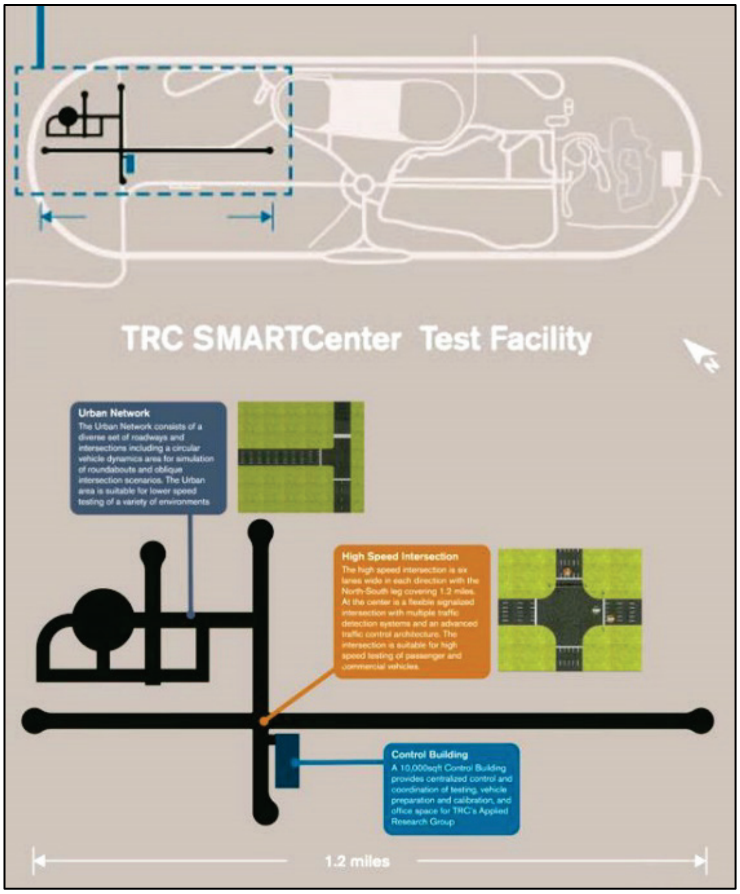
Technologies: ● site access to DSRC, CV2X, and high-speed wireless communication ● multiple traffic detection systems and advanced traffic-control architecture ● underground power distribution and fiber network (nearly 4 mi of underground conduits)

Obstacles: ● mobile and stationary obstacles, simulated pedestrians, small children, and deer ● "soft" simulated vehicles

Support infrastructure: ● 10,000 sf all-season control building with a garage and offices

Figure 42. Satellite imagery of the Smart Mobility Advanced Research and Test (SMART) Center, which is designed to test new technologies and highly automated vehicles in a closed, safe, and secure environment. (Map data: Google Landsat / Copernicus, SIO, NOAA, US Navy, NGA, GEBCO.)

Figure 43. The SMART Center development is located within the infield of the larger Transportation Research Center (TRC) facility. (Image reproduced from Drive Ohio 2019. Public domain.)



Urban Network

The Urban Network consists of a diverse set of roadways and intersections including a circular vehicle dynamics area for simulation of roundabouts and oblique intersection scenarios. The Urban area is suitable for lower speed testing of a variety of environments

High Speed Intersection

The high speed intersection is six lanes wide in each direction with the North-South leg covering 1.2 miles. At the center is a flexible signalized intersection with multiple traffic detection systems and an advanced traffic control architecture. The intersection is suitable for high speed testing of passenger and commercial vehicles.

Control Building

A 10,000sqft Control Building provides centralized control and coordination of testing, vehicle preparation and calibration, and office space for TRC's Applied Research Group

2.27 Smithers Winter Test Center (SWTC)—Raco, Michigan

Description: Smithers Winter Test Center (SWTC) opened in 2018 on an 800-acre site 25 mi southwest of Sault-Ste. Marie. It is equipped for durability and performance evaluations of vehicles and associated automotive components in extreme cold and with hazardous road features. The site also provides cold weather performance testing of AVs and sensor proficiency (Figures 44 and 45).

URL: https://www.smithers.com/industries/transportation/automotive/winter-proving-grounds

See for this section: Smithers (n.d.)

Physical features: • 3% and 6% slopes • 300 ft, 600 ft, and 1,600 ft diameter circles with ice inner lanes and packed snow outer lanes • alternative friction and split friction surfaces • approximately 40 acres of ice • bare pavement surfaces • customizable track set ups to accommodate automated vehicles ● ice-asphalt split friction inclines at 10%, 15%, and 20% grades ● ice pads ● over 750 acres of snow ● packed snow handling and test lanes

Technologies: NA

Obstacles: NA

Support infrastructure: NA

Figure 44. Satellite image of Smithers Winter Test Center (SWTC), which was developed on what was formerly Raco Army Airfield and features a variety of testing environments to challenge vehicles. (Map data: Google Earth 2016.)

Figure 45. SWTC benefits from a natural snow environment in Northern Michigan and is used to test AV capabilities and overall stability.

2.28 Southwest Research Institute (SwRI)—San Antonio, Texas

Description: Southwest Research Institute (SwRI) houses a diverse range of research facilities on their 1,200-acre campus. While the institute's research is not exclusive to transportation innovation, it is a leader in algorithm and component technology integration for automated driving. Since 2008, SwRI has developed over 20 fully automated vehicle platforms (e.g., from golf carts to class 8 trucks) for government and commercial clients. The institute provides a full-service test track along with complementary research and testing support for public and private sector stakeholders. Figure 46 contains an aerial view of the facility.

URL: https://www.swri.org/technical-divisions/intelligent-systems

See for this section: Brown (2017); Medina et al. (2018); SwRI (2017); Texas Automated Vehicle Proving Ground Partnership (2016)

Physical features: ● 1.2 mi test track ● four-way signalized intersection ● 7+ mi of paved roads, dirt tracks, and off-road areas ● large network of private roads ● on- and off-road testing facilities ● varied pavement features (e.g., gravel, dirt, paved marked, and unmarked)

Technologies: ● DSRC roadside infrastructure and communication towers ● Intelligent Systems Division Lab specializing in localization, perception, cybersecurity, and connected automation ● real-world traffic simulator based on real data from traffic sensors in Fort Worth

Obstacles: NA

Support infrastructure: NA

Figure 46. Satellite imagery of Southwest Research Institute (SwRI) features a 1.2 mi track loop to test transportation technologies. (Map data: Google Earth, n.d.)

2.29 SunTrax—Auburndale, Florida

Description: SunTrax is located on a 475-acre site near Florida Polytechnic University, between Orlando and Tampa. Its high-speed oval was completed and opened for testing in 2019, but the infield does not open until 2021. The SunTrax facility is dedicated to research, development, and testing of innovative transport technologies (e.g., truck platooning) in a controlled environment. The main goal of the site is to continuously evolve to improve transportation safety, efficiency, and accessibility. SunTrax is customizable and reconfigurable to meet the solutions needed by the tester. The Kennedy Space Center Swamp Works lab acts as a secondary testing facility for research on extreme weather and unusual roadway conditions. Figures 47 and 48 contain different views of the facility.

URL: http://www.suntraxfl.com/

See for this section: DC Velocity Staff (2018); Florida Department of Transportation (n.d.); Lawrence (2017); SunTrax (n.d.)

Physical features: ● 1 mi long, independently operable five-lane straightaways ● 2.25 mi oval track for high-speed testing (i.e., up to

70 mph) with 200 acres infield for CAV testing ● four free-flow toll gantries ● complex horizontal and vertical curves with irregular grade changes ● entrance and exit ramps into a multilane continuous loop track, on which collision avoidance and traffic maintenance during active road construction can be tested ● flexible lane striping, signing, and curbside pick-up and drop-off scenarios that can be configured to the needs of a specific test ● pedestrian and bicycle interactions with AVs ● pick-up and drop-off area to replicate various multi-modal passenger transfers (e.g., airports, hotels, and transit centers) ● simulated urban and suburban areas that feature intersection configurations and complex lighting, signing, and signal conditions ● undulating topography built into a manufactured hillscape ● varied pavement materials and markings to test surface durability, lane keeping, and auto braking (designed to challenge sensors and monitor vibration control)

Technologies: ● 28 acre paved technology pad that accommodates virtual and augmented reality platforms (i.e., replicates real-world geometric configurations) ● enclosed sensor test chamber for testing precisely controlled and repeatable scenarios (i.e., under manufactured rain, lighting, smoke, fog, and dust conditions) ● resilient high-speed data connections with controlled access

Obstacles: ● reconfigurable facades using shipping containers and prop features

Support infrastructure: ● 20,000 sf welcome center (with offices, classrooms, and indoor and outdoor event spaces) ● 27,000 sf warehouse building ● 56,000 sf air-conditioned workshop buildings (with 2,800 sf bays, controlled access, and resilient high-speed data connections)

Figure 47. The SunTrax site features a large testing loop with connected infield testing areas and associated research facilities. (Image reproduced from Florida Department of Transportation, n.d. Public domain.)

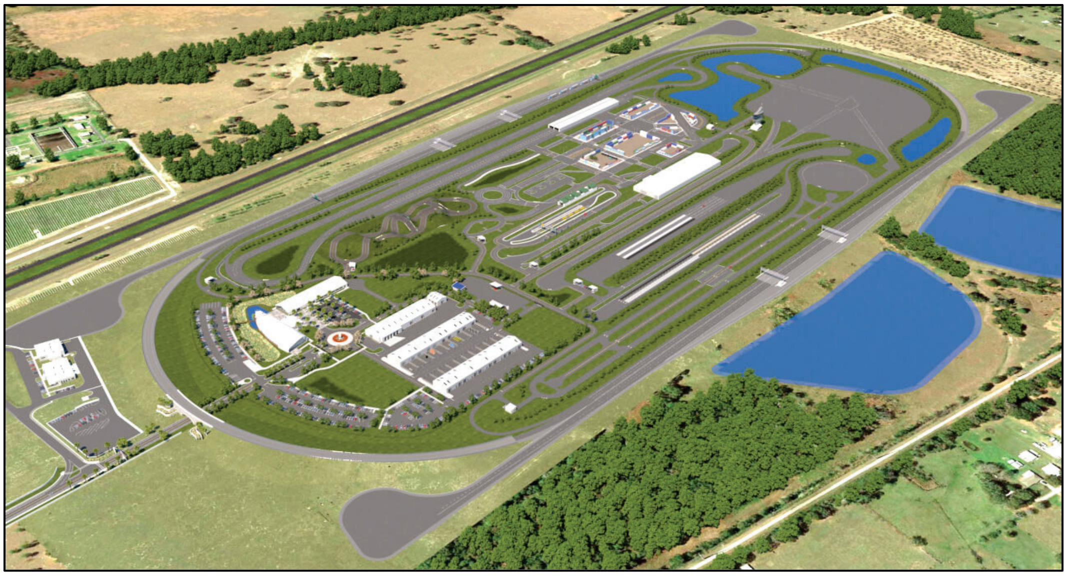


Figure 48. The SunTrax urban simulation zone provides a realistic city environment with signalized intersections and buildings constructed from shipping containers. (Image reproduced with permission from SunTrax, n.d.)

2.30 Virginia Tech Transportation Institute (VTTI) Smart Roads—Blacksburg, Virginia

Description: Virginia Tech Transportation Institute's (VTTI) Smart Roads is a closed course suite of test tracks that opened in 2000 and provides advanced vehicle testing (Figures 49 and 50). The four primary test areas include a highway, surface street, live roadway connector, and rural roadway. Each element offers different environments to challenge self-driving vehicles in real-world scenarios. Examples include flooded pavement testing and surface friction testing. The test beds help facilitate the institute's research mission of saving lives on our nation's roadways.

URL: https://www.vtti.vt.edu/

See for this section: VTTI ("Live Roadway Connector," n.d.; "Surface Street," n.d.)

Physical features: ● 2.2 mi controlled access highway test track ● three bridge features ● 14 varying pavement sections ● control room where research is scheduled and overseen ● dynamic actor scenarios (e.g., vehicle, pedestrians, and cyclists) ● flooded pavement testing ● grass shoulders ● interfering terrain ● linkage road from smart road to public roads, allowing tests between live traffic and closed environments ● multiple lane layouts ● multiple merge areas ● narrow sections ● natural foliage ● off-road areas ● parking and pickup and drop-off areas ● reconfigurable buildings and infrastructure elements ● reconfigurable pavement markings ● reconfigurable roundabout ● rural intersections ● rural roadway to mimic realistic rural settings ● signalized intersections with various lane geometries ● small bridges ● suburban and urban environments ● surface friction testing ● varying elevation with winding roads ● wide shoulder areas for safe maneuvering

Technologies: ● nine DSRC units and two mobile roadside sites ● 88 weather-making towers ● Automation Hub to facilitate project development ● artificial snow production ● cellular and DSRC connectivity ● DGPS broadcast ● Ethernet fiber transceivers and switches ● fog production ● in-pavement sensors ● lighting and weather systems controls ● optical fiber network ● rain production of different intensities ● signalized intersection with signal phase and timing by remote and DSRC ● varying lighting conditions

Obstacles: NA

Support infrastructure: NA

Figure 49. Satellite imagery of Virginia Tech Transportation Institute (VTTI), where AVs can be properly challenged for real-world urban and suburban situations on the designated surface street. (Map data: Google Landsat / Copernicus 2019.)

Figure 50. Satellite imagery of VTTI's live roadway connecter, which is a unique feature that allows a seamless transition between the closed testing environment and public roads. (Map data: Google Landsat / Copernicus.)

3 Typology of Test Site Features

The development of AVs requires comprehensive testing in diverse scenarios. This chapter examines the variety of test-site features used to facilitate the maturation of AV technology. The features are drawn from the 30 known test sites presented in Chapter 2, and assessments fall under the same four feature categories: physical features, obstacles, technology, and support services. Each attribute within the categories is placed into the features typology and then evaluated in terms of application for AV use.

3.1 Physical Features

The structural attributes of test sites are outlined in this section. Physical features refer to built-in elements that are often unmovable and contribute directly to evaluating AV driving maneuvers. They range from basic configurations and surface materials to more challenging test courses and vehicle dynamics pressures. Diverse physical features at a test site provide opportunities for greater understanding of AV performance, thus inspiring AV advancement. To aid in fluid and repeatable testing between features, wide shoulders and paved access roads allow for efficient connections.

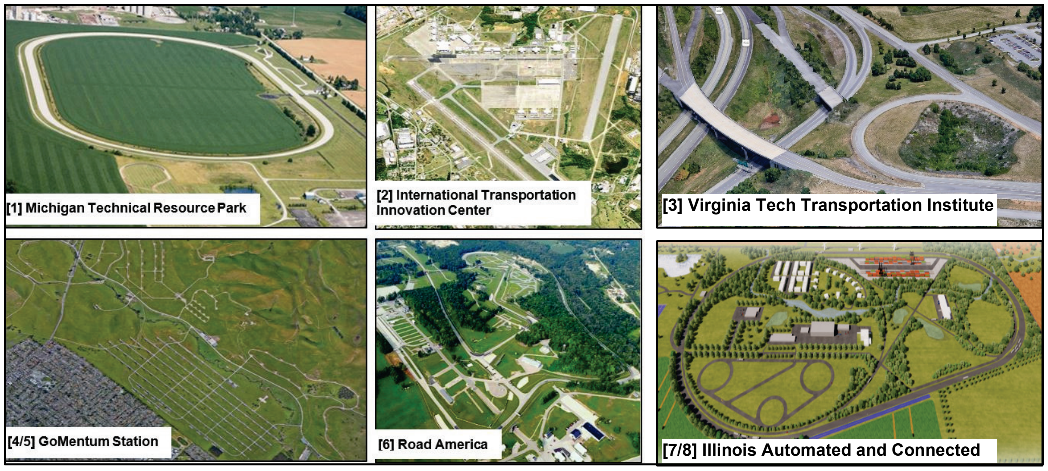
3.1.1 Track Configuration

Track configuration identifies the layout of the main tracks being used for AV testing. There are many possible configurations that boast varying sizes and dimensions (Figure 51). Nine qualified track types that support AVs in an effort to maximize situational efficacy are detailed here:

1. **Oval loop**—This is a common layout that provides a consistent and repeatable test platform. It combines both straightaways and gradual turns to effectively tailor to the needs of both low- and high-speed capabilities. Other basic driving maneuvers, including signaling, lane change, lane correction, and cruise control, can benefit from the consistency of the loop.
2. **Straightaways**—This feature is useful for high-speed application and simple maneuvers that do not require a large radius. In many cases, a turnaround loop may be present at the end of the straightaway to allow for greater fluidity in testing. A preexisting paved runway is often used to provide a straightaway.
3. **Active public roadways**—An active public roadway or linkage to the site allows for a seamless transition between live traffic and the closed-environment testing.

4. **Road network**—A network emphasizes the connectivity of the whole site and allows continuous patterns to be repeated. This may help the vehicle learn a wider variety of situations in one outset.
5. **Spine road**—These are useful for low- and high-speed testing. The road lays in a straight direction, but the structure itself possesses minor curvatures. This type of road will also radiate lateral roads to other site destinations, thus improving overall connectivity for continuous vehicle navigation.
6. **Road circuit**—A circuit is a connected loop with a varied shape and structure, typically including formidable curves or turns. In the case of autonomy, a circuit challenges predictive and speed behaviors of AVs in ways that a uniform loop cannot.
7. **Infinity loop**—An infinity loop has similar benefits to that of an oval loop. However, infinity loops may allow for the additional capability of highway interchange and overpass or underpass functionality.
8. **Circle loop**—A circle loop emphasizes vehicle dynamics, challenging AVs to properly assess and adapt to higher intensity road curvatures.
9. **Existing roadway**—If space or funding is limited, existing roads and parking lots can be used for testing. Allowing access only to AVs in these areas enhances safety and overall testing capability.

Figure 51. Varying track configurations offer diversity in AV testing to advance development for public road deployment. The numbers on the images refer to the list of track configurations in this section. (Images reproduced with permission from [1] Google Earth, [2] Wikimedia Commons 2006, [3, 4/5, and 6] Google Earth, and [7/8] University of Illinois 2023.)



3.1.2 Surface Configuration

Surface configuration, here, is defined as large areas of pavement that are used to facilitate a specific testing environment. This is commonly achieved through pavement striping and added infrastructure that mimics the desired conditions to reflect a real-world setting. By maintaining flexibility in pavement configurations, testing capabilities can be maximized while adhering to the varied needs of the testing entity. Six noteworthy layouts are described here and are demonstrated in Figure 52:

1. **Urban grid**—An urban configuration reflects a traditional street structure, including varied intersections, signage, and lighting, to challenge AVs in a common use case.
2. **Suburban environs**—A suburban layout typically simulates a low-speed neighborhood setting.
3. **Commercial strip**—These are generally low-speed environments. They may resemble a smaller scale urban grid, with heavy emphasis on vehicles being able to sense and effectively respond to buildings, crosswalks, intersections, signage, cyclists, and pedestrians.
4. **Highway**—High-speed configurations commonly present in loops or straightaways. A highway portion of a track may offer features, including multiple lane stripes, on- and off-ramp simulations, or toll gantries.
5. **Rural roadway**—In a public setting, not all roadways will be free from deterioration or faded markings. A rural roadway is therefore a valuable resource to challenge AVs to navigate common roadway imperfections.
6. **User-defined area**—This is a designated plot of land that remains flexible in features and internal configuration to fit any desired testing context. Such areas are crucial for a site to remain competitive in today's evolving AV environment.

Figure 52. Surface configurations allow testing of needed use cases in a replicated public environment. The numbers on the images refer to the list of surface configurations in this section. (Images reproduced with permission from [1/2] Google Earth, [3] Mcity 2015, [4] Pennsylvania Department of Transportation 2020, [5] Microsoft Word stock photos, and [6] Google Earth.)

3.1.3 Surface Materials

Using or simulating a variety of roadway surfaces is critical for comprehensive AV testing. Not every road in a real-world setting is paved the same or produces the same friction factors. Therefore, it is important to challenge AVs on their ability to make the proper adjustments based on the surface material itself or adverse weather conditions that alter the existing surface. Additionally, the diversification of surface densities extends into off-road autonomous testing, which is currently an under-researched arena. Table 1 identifies each condition and describes its properties and the associated challenges produced.

Table 1. Description of road surface conditions and their properties.

Condition	Properties	Condition	Properties
Wet	Low friction	Brick	Causes vibrations, durable
Snow	Low friction, glare	Dirt	Produces dust and mud, unpaved, typically nongraded
Ice	Low friction, low visibility of condition	Gravel	Loose, unpaved, typically graded
Asphalt	Durable, stable, skid resistant, smooth	Around the world	Replicates various road patterns found globally
Cement	Bulk density, stable under heavy loads	Limestone/sand/silt	Low density, high tractive force

Note: The force needed to overcome the resistance caused by friction when two bodies (in this case the car tires and the low density material) slide or roll on each other (ELESA, n.d.).

3.1.4 Surface Features

The categorization of surface features is intended to expand upon physical makeup to describe varying surface inputs that are beneficial for amplifying AV capabilities. These basic features highlight real-world roadway encounters that draw upon sensor perception proficiency. Questions are proposed for each applicable feature to call attention to needed considerations when employing surface feature testing (Table 2).

Table 2. Description of road surface features and the sensor proficiency questions related to the feature.

Surface Feature	Sensor Proficiency Question	Surface Feature	Sensor Proficiency Question
Road markings	Does the AV recognize road markings and their meaning to respond appropriately?	Chatter bars	Does the AV keep in lane, recognizing the associated reflective raised road markers?
Curbing	Can the AV properly recognize a curb as a boundary feature to the roadway?	Split friction	Can an AV properly adjust to differing frictions on the right and left wheel paths?
Faded road markings	Can the AV keep in the lane space without clean white lines to detect?	Manhole cover	Can the AV recognize the solid object is not a barrier and continue driving?
Varying grades	Can the AV assess the elevation to approach grade with proper speed?	Speed bump	Can the AV assess the bump and decide to slow speed accordingly?
Pothole/ chuckhole	Can the AV perceive holes of varied size and intensity to safely traverse the obstacle?	Banking	Does the AV recognize the angle to which an edge of a road is raised above the inner edge to safely continue?
Rumble strips	Will the AV assess continuous pavement divots as a boundary and react to keep lane if afflicted?	Deteriorated roadway	Can the AV safely recognize and adjust to inconsistent road patterns that may pose as obstacles?

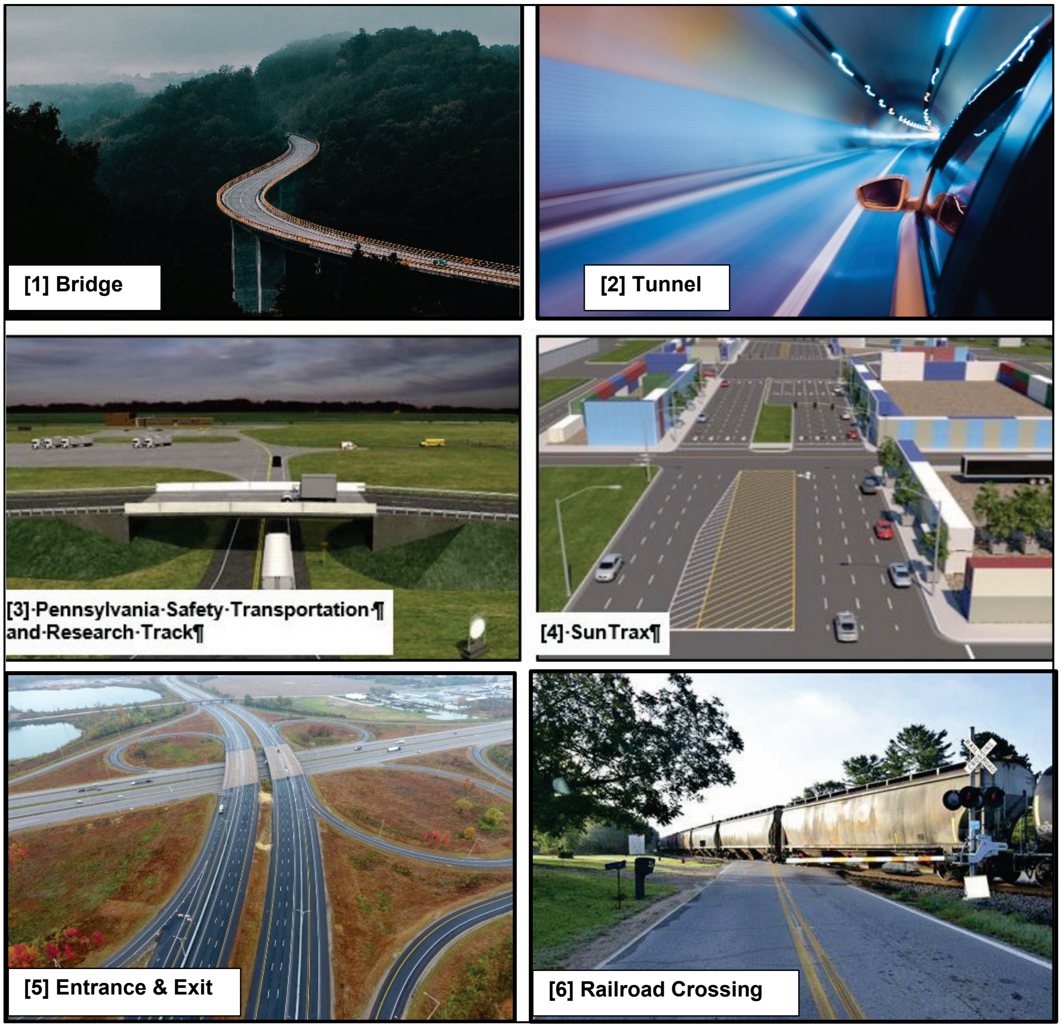
3.1.5 Structures

Structures refers to large built elements that enhance capabilities in testing environments. These features are attributes that an AV would commonly encounter on a public roadway (Figure 53). When these structures are implemented in a controlled setting, the AV can be taught, through repeatable testing, to recognize them and to interact with them properly. Each feature is described here to provide context on the situational efficacy of the structure for AV development:

1. **Bridge**—A bridge creates a scenario with few known environmental cues for the AV to accurately understand its positioning.
2. **Tunnel**—A tunnel feature is meant to challenge AVs to navigate a low visibility and restricted location positioning environment.
3. **Interchange**—An interchange creates an overpass and underpass scenario to aid in *z*-axis comprehension for AVs.
4. **Building facades**—Buildings create visual obstructions for AVs. This structure is a key feature in developing urban, suburban, and commercial environs. Simulated facades on test sites are often constructed from shipping containers.

5. **Entrance and exit ramps**—Ramps are useful for mimicking a highway or interstate setting. For an entrance or exit ramp, an AV must learn to (a) recognize the associated signage and pavement markings and (b) make appropriate speed, signal, and lane changes to safely execute a maneuver onto a ramp.
6. **Railroad tracks and crossings**—A railroad and crossing is meant to define an AV's sensor capabilities to recognize an oncoming train, associated signage in place, and difference in paving at a rail crossing. Additionally, a rail crossing will test an AV's listening comprehension to recognize if a train is coming—a factor that is especially important if a crossing is not equipped with a safety bar.

Figure 53. Built structures onsite aim to enhance the provision of realistic driving scenarios for testing. The numbers on the images correspond to the list of structures provided in this section. (Images in the *top row* reproduced from Microsoft Word stock photos; images in the *second row* reproduced from [*left*] Pennsylvania Department of Transportation 2020 and [*right*] SunTrax, n.d.; images in the *third row* reproduced from [*left*] Pennsylvania Department of Transportation 2020 and [*right*] Google Maps 2020. All images used with permission.)

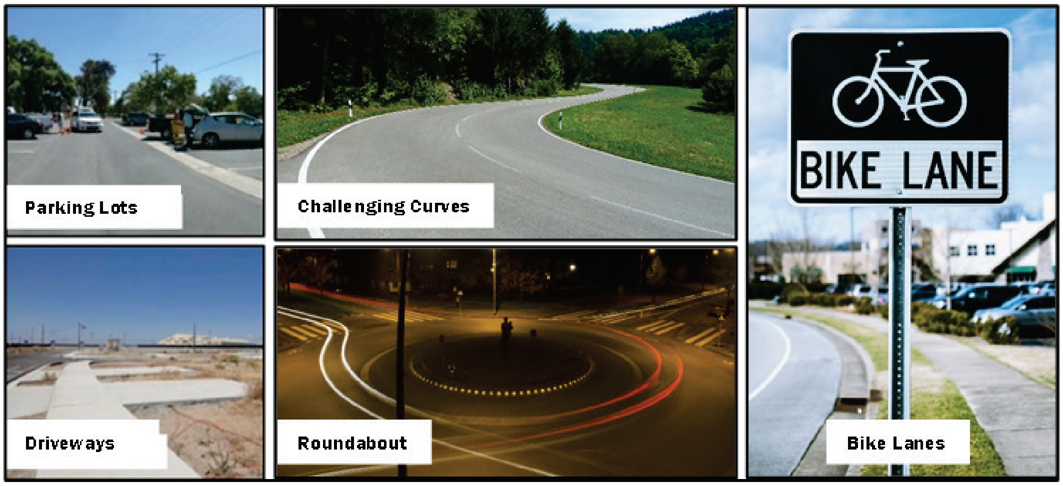


3.1.6 Public On-Road Inputs

For the purposes of this technical report, public on-road inputs are features that offer small-scale layouts on present tracks or surfaces (Figure 54). They provide plausible and specific test cases for AV development. The AV must learn to traverse these common scenarios to make progress toward public deployment. These features primarily reflect structural inputs. Technology features relating to the on-road environment will be discussed in Section 3.3 of this report. The list that follows contains common public on-road inputs:

- Intersections
- Roundabouts
- Dedicated AV lanes
- Cul-de-sacs
- Urban corners with small radii
- Shared bike and auto lanes
- Separated bike and auto lanes
- One-way streets
- Two-way streets
- Lane merges
- Driveways
- Roadside crash cushions
- Challenging turns and curves
- Parking
- Turn around areas
- Traffic signage
- Pick-up and drop-off areas

Figure 54. On-road inputs supply baseline public features an AV must learn to traverse. (Images reproduced with permission from [*left top* and *bottom*] Madrigal 2017, [*middle top*] Pixabay 2012 [*middle bottom*] Pixabay 2014, and [*right*] Pixabay 2018.)



3.1.7 Test Pads

Test pads are defined spaces on a test site that are used to conduct variable tests. Such features typically exist as a large section of paved open space that allows for common maneuver testing. Some pads may intentionally be open and reconfigurable, exemplifying the most flexibility by allowing the testing entity to prioritize its needs. Others may have unique additions or special features that enhance maneuver challenges. Providing a straightaway approach to specific areas allows for reasonable transitions, thus expanding testing possibilities. Examples of test pads follow:

1. **Ice and packed snow vehicle dynamics areas**—Simulated winter weather conditions are used to test AV capabilities in a low-friction environment with the potential for low visibility and glare.
2. **Lane change vehicle dynamics area**—This pad is one that highlights the need for AVs to make safe lane changes by checking for oncoming obstacles, signaling, and lane keeping. Such areas commonly contain proper lane markings to help an AV's situational awareness.
3. **Vehicle dynamics pads**—This type of test pad is the most general because it is not confined to a specific test type. Having an open site allows for productive creativity and flexibility in the AV testing environment.
4. **ADAS test pad**—In test sites originally developed for conventional vehicle testing, an ADAS pad can bridge the gap toward innovation. This type of pad focuses specifically on automated technologies and their use cases.
5. **Customizable test pad**—This testing environment is another general test pad formation that emphasizes its reconfigurable nature. Customizable test pads have a distinct ability to fit a given testing need with changeable pavement markings, obstacles, or infrastructure, for example.
6. **Wet pad**—This is a low-friction environment in which to test vehicle reaction and perception for safety. They can be created using sprinkler systems under pavement (Fowlerville Proving Ground, "Track and Facilities," n.d.).
7. **Skid pads**—Skid pads are traditionally open circular shaped test pads. They are used to test an AV's handling in basic control skills, including left foot breaking and weight transfer (Wert 2016).
8. **Roadway safety device test bed**—As the name suggests, this type of test bed focuses on the use of items, including signage, pavement markings, and crash cushions. Additionally, this is an area to home in on V2I and V2X connectivity in terms of technology oriented safety devices such as traffic lights or real-time traffic displays.
9. **Autonomous multimodal transportation test area**—This test area type reflects the convergence of varied travel modes, including taxi, bus, personal automobile, bicycle, and pedestrian. Such an environment allows an AV to understand and adapt to real-world actions.
10. **Braking and handling course**—This course produces noise, vibration, low friction, and harsh surface environments to test resilience scenarios and lane keeping (SunTrax 2019).

3.1.8 Test Course

The list that follows defines courses or unique road strips meant to challenge vehicle dynamics. These challenges reflect various facets of off-road environments (Figure 55). Off-road situations are a particular obstacle in current AV development because of the amount of environmental features AVs need to evaluate and consider. Whereas on-road conditions provide a relatively clear path of direction, off-road conditions may include large vegetation, rock formations, or unsteady terrain to traverse. Therefore, in a military context, the development of off-road capabilities is especially needed for mission readiness where terrain may be unpredictable. Nine unique constructs are defined here:

1. **Culvert course**—A culvert course is composed of large culverts of varying sizes anchored in dirt at varying angles (MITRP, "Off-Road Courses," n.d.).
2. **Chassis course**—A chassis course implements variable road inputs at high frequency and low amplitude (University of Wisconsin–Madison and MGA Research Corporation 2016).
3. **Railroad tie course**—The course configuration utilizes a series of railroad ties staggered on a dirt surface in varying angles (MITRP, "Off-Road Courses," n.d.).
4. **Camel hump course**—This course is outfitted with large and frequent humps of varying sizes and grades.
5. **Burma road**—A burma road is one of cobble stone embedded in a concrete base (MITRP, "On-Road Courses," n.d.).
6. **Winding "Tortuous Road"**—A winding tortuous road is developed with high intensity twist cornering.
7. **Dust track**—A dust track is an intentionally dry, unpaved roadway that will produce large dust formations.
8. **Rough country course**—This course topography features rocky terrain, washboard surfaces, and rigorous bumps (MITRP, "Off-Road Courses," n.d.).
9. **Camber course**—A camber course consists of packed snow handling lanes that transition to multigrade vehicle dynamics areas, producing various camber angles (AET, "Automotive," n.d.).

Figure 55. Off-road capabilities for AVs can be developed by integrating intense vehicle dynamics platforms. (Images of MITRP reproduced with permission from MITRP, "Off-Road Courses," n.d.; remaining images reproduced from Google Earth map data.)

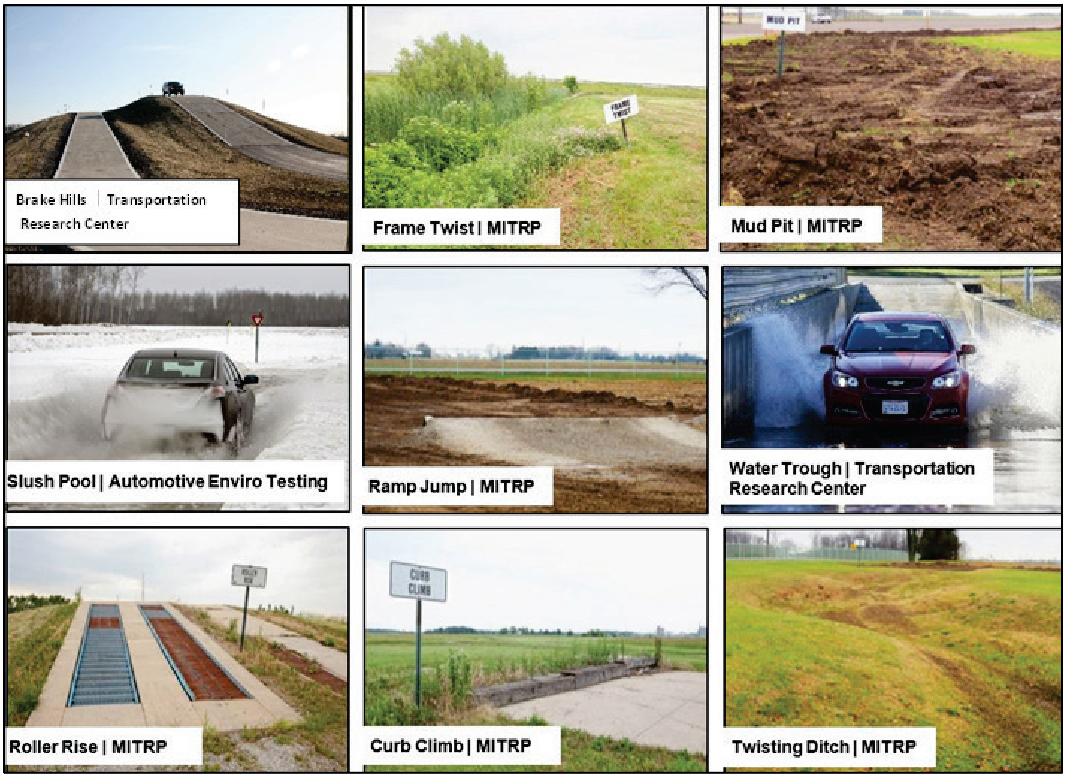
3.1.9 Vehicle Dynamics

Vehicle dynamics features expand upon the challenging environments detailed in the preceding section. Instead of full courses, this category outlines individual attributes made to enhance autonomous sensor and reaction capacity. As in the preceding list, this set of features is traditionally used for testing the abilities of in-vehicle mechanics, such as suspension, braking, and traction. However, they can be adapted for evaluating common off-road or high-intensity situations. The list and photos that follow are physical constructions present at choice test sites in the United States (Figure 56):

1. **Brake hills**—Brake hills are steep graded hills traditionally used to assess brake strength. For autonomy, hills can be used to assess a vehicle's ability to safely navigate hills and make appropriate braking maneuvers based on incline awareness.
2. **Frame twist**—A frame twist consists of a flat riding surface on one side with washboard surface on the other for challenging suspension (MITRP, "Off-Road Courses, n.d.).
3. **Mud pit**—A mud pit creates a soft, wet, and slippery surface used as a low traction off-road scenario.
4. **Slush pool**—A slush pool is a standing water and ice combination for temperature and flooding challenges.

5. **Ramp jump**—This feature is an inclined ramp the vehicle drives on to test the setting of fully loading and unloading suspension on a vehicle (MITRP, “Off-Road Courses,” n.d.).
6. **Water trough**—A water trough is a standing water area to simulate a low-friction or hydroplaning scenario.
7. **Roller rise**—A roller rise is a concrete pad with steel rollers for evaluating axel, brake, and driveline readiness (MITRP, “Off-Road Courses,” n.d.).
8. **Curb climb**—A curb climb is wooden curb structure used to assess suspension and a vehicle’s clearance capabilities (MITRP, “Off-Road Courses,” n.d.).
9. **Twisting ditch**—A twisting ditch is a section of land constructed with an intense twist and depth made to articulate load and unload of each wheel (MITRP, “Off-Road Courses,” n.d.).

Figure 56. Individual off-road experiences can help further enhance off-road capabilities. (Images, *left to right* and *top to bottom*, reproduced with permission from TRC Ohio, “Virtual,” n.d.; MITRP 2013b; MITRP, “Off-Road Courses,” n.d.; Gluckman 2010; MITRP, “Off-Road Courses,” n.d.; TRC Ohio, “News,” n.d.; MITRP 2013c; MITRP 2013a; and MITRP, “Off-Road Courses,” n.d.)



3.2 Obstacles

Obstacles are physical elements that intentionally challenge AV capabilities to recognize real-world occurrences and make appropriate action.

Obstacles are split into three defining categories (Table 3). The first category details stationary objects on the roadway that an AV must recognize and avoid. The second category is moving objects, highlighting the potential spontaneity of objects coming in the drive line in a public setting. The last category is specific to sensor efficiency and tests potentially hazardous blind spot scenarios.

Table 3. Stationary, mobile, and vehicle-sensor obstacles present valid scenarios in which a vehicle must react to avoid potential conflict or danger.

Stationary	Mobile	Sensor
1. Pedestrians	1. Pedestrians	1. Tree cover
2. Soft cars / SSV	2. Cyclists	2. Overpass
3. Road workers	3. Automobiles	3. Tunnel
4. Small children	4. Road workers	4. Buildings
5. Animals	5. Small children	5. Dust and debris
—	6. Animals	6. Graffiti blocking signage
—	7. Soft cars / SSV	7. Variable lighting
—	—	8. Glare source

Note: Strikeable Surrogate Vehicle (SSV) is a test system used to test AEB. It is a carbon target that replicates the rear end of a car. If paired with a towing rig system, it reduces the need to provide a rail and track to operate the target.

3.3 Technology

Technology inputs are made to enhance testing, data collection, site connectivity, and research. The attributes are compartmentalized into five distinguishing categories, including testing, data, traffic scenarios, connectivity, and simulation. Each category calls attention to an individual area of testing; when combined, the categories will produce robust and effective AV development. The inputs are fundamentally important in testing to create and capture innovation.

3.3.1 Testing

Broadly, testing technology refers to systems that advance the site landscape to strengthen AV competence (Figure 57). Other features of testing technology are integrated for testing vehicle readiness on a site:

1. **Weather making systems**—Weather systems are towers that reproduce a desired weather condition for testing the AV. This may include conditions such as artificial snow, rain of varying intensity, and fog.

2. **Controllable lighting**—With the ability to change brightness conditions on the test sites, controllable lighting can successfully recreate variable driving scenarios for AVs to traverse.
3. **Stadium lighting**—A higher intensity lighting system allows for another use condition to test and logistically provides the ability for full day operation of vehicle testing on the site.
4. **Instrumentation for truck platooning**—These provide the necessary mechanisms to facilitate platooning further and diversify autonomy testing to the freight level.
5. **Test vehicles**—A variety of vehicle types with various levels of autonomy and connected technology are offered for diverse testing capabilities.
6. **Energy harvesting**—Energy harvesting can be used to maintain site sustainability. Energy can be collected through solar, for example, and used to power various features or charge vehicles.
7. **Environmental test chamber**—Similar to a weather making system, a test chamber is used for testing controlled and repeatable simulated environmental scenarios. Testing is conducted in an enclosed drivable track setting.

Figure 57. Testing technology features bridge gaps in testing to facilitate enhanced scenarios. The numbers on the images correspond to the list of testing technology provided in this section. (Image in the *top row* was reproduced from Washington State DOT 2016. Images in the *bottom row* were reproduced from [*left*] Choi 2021, and [*right*] Dupre 2023. All images used with permission.)

3.3.2 Data

The data collected in testing procedures are crucial; they allow developers to further refine the capabilities of an AV before deploying it publicly. The attributes that follow are technology inputs used to collect data to better understand an AV's interaction with infrastructure and the roadway:

1. **Smart street lights**—Beyond conventional lighting, smart street lights contain sensors that collect anonymous event data, including information on parking, vehicle counts, cyclists, and weather. This is useful in the AV test environment for surveillance and data performance.
2. **In-pavement sensors**—Pavement sensors allow for feedback on road conditions from the infrastructure to the AV.
3. **Video surveillance and cameras**—Surveillance and cameras can be used effectively during an AV test procedure to actively monitor performance of the vehicle.

4. **Video vehicle detectors**—Video detectors are an aspect of V2X connected technology. It is a system of detecting vehicles and measuring traffic parameters. The detectors operate for large scale data collection and advanced traffic control. The technology can be used for AV guidance, setting the foundation for vehicle tracking (Chintalacheruvu and Muthukumar 2012).
5. **Mobile mapping vehicle and track mapping**—Mapping tools collect a large amount of geospatial data and transform it into intricate 3D models (Trimble, n.d.). Mobile mapping can be useful to help AVs learn an environment using the geo-referenced information of the topography and features (Bonnifait et al. 2007).

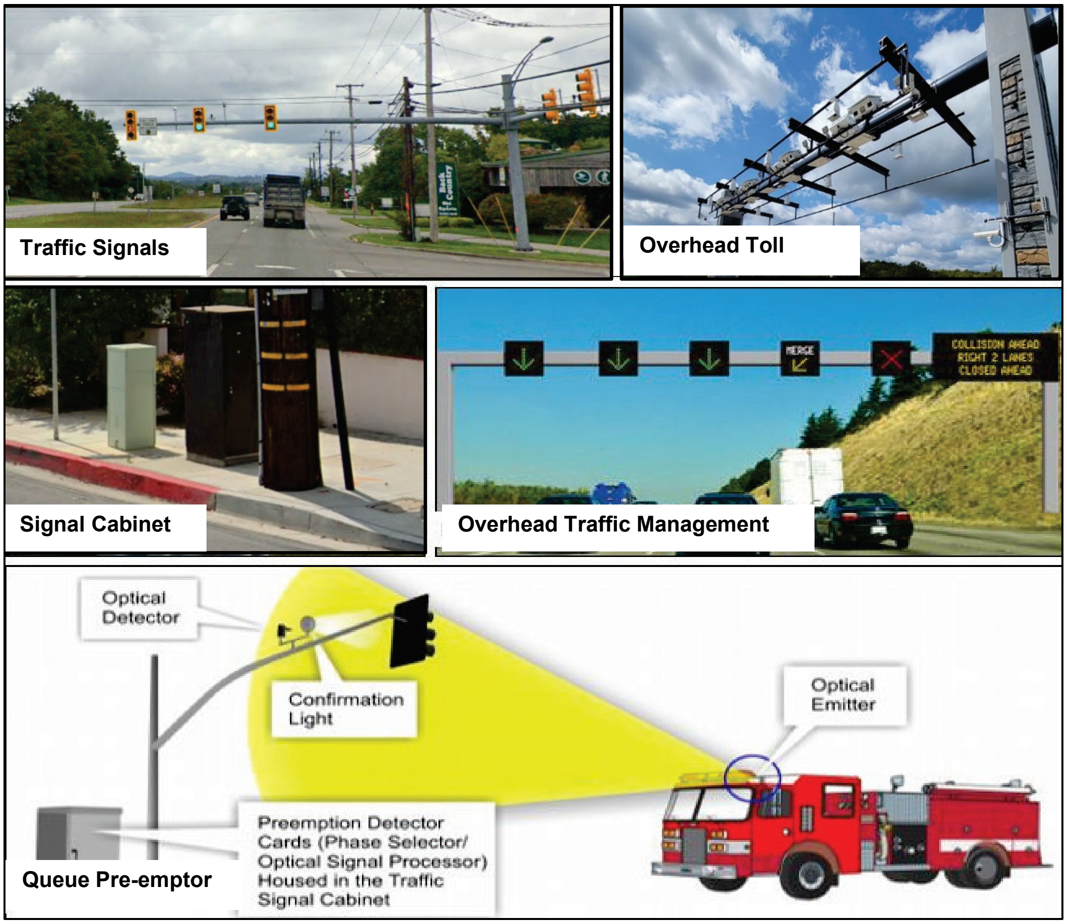
3.3.3 Traffic Scenarios

Technology inputs are abundant on today's public roadways; they serve as a way to guide and manage automobile traffic. Therefore, it is necessary to implement such structures on a test site so AVs can properly recognize and react to these vital signals, which are needed for the safety of passengers and other roadway users (Figure 58). Seven noteworthy traffic-scenario technologies are described in this section:

1. **Toll gantries**—Toll gantries allow for a genuine simulation of a highway environment. AVs must learn to properly interact with this technology, which emits independent signals to recognize the vehicle.
2. **Smart parking**—Smart parking utilizes sensor devices to determine parking occupancy. As the popularity of smart parking increases, it is important to integrate an AV's awareness of the technology to further enhance efficiency.
3. **Traffic signals**—AVs should be able to recognize traffic light meanings and anticipate light changes. Signals can be networked and timed or controlled by devices remotely or through DSRC. A traffic signal cabinet is used as a central source for the technology.
4. **Ramp meter**—Ramp meters aim to regulate the flow of traffic entering a highway and, here, are used to simulate a highway environment. Such interaction with an AV will likely be similar to a traffic light use case.
5. **Overhead traffic management system**—Overhead traffic management systems exist in the public realm; they are electronic boards that provide variable information about upcoming traffic conditions. AVs should be able to assess this signage and make speed or lane change adjustments as directed. This system is also paired with traffic detection systems to supply information to overhead signage.

6. **Queue preemptor**—This technology recreates a unique traffic scenario that temporarily interrupts traffic signals. On public roadways, this instance typically occurs for emergency vehicles or train passages.
7. **Connected work zone**—The simulation of a connected work zone provides an additional dimension of connected vehicle technology. In this case, it is to improve safety and mobility through work zones. An AV must learn to properly respond to incoming data about lane closures, queue lengths, and delay to maximize travel efficiency.

Figure 58. Technology that supports physical traffic scenario infrastructure is vital to AV testing and connectivity. (Images, *left to right* and *top to bottom*, reproduced with permission from Google maps; Pennsylvania Turnpike Commission, n.d.; Google Maps; Washington State DOT, n.d.; and Maricopa Association of Governments, n.d.)



3.3.4 Connectivity

Connected vehicle technologies are pivotal in the era of automated vehicles. Connectivity allows vehicles to communicate with their surroundings and, conversely, allows surroundings to “talk” to the vehicle. Such connection provides a gateway for the exchange of useful safety and mobility information. The list that follows describes broader connected technologies and those features that support the overall connectivity mission:

1. **DGPS**—DGPS provides positional corrections to GPS signals using a fixed, known position to adjust GPS signals, eliminating error present in the range between the satellite and GPS system (Racelogic Limited 2018).
2. **RTK**—Similar to DGPS, RTK is used to increase the accuracy of traditional GPS by using a fixed base station that sends out corrections to the moving receiver (VBOX Automotive, n.d.).
3. **DSRC**—DSRC is a high speed wireless technology for secure communication between vehicles and infrastructure.
4. **The mmWave wireless communication system**—Operating at a near-millimeter wavelength, mmWave allows detection of objects that larger waves are unable to recognize, and it provides enhanced direction detection. These attributes help AVs to swiftly determine optimal action.
5. **Connected vehicle wireless roadside devices**—Roadside devices are the physical equipment feature that is used to send messages to and receive messages from wireless communication technologies such as DSRC (DOT, "Connected Vehicle," n.d.).
6. **Fiber optics network**—Fiber optics refers to the technology associated with the transmission of information through pulses in strands of fiber (English, n.d.). The technology is common in smart city applications and is used to connect features and move data. AVs will need to integrate into smart city systems that enhance communication to and from the vehicle.
7. **5G network**—Widespread adoption of the next generation wireless technology is largely viewed as necessary for breakthroughs in AV technology. It has the capability to support the speed needed to transmit a message from sensors through the in-car software and out as a decision in less time than a human could (i.e., around two milliseconds; Llanasas 2019).
8. **4G LTE network**—The geographic dominance of 4G LTE makes it a vital technology for operating AVs in the short term while 5G technology continues to emerge.
9. **V2V connectivity**—V2V communication allows vehicles to exchange information about their speed, location, and direction via a wireless connection. The technology allows for heightened awareness of the driving environment, utilizing the messages to evaluate threats and send alerts to other drivers (NHTSA, n.d.).
10. **V2I connectivity**—V2I technology allows vehicles and external systems to exchange information regarding safety, mobility, and the environment via a wireless connection (DOT, "Vehicle-to-Infrastructure," n.d.). The

infrastructure captures vehicle and environment data and uses them to send signals to drivers.

11. **V2X connectivity**—V2X encompasses all connected vehicle technologies, allowing vehicles to communicate with all aspects of a traffic system using short-range wireless signals (Segal 2020). V2X connectivity is used to alert drivers to inclement conditions for the purpose of enhancing safety.
12. **CV2X connectivity**—CV2X technology achieves the communication aspects of standard V2X in providing real time information beyond the driver's line of sight. However, instead of relying on roadside devices, CV2X utilizes the existing cellular infrastructure (GSMA, n.d.).
13. **EMI technology**—EMI technology creates an intruding signal at the signal receiver (Electronics Notes, n.d.). This technology can be used in testing to cut signal to the AV so it must learn to find its way independently.
14. **Open source API**—Broadly, an API is a structure that allows applications to communicate with each other (Eising 2017). An open API makes aggregate data publicly available to be used in a different application. At an AV testing facility, these data can be used to control testing applications throughout the whole facility (see Mcity, Section 2.18).
15. **Uninterruptible power supply (UPS)**—This is an electrical device that provides backup emergency power when a regular power source fails or voltage drops significantly (Archtoolbox, n.d.). It can provide greater reliability to electric inputs of site features and the physical vehicle itself.
16. **Underground power distribution**—Underground power distribution provides a clean and seamless transfer of electricity from given substations to site features. Additionally, it allows for a cleaner overall landscape to reduce interference from site operations. This distribution method also upholds the ideal of resilience remaining vastly unaffected by inclement weather, offering longer effective life, and generally low maintenance cost over operation (Khuram, n.d.).

3.3.5 Simulation

Simulation is a vital process in the development of automated vehicle technology. Simulation provides a safe environment to test both hardware and software elements before on-road testing. A variety of components are included when developing a successful simulation interface. Flexibility is emphasized because it allows individual testers to edit scenarios as they see fit. Visual, audio, and dynamic technologies help to create scenarios that directly mimic features of a real driving environment. The list that follows discusses technologies that are essential for simulations:

1. **Platform for testing algorithms**—A platform for algorithm testing provides hands-on experience and trials with minimal risk.
2. **Sensor test chamber**—A sensor test chamber is an individual vehicle chamber for testing controlled and repeatable scenarios. The chamber allows the AV's sensors to be challenged under manufactured rain, lighting, smoke, fog, and dust conditions (SunTrax 2019).
3. **Digital twin simulator**—A digital twin simulator is an application that allows test driving in the simulated environment of a test site. With this, third parties can develop and test functions and script their own scenarios without being physically present at a given site GoMentum Station, n.d.).
4. **Dome simulator with vehicle cab**—Dome simulators provide an ideal simulation environment with 360 degree display and surround sound audio. A dome can provide noteworthy degrees of motion or operate on a fixed base, depending on testing need or scenario (University of Iowa, "National Advanced," n.d.).
5. **Custom graphic software**—Graphic software is useful in a simulation environment for optimal quality and continuous image display. It can utilize a library of realistic driving environments for testing. When paired with high resolution projection, AV technology may be effectively challenged in various driving situations.
6. **Audio system**—An audio system simulates real-world traffic features that are connected with vehicle behavior. Audio enhances vehicle reaction and understanding in varied public environments (University of Iowa, "National Advanced," n.d.).
7. **Vibration production**—By reproducing vibration events, AVs can associate with driving on varied road surfaces.
8. **Simulation software**—An effective simulation software may feature open architecture where systems can communicate with each other using a published interface. Maintaining flexibility in architecture allows for integration of third-party systems, enhancing the ability to fit the testing needs of a client (University of Iowa, "National Advanced," n.d.).
9. **Portable simulator**—A portable high-performance simulator provides an easily accessible, and likely more affordable, simulation model. The flexibility in cab configuration provides testing entities with approaches that replicate their desired AV layout (University of Iowa, "National Advanced," n.d.).
10. **ISAT**—ISAT is a user friendly software tool that provides a graphical interface where researchers can develop their own scenarios based on their testing needs. The interface allows for the execution of scenarios for testing

and debugging. The tool also supplies the replay of data collection for further verification and analysis (University of Iowa, *NADS*, n.d.).

11. **Library of realistic driving environments**—Realistic driving environments are fed to simulation displays to test a vehicle's capabilities before public deployment. Scenarios can include, but are not limited to, the following environments:
    - Urban
    - Suburban
    - Rural
    - Interstate
    - Day conditions
    - Night conditions
    - International roadways
    - Controlled intersections
    - Uncontrolled intersections
    - Roundabouts
    - Signage inputs
    - Traffic light inputs
    - Dry conditions
    - Wet conditions
    - Snow conditions
12. **Library of driving models**—Simulations providing many vehicle models allow researchers to understand various components and challenges to different vehicle types. Driving models can include, but are not limited to, the following:
    - Standard automobiles
    - Trucks
    - Construction equipment
    - SUVs
    - Vans
    - Utility vehicles
13. **Scenario packages**—Scenario packages may be referred to as a set of scenarios fed to a simulation that are designed to evaluate and test driver behavior. Scenarios may include but are not limited to the following:
    - Vehicle following
    - Intersection navigation
    - Yellow light dilemmas
    - Driver impairment direction

3.4 Support Services

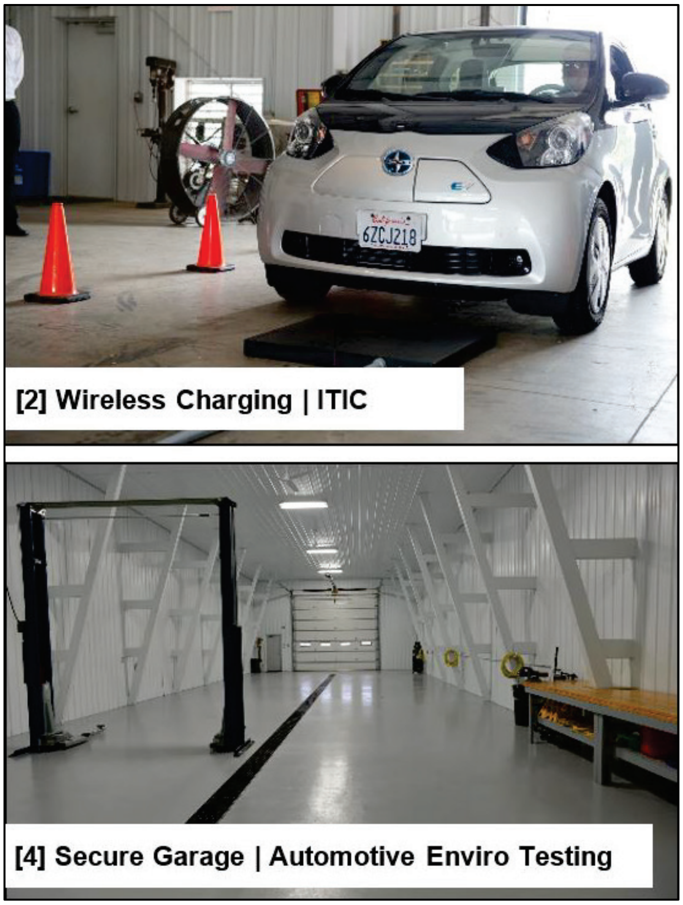
Support services are additional services on a test site that aid in vehicle testing, research, and general client support. For the purposes of this technical report, features are placed in three categories of analysis: vehicle; education, communication and logistics; and R&D. Each feature category aids in facilitating a comprehensive understanding of the many elements that contribute to AV development and testing.

3.4.1 Vehicle

Vehicle features here insightfully refer to attributes that directly assist in the welfare and security of a vehicle on site. This subcategory highlights items that are commonly used in a conventional vehicle setting yet still offer needed support to advance the testing mission of AVs (Figure 59):

1. **Fueling stations**—Fueling stations will benefit readiness for traditional vehicles that have been retrofitted with AV technology and for dynamic site features.
2. **Electric vehicle charging**—Both conventional and wireless on-site electric charging enhances vehicle readiness for testing.
3. **Vehicle lifts**—A lift is beneficial to effectively conduct needed vehicle or sensor maintenance.
4. **Secure garage spaces**—Secure garage spaces benefit testing accessibility by providing a secure facility for entities to store their vehicle(s) and their associated equipment.
5. **Scale**—A scale feature can be used, for example, to simulate weighing events for freight platoons or for basic maintenance purposes.
6. **Fabrication shop**—A fabrication shop provides the on-site ability to create machines, parts, and structures that are needed for AV advancement.
7. **Machine shop**—In a machine shop, parts are cut, fabricated, and finished to prepare for use.
8. **Maintenance facility**—A maintenance facility is an area with qualified materials and equipment to provide servicing to vehicles being tested.
9. **Customer work spaces**—Work spaces can provide a secure place exclusively for testing entities to make needed adjustments to their AV on site.

Figure 59. Vehicle support services provide critical functions to prepare and sustain the AV for testing. The numbers on the figures correspond to entries in the list of vehicle features provided in this section. (Images reproduced with permission from [*top*] ITIC 2015 and [*bottom*] AET, "Garages," n.d.)



3.4.2 Education, Communication, and Logistics

This subcategory defines services that specifically support the client. The resources listed largely include spaces for collaboration or dissemination of findings to interested parties. Others inform the safety and security of the track and its operations. They are as follows:

- Classrooms
- Office spaces
- Warehousing
- Trackside offices
- Conference rooms
- Welcome center
- Indoor event spaces
- Outdoor event spaces
- Emergency services
- Auditorium education center
- Cold storage warehouse
- Security system

3.4.3 Research and Development (R&D)

R&D services focus on facilities that help researchers develop and test specific functionalities in a closed environment. Many R&D services exist as laboratories providing the needed equipment and staff to maximize efficiency. Other services allow individuals to observe various conditions. The location of these resources is vital because services should be accessible to the track and vehicles. In this manner, new developments can be quickly tested on the road, adjusted, and tested again as needed, reducing unnecessary delays in innovation. The R&D services offered are as follows:

1. **Crash safety research facility**—This facility examines crash-related injuries and occupant safety matters, analyzes vehicle and highway apparatus design and testing, and evaluates vehicle interactions with road features (LTI, "Crash Safety," n.d.).
2. **Dummy and instrument calibration laboratory**—The instrument calibration laboratory is responsible for calibrating dummies, sensors, and equipment to support testing throughout the site (University of Wisconsin–Madison and MGA Research Corporation 2016).
3. **Component test laboratory**—A component test laboratory is primarily used to test facets of individual vehicle components, typically for fatigue or durability.
4. **Crash and sled laboratories**—Crash labs conduct high impact crash testing. This is useful in the AV context to evaluate a AVs ability to deploy needed safety protections, for example.
5. **Corrosion chambers**—Corrosion chambers are used to test how corrosion affects a product. In an AV context it services may be utilized to assess sensor and camera durability, for example.
6. **Cold cells**—Cold cells refer to large holding areas that produce extremely low temperatures. Again, in an AV context this can be to assess sensor and camera durability in adverse conditions.
7. **Workshop buildings**—A workshop building is general feature facility for clients typically made up of vehicle bays with tools available for maintenance or repairs on their AV.
8. **Cybersecurity testing laboratory**—A cybersecurity lab allows researchers to hack vehicles in controlled conditions and analyze security threats (Lawrence 2017).
9. **Instrumentation facility**—An instrumentation facility is an area devoted to providing advanced modern vehicle research equipment for shared use.

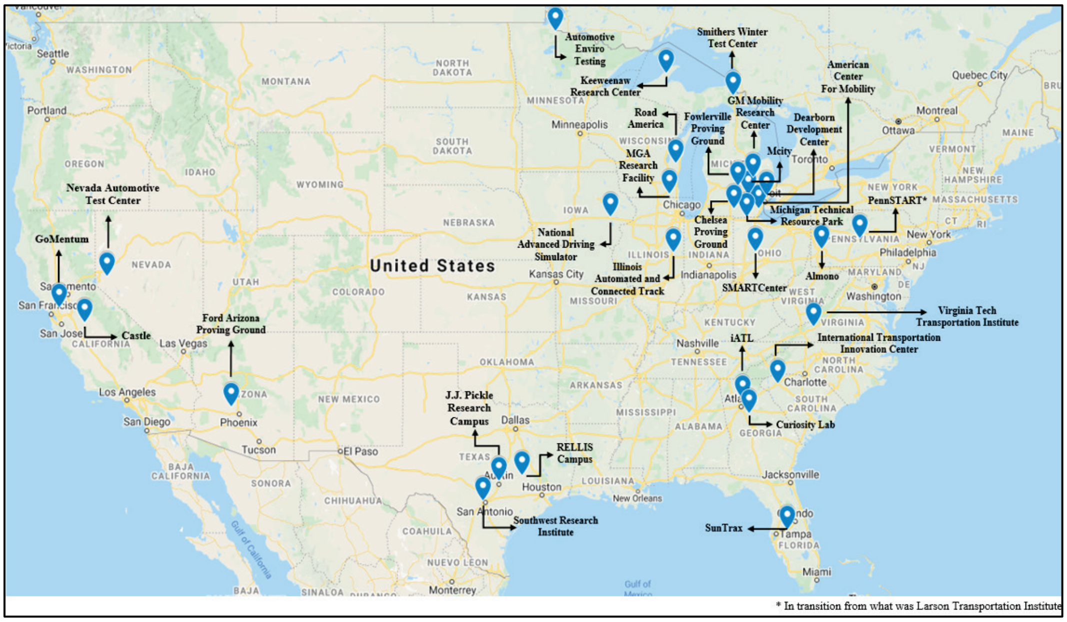
10. **Indoor virtual simulation laboratory**—A simulation lab is a space providing necessary equipment, hardware, and software inputs to test AV technologies in a predictable, safe environment before deploying on a test track. A virtual simulation of a given testing environment can help to reveal gaps in an AV's operation capabilities allowing R&D teams to make changes before public road operation.
11. **Scaled indoor vehicle test facility**—A scaled testing facility offers defined ratio scaled AVs that host sensors and computing hardware comparable to real cars. The main benefits of scaled testing are safety, affordability, and independence from regulation (Rupp et al. 2019)
12. **Command center**—A command center facilitates multiple resources for entities and researchers in one location. Resources may include control of on-site communication technologies and operations, general observation and monitoring, and test vehicle support.

4 Conclusions and Recommendations

4.1 Conclusions

In this technical report for the Autonomous Transportation Innovation Project, 30 known sites used to test AVs in the United States were thoroughly reviewed (Figure 60). Individual site features were then detailed and further analyzed to determine their productive use toward developing autonomous driving technology. With this information, a comprehensive understanding of infrastructure, specific features, and technology used by the industry to effectively test AVs was produced. The research conducted advances future decision-making related to site requirements.

Figure 60. Map of the commercial AV test sites covered in this report, showing the trend of being located in areas in which automobile manufacturing companies are well established and in hubs of technological innovation. (Image was modified from Google Maps.)



* In transition from what was Larson Transportation Institute

It quickly became evident that many of the AV testing locations are centered in and around Michigan. This is likely due to the area's long-standing history as an automotive manufacturing hub for the United States. Besides being the epicenter for automotive R&D, the region's natural environment is conducive to productive AV testing. Most of the cluster is located in a four-season climate, allowing researchers to test in various weather situations throughout the year. As one travels farther north, there is a greater emphasis on extreme winter and cold weather capabilities.

Many of the remaining sites trend toward another notable hub of assembly plants in the southern region of the United States. These locations undoubtedly benefit from the weather conditions, which provide fewer uncertainties. However, this may also be seen as a limitation because it can provide a false sense of progress. Autonomous systems need to be challenged by varying conditions. In addition to these weather benefits for initial test procedures, the West also supplies vast open land for safe testing. California is noteworthy for its influential role as a technology hub with a booming startup culture.

Fort Leonard Wood, in Missouri, is a focal point for the development of a military AV testing site under the Autonomous Transportation Innovation research project. The installation is prominent in this sector because it is home to the 58th Transportation Battalion, which operates the Army Motor Transport Operator Course. The military generally has a strong interest in enhancing off-road capabilities due to the unpredictable terrain in deployed areas. The geography at the installation is well suited for adapting to the variety of off-road features discussed. Fort Leonard Wood, however, will likely not be able to naturally produce intense snow or ice features due to its temperate climate. However, it contains unique features to simulate such conditions. Also, its setting on a military installation means that risk aversion and security are elements that must be considered. It is likely the installation will not allow interference technology to intentionally block the signal to the vehicle.

Two defining site typologies emerged from the research. The first type encompassed sites that were originally developed for the testing of conventional vehicles. The goal of these courses and their associated features was to examine the efficacy of certain mechanics for the safe operation of the vehicle. The second type included those sites that were developed specifically for AV testing. The mission of these facilities was to test if the vehicle could complete a given operational task. While they were equally focused on the safety of drivers, passengers, and other roadway users, dedicated AV testing sites focused more on software performance for sensing and reaction to produce a desired maneuver than on performance of overall vehicle mechanics.

As technology has advanced to provide automated features in vehicles, conventional test sites have begun to adapt to these changing needs. As a result, many of these sites offer unique capabilities to AV testing that are typically not available at those locations originating exclusively for autonomous testing. Sites developed specifically for AVs are most commonly constructed to fit flat urban, suburban, or highway scenarios. Meanwhile, sites originating for conventional vehicle testing have more extreme scenarios of elevation change, challenging curves, or rough road experiences, for example. Thus, it can be especially useful for off-road autonomous testing, where more R&D is needed to maximize capabilities. Contrarily, conventional vehicle sites may still be limiting in some respects and may not have the ability to expand in constructing urban simulations, for example.

4.2 Summary of Findings

The bottom line for site development is that it should recreate scenarios that simulate real-world environments. A flexible space and comprehensive set of features is desirable to help achieve the needs of the customer or testing entity. The most effective sites exploit technology features for data collection, vehicle connectivity, and overall site operation.

Among the 30 facilities reviewed, five track settings were the most cited: urban, suburban, high speed or highway, rural, and off-road. The urban and suburban arenas are typically low-speed traditional grid structures that include additional features that mimic the environment, such as intersections, street signage, lane markings, crosswalks, and building structures. This track setting is vital in AV development because, compared to an open highway, it is an environment with many moving parts and vulnerabilities. A highway or high-speed setting can be maintained through vehicle ovals, straightaways, or other constructed road networks with extensive space to reach the desired speed. Twenty five facilities support this setting to some extent. Infrastructure to accommodate AV interactions in this environment include toll gantries, overhead traffic management systems, and on and off ramps. Rural road constructions typically deliver roadway deterioration with no definitive shoulder or curb. Conversely, off-road testing environments provide unpredictable and high intensity topography. Rural or off-road settings challenge sensor perception and resulting navigation decisions in a unique environment that lacks many of the visual cues that AVs rely on for operation. Table 4 details the popular settings and track configurations that are available (marked in red) at each site that was reviewed.

Table 4. Settings and track configurations available (marked in *red*) at the 30 sites reviewed in this research.

	Setting				Track Configuration			
Site Name	Urban	Sub-urban	Rural	Off-Road	High speed	Circle	Oval	Straight-away
Almono	🟥	🟥			🟥			
American Center for Mobility (ACM)	🟥		🟥		🟥			
Automotive Enviro Testing (AET)				🟥	🟥	🟥	🟥	
Castle	🟥				🟥		🟥	🟥
Curiosity Lab	🟥							
Fiat Chrysler Chelsea Proving Grounds					🟥	🟥	🟥	
Ford Arizona Proving Ground				🟥	🟥	🟥	🟥	🟥
Ford (Dearborn) Development Center					🟥			🟥
Fowlerville Proving Ground	🟥		🟥		🟥		🟥	🟥
GM Mobility Research Center / Kettering University					🟥		🟥	🟥
GoMentum Station	🟥		🟥		🟥			
Illinois–Automated and Connected Track (I-Act)	🟥	🟥			🟥	🟥	🟥	
Infrastructure Automotive Technology Laboratory (iATL)								
International Transportation Innovation Center (ITIC)	🟥			🟥	🟥			🟥
J. J. Pickle Research Campus / University of Texas	🟥							
Keweenaw Research center (KRC) / Michigan Technological University				🟥	🟥	🟥		🟥
Larson Transportation Institute (LTI)					🟥		🟥	
Mcity / University of Michigan	🟥	🟥	🟥		🟥			🟥
MGA Research Facility				🟥	🟥			
Michigan Technical Resource Park (MITRP)				🟥	🟥		🟥	🟥
National Advanced Driving Simulator (NADS) / University of Iowa	🟥	🟥	🟥	🟥	🟥			
Nevada Automotive Test Center (NATC)				🟥	🟥			
Pennsylvania Safety Transportation and Research Track (PennSTART)	🟥		🟥		🟥		🟥	
RELLIS Proving Grounds Research Facility / Texas A&M University	🟥		🟥		🟥			
Road America				🟥	🟥			🟥
Smart Mobility Advanced Research and Test (SMART) Center	🟥	🟥	🟥					🟥
Smithers Winter Test Center (SWTC)					🟥	🟥		
Southwest Research Institute (SwRI)				🟥	🟥			
SunTrax	🟥	🟥			🟥		🟥	🟥
Virginia Tech Transportation Institute (VTTI) Smart Roads	🟥	🟥	🟥	🟥	🟥			

To maximize situational diversity, low-friction surfaces, including water, ice, and snow, are highly utilized. Split friction surfaces are also noteworthy additions. In places where the events do not occur authentically or are not situationally available, weather events can be simulated using underground sprinklers or weather making machines. An active fall of precipitation or snow can provide additional vehicle sensor and camera challenges. Gravel is also a significantly crafted surface variation. The characteristic of loose rock provides an unsteady topography for AVs to traverse. Dirt tracks can have similar effects and may also produce dust for potential sensor obstruction pursuits. Potholes and faded lane markings are useful inputs to present common road imperfections that may skew perception. Other surface features, including varying grades or banking, challenge vehicle navigation due to the limited sight distance created. Table 5 contains a list of the unique surface scenarios available at each of the 30 AV sites reviewed for this research.

Table 5. Unique surface scenarios that are available (marked in *red*) at the 30 sites reviewed in this research to enhance AV operating capabilities.

Site Name	Surface Scenarios/Terrain							
	Water	Ice	Snow	Gravel	Asphalt	Dust conditions	Split Friction (μ)	Dirt
Almono								
American Center for Mobility (ACM)	🟥	🟥	🟥	🟥	🟥			🟥
Automotive Enviro Testing (AET)		🟥	🟥		🟥		🟥	
Castle								
Curiosity Lab								
Fiat Chrysler Chelsea Proving Grounds				🟥				
Ford Arizona Proving Ground						🟥		🟥
Ford (Dearborn) Development Center				🟥				
Fowlerville Proving Ground	🟥	🟥	🟥	🟥	🟥			
GM Mobility Research Center / Kettering University	🟥							
GoMentum Station								
Illinois–Automated and Connected Track (I-Act)								
Infrastructure Automotive Technology Laboratory (iATL)								
International Transportation Innovation Center (ITIC)					🟥			
J. J. Pickle Research Campus/University of Texas								
Keweenaw Research Center (KRC) / Michigan Technological University		🟥	🟥	🟥			🟥	🟥
Larson Transportation Institute (LTI)								
Mcity / University of Michigan				🟥				
MGA Research Facility	🟥			🟥				
Michigan Technical Resource Park (MITRP)	🟥	🟥	🟥	🟥	🟥			🟥
National Advanced Driving Simulator (NADS) / University of Iowa	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
Nevada Automotive Test Center (NATC)	🟥			🟥		🟥		
Pennsylvania Safety Transportation and Research Track (PennSTART)	🟥							
RELLIS Proving Grounds Research Facility / Texas A&M								
Road America								🟥
Smart Mobility Advanced Research and Test (SMART) Center					🟥			
Smithers Winter Test Center (SWTC)		🟥	🟥		🟥		🟥	
Southwest Research Institute (SwRI)				🟥				🟥
SunTrax	🟥					🟥		
Virginia Tech Transportation Institute (VTTI) Smart Roads	🟥		🟥					

Test pads generally refer to a large section of paved open space to be used for maneuver testing. Test pads are readily adaptable to the fast pace at which technologies are developing because they can be customized to meet specific testing needs. Test pad variations include water, ice, or snow. They may also be designated as skid pads meant to test handling maneuvers.

Vulnerability is especially pertinent in urban situations with increased traffic density and a higher overall likelihood of unpredictable driver behavior. These situations can be simulated for AV interaction planning and observation using physical vehicles with conventional drivers or with guided soft target (GST) vehicles. GSTs are made to look like a normal car using foam materials with the radar signature of a regular car (Nguyen 2019). It is also important to account for other modes of transportation, such as pedestrians or cyclists, that may present themselves in a public environment. Outside of traditional awareness, the AV must anticipate and react to spontaneous scenarios such as people walking or riding against a signal or being cutoff. These tasks can be replicated in a testing environment using real persons or dynamic mannequins.

There is a noticeable priority in implementing public road features to maximize necessary operating capabilities. Navigating traffic lights and signage, for example, are common operating scenarios. Basic traffic skills are further enhanced with the relatively low-cost element of road markings to promote lane keeping and direction understanding. Road markings can be used to assist in the construction of public road features such as intersections, roundabouts, and parking infrastructure. Table 6 lists the public road features available at each of the 30 sites reviewed for this study.

Prior to physical testing on a driving course, virtual simulation is a feasible step for evaluating AV operating algorithms in a no-risk setting. The technology allows a testing entity to develop and use a multitude of scenarios or interactions. Also, vehicles have become more connected to the environment around them through data sharing functions, including V2I, V2V, and V2X. Technology to support this innovation is more commonly found in sites developed exclusively for autonomous use. As a foundational feature, several sites provide high speed data connections at 4G or 5G levels. Many boast the use of DSRC, a wireless communication technology that enables vehicles to communicate with each other and with the surrounding infrastructure. This function is often maintained by physical roadside devices used to receive and transmit communications.

Table 6. Public on-road inputs that are available (marked in *red*) at the sites reviewed for this research and can be used to fortify a testing environment that simulates real-world events.

Site Name	Public On-Road Inputs			
	Parking	Traffic Signage	Intersections	Roundabout
Almono		🟥	🟥	🟥
American Center for Mobility (ACM)		🟥	🟥	🟥
Automotive Enviro Testing (AET)	🟥			
Castle	🟥	🟥	🟥	🟥
Curiosity Lab		🟥	🟥	
Fiat Chrysler Chelsea Proving Grounds				
Ford Arizona Proving Ground				
Ford (Dearborn) Development Center				
Fowlerville Proving Ground			🟥	
GM Mobility Research Center / Kettering University				
GoMentum Station		🟥	🟥	
Illinois–Automated and Connected Track (I-Act)		🟥	🟥	🟥
Infrastructure Automotive Technology Laboratory (iATL)		🟥	🟥	
International Transportation Innovation Center (ITIC)		🟥	🟥	
J. J. Pickle Research Campus / University of Texas	🟥			
Keweenaw Research center (KRC) / Michigan Technological University				
Larson Transportation Institute (LTI)		🟥		
Mcity / University of Michigan	🟥	🟥	🟥	🟥
MGA Research Facility				
Michigan Technical Resource Park (MITRP)				
National Advanced Driving Simulator (NADS) / University of Iowa		🟥	🟥	🟥
Nevada Automotive Test Center (NATC)	🟥	🟥		
Pennsylvania Safety Transportation and Research Track (PennSTART)	🟥		🟥	🟥
RELLIS Proving Grounds Research Facility / Texas A&M University		🟥	🟥	
Road America				
Smart Mobility Advanced Research and Test (SMART) Center		🟥	🟥	🟥
Smithers Winter Test Center (SWTC)				
Southwest Research Institute (SwRI)			🟥	
SunTrax		🟥	🟥	🟥
Virginia Tech Transportation Institute (VTTI) Smart Roads	🟥	🟥	🟥	🟥

To make continued improvements to vehicle technology, it is important for sites to provide services that support their mission and the needs of the customer. Over 30% of the locations reviewed have some form of laboratory for R&D purposes. This allows tests to be conducted for individual features or components. Similarly, some form of workshop facility with appropriate vehicle tools is useful to make needed adjustments while on site. Offices allow for collaboration space and support for basic facility operations. Garages provide safe and secure storage for a customer's vehicle in between tests.

4.3 Recommendations

The sites reviewed individually possess a strong network of affiliations. This is crucial for entities to stay competitive in the AV era, which is characterized by fast innovations in technology. Affiliations for autonomous operations commonly come from educational entities, private sector developers or manufacturers, and various transportation agencies. Partnerships are mutually beneficial because they provide consistent information sharing, research, and development. Additional funding benefits can be helpful for moving progress forward. In the military context, establishing agreements with other DoD or federal agencies might be the most efficient channel for enhancing the Army's internal capabilities.

To further the advancement of AV testing in a military setting, mission-related AV scenarios should be thoroughly investigated. Then, specific operating capabilities required to complete the identified task can be determined. The necessary operating capabilities should then be paired with features, technology, and infrastructure to produce a testing course. In this manner, the course will be designed intentionally, for the specific needs and challenges of an AV to complete mission requirements while upholding safety and avoiding unnecessary risk.

Additionally, a greater emphasis needs to be placed on cybersecurity during testing phases (Hodge et al. 2019). Facilities should be equipped with technology that recreates hacking events or information interception between connected devices. This will allow developers to observe, prepare for, and mitigate risk. Such testing is vital in the military context, where hacking events could be detrimental to mission success or national security. To address current security restrictions on military installations, additional infrastructure that isolates AV technologies and permits hacking or jamming events that do not interfere with nearby military systems and operations should be built.

Throughout the research period, it was apparent that testing facilities are quickly adapting to new technologies and the changing needs of AVs. It is important, however, to anticipate impending advances in the driving landscape itself. By incorporating such advances into testing infrastructure, entities can address new developments and stay competitive. Things to consider include the likely reduction in parking needs, less private vehicle ownership, and traffic signage and signals becoming obsolete. Remaining flexible is key to staying viable as testing continues.

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Abbreviations

ACM	American Center for Mobility
ADAS	Advanced driver-assistance system
AEB	Autonomous emergency braking
AET	Automotive Enviro Testing
API	Application programming interface
AV	Autonomous vehicle
CAV	Connected and automated vehicle
CRREL	Cold Regions Research and Engineering Laboratory
CV2X	Cellular vehicle-to-everything
DGPS	Differential GPS
DSRC	Dedicated short-range communications
GM	General Motors
GST	Guided soft target
I-ACT	Illinois–Automated and Connected Track
iATL	Infrastructure Automotive Technology Laboratory
ISAT	Interactive Scenario Authoring Tool
ITIC	International Transportation Innovation Center
ITS	Intelligent transportation systems
KRC	Keweenaw Research Center
LCD	Liquid crystal display
LTI	Larson Transportation Institute
MITRP	Michigan Technical Resource Park

mmWave	Millimeter wave
NA	Not applicable
NADS	National Advanced Driving Simulator
NATC	Nevada Automotive Test Center
NHTSA	National Highway Traffic Safety Administration
PennSTART	Pennsylvania Safety Transportation and Research Track
R&D	Research and development
RTK	Real-time kinematic
SAE	Society of Automotive Engineers
SIPRE	Snow, Ice, and Permafrost Research Establishment
SMART	Smart Mobility Advanced Research and Test
SSV	Strikeable Surrogate Vehicle
SwRI	Southwest Research Institute
SWTC	Smithers Winter Test Center
TRC	Transportation Research Center
UPS	Uninterruptible power supply
VRTC	Vehicle Research and Test Center
VTTI	Virginia Tech Transportation Institute
V2I	Vehicle-to-infrastructure
V2V	Vehicle-to-vehicle
V2X	Vehicle-to-everything

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14. ABSTRACT

Connected and autonomous technologies are valuable to the Army because of their recognized potential to reduce the number of personnel exposed to threats in forward operations. The successful integration of such technologies has the potential to reduce Soldier deaths and injuries. Automation of routine tasks can also allow warfighters to focus their time on more strategic efforts. Furthermore, a reduction in manpower is expected to proportionally reduce energy use and material supply and resupply demands while bolstering resilience. To achieve these benefits, the reliability, safety, and utility of connected and autonomous systems must be successfully demonstrated in a variety of conditions before widespread adoption. Therefore, the Army needs a realistic testing environment to develop, test, and evaluate emerging technologies. This environment and its supporting infrastructure should provide a variety of terrain, functional areas, and power scenarios and should be able to demonstrate the viability of connected and autonomous technologies on an operational scale. The primary objective of this research was to survey US commercial facilities associated with autonomous vehicle development, testing, and evaluation.

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