Designation of Purdue University's Automated Vehicle Proving Ground

Mandatory Criteria

- A Designated Safety Officer responsible for the entity's safety management plan and who will participate in the Community of Practice's regular quarterly meeting of Safety Officers.

Upon receiving designation as a USDOT Automated Vehicle Proving Ground, Purdue will identify a Designated Safety Officer (DSO) who will participate in all Community of Practice safety meetings.

- Commitment to sharing the entity's approaches to safety and safety data generated through testing and operation.

Purdue is committed to sharing best-practice safety approaches and generated safety data as demonstrated in our participation in the three-year ARPA-E NEXTCAR program. The NEXTCAR collaboration with Cummins, Peloton Technologies, Peterbilt, and ZF TRW will develop connectivity/autonomy-enabled fuel savings in Class 8 trucks, specifically via remote powertrain component re-calibrations, cloud-based control, and more efficient two-truck platooning. This effort will include real-world testing with Class 8 trucks. Purdue will work with partners to develop safety procedures for the real-world testing with Class 8 trucks and draw on the significant experience of Cummins, Peterbilt, and Peloton for an accelerated learning process. Both Cummins and Peloton have developed connectivity- and autonomous operation-enabled fuel saving engine and vehicle control strategies that have been tested extensively on both tracks and highways. As such, Purdue and its partners will be at the cutting edge of testing connected and automated vehicles (CAVs). Purdue and its partners would welcome the opportunity to share with the Community of Practice the approaches to safety and safety data generated through our testing and operations during the NEXTCAR program.

The Purdue DSO will be responsible for documenting and managing Purdue's Automated Vehicle Proving Grounds (PAVPG)-related approaches to safety and will manage our efforts to share safety data generated through testing and operation. The DSO will help integrate NEXTCAR and PAVPG safety best practices and data through a new Connected and Autonomous Transportation (CAT) Hub (CAThub) that will leverage the novel HUBzero® open source software platform for scientific collaboration developed at Purdue and highlighted by the National Science and Technology Council as an exemplar for open innovation and advanced computational tool development.

Proposed Contributions

- The extent to which the applicant meets the above eligibility and administers an established automated vehicle program, either independently or through a partnership.
- The capability of the applicant to provide leadership in making national and regional contributions to the solution of both long-range and immediate mobility challenges through the testing and deployment of automated vehicle technology.
- The applicant's proposed contributions to the Community of Practice.

Purdue proposes a multi-pronged approach for PAVPG that establishes novel, state-of-the-art infrastructure; ensures research and administrative expertise; and integrates stakeholder vision and investments:

1) Purdue and the Indianapolis Motor Speedway (IMS) are developing a partnership to work together for the testing of autonomous vehicles at the IMS facilities in Indianapolis, Indiana, in order to explore ways to leverage autonomous technology for better safety in motorsports.
2) We have identified a 1.5-mile oval adjoining Purdue's West Lafayette campus for potential development of CAT testing and operations capabilities over the next year.
3) Purdue is collaborating with an industry-led consortium (Transportation Research and Development District Consortium) to develop a long-term plan for building various infrastructure for automated, autonomous, and connected transportation capabilities in the vicinity of the Purdue campus on a much-larger scale. This public-private partnership involving Purdue University, private sector firms and entities, and the State of Indiana will develop niche and specialized CAT capabilities through its long-term infrastructure development plan.

Importantly, the proposed PAVPG will build on and further integrate two recent automated vehicle efforts at Purdue University—the newly awarded Region 5 USDOT **Center for Connected and Automated Transportation (CCAT)** and the ARPA-E **NEXTCAR** program—as well as substantial CAT-related research conducted through the current Purdue-led Region 5 UTC, the **NEXTRANS** Center. These programs are clear demonstrations of Purdue's national and regional transportation leadership and contributions to addressing mobility challenges, including specifically automated vehicle technologies in CCAT and NEXTCAR.

Additionally, Purdue plays a key education role for meeting the mobility challenge impact through the Hoosier Heavy Hybrid Center of Excellence, funded by the Department of Energy Graduate Automotive Technology Education (GATE) Program, with a focus on the hybridization of medium and heavy-duty vehicles. Purdue has also established a Hybrid Vehicle Systems Certificate program for graduate engineering students at Purdue, the first multi-disciplinary certificate program at the university.

Established National and Regional Research Contributions

The recently selected Region 5 UTC, the USDOT CCAT, led by the University of Michigan, focuses exclusively on automated and connected transportation. Purdue's partnership as part of the CCAT provides substantial synergy to further address problems related to the planning, design, and operation of automated and connected vehicles. In this context, Purdue is primarily interfacing on five of the six CCAT focus areas: 1) enabling technologies, 2) policy and planning, 3) human factors, 4) infrastructure design and management, and 5) modeling and implementation. Through these, and the building of automated transportation-related facilities and research infrastructure, we will pursue all facets from design to deployment, including now the real-world testing and operations using the PAVPG.

ARPA-E **NEXTCAR** program (Figure 1) led by Purdue is addressing the gap of isolation of new engine and transmission technologies from emerging connected and automated vehicle

applications such as cooperative adaptive cruise control, predictive cruise, speed harmonization, and freight signal priority. The Purdue-led team will together with industry leaders Peloton, Cummins, ZF TRW, Peterbilt, and NREL, co-develop an integrated, connectivity-enabled, vehicle-dynamic and powertrain control system for diesel-powered on-highway Class 8 trucks (CS-8) to achieve greater than 20% fuel and CO_2 reductions relative to 2016 baseline vehicles while demonstrating a technology pathway to meet 0.02 g/hp-hr NOx levels. This system-of-systems approach will integrate hardware and software components including the powertrain, vehicle-dynamic control systems, and vehicle-to-everything communication, backed by cloud computing. The effort will account for vehicle interactions and support their connection with cloud computing and V2X communication systems, reduced system fuel consumption and CO_2 across multiple vehicles, varied operating conditions, and differing time horizons. System capabilities will include local and remote sensing and communications, data logging, predictive analytics, real-time controls and remote calibrations.

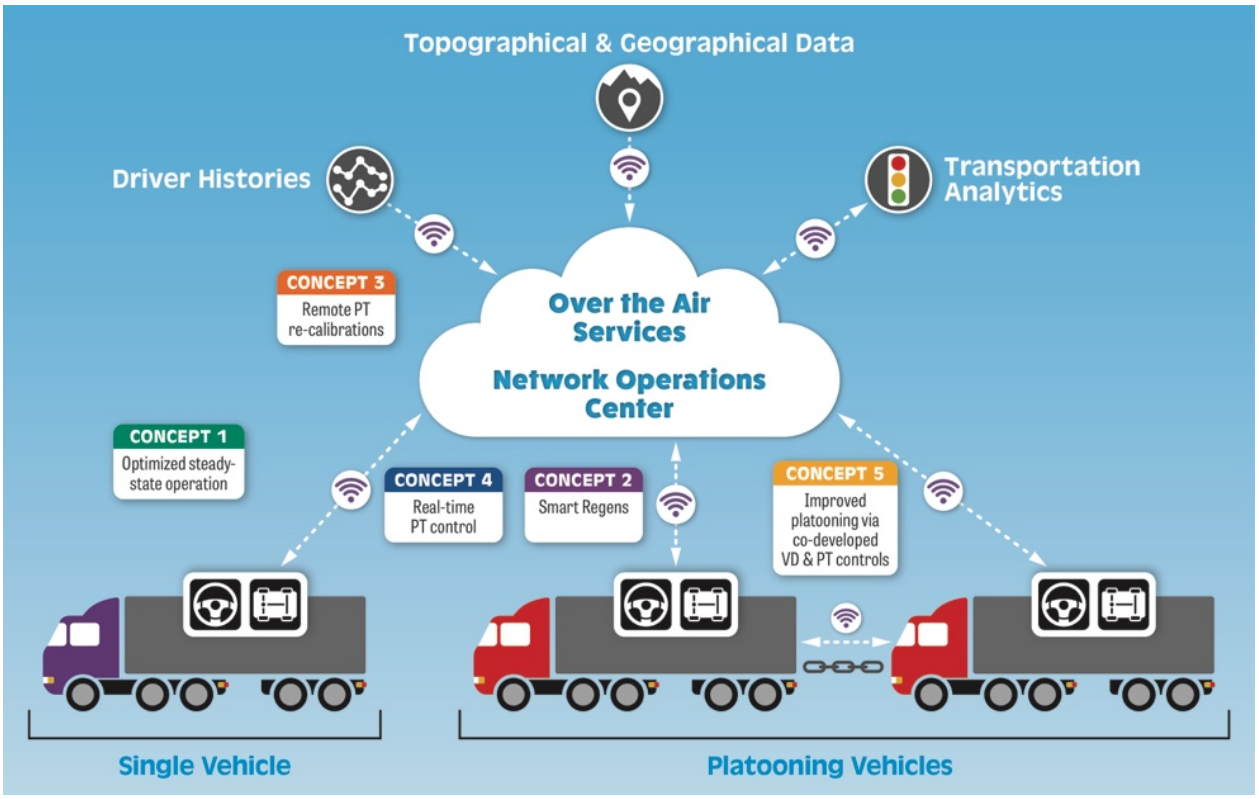

Figure 1. NEXTCAR CS-8 Concept

For the past ten years, Purdue has led the Region 5 UTC, the **NEXTRANS** Center to provide leadership in addressing national and regional challenges in transportation, including in the domains of automated and connected transportation. The current research focus in NEXTRANS is on modeling and simulator-based studies for connected and/or automated vehicles. The modeling component will use analytical tools to understand how connectivity occurs among vehicles, how platoons of automated vehicles form, and how these can be leveraged to meet mobility, safety, energy and environmental goals. Further, a unique driving simulator environment at Purdue, known as the Purdue Driving Simulator, integrates in real-time a driving

simulator with a microscopic traffic simulator and has been innovatively leveraged to address human behavior and human factors aspects related to automated and connected vehicles. These simulator studies follow protocols approved by Purdue's Institutional Review Board. In this context, the Purdue Driving Simulator is contributing additional capabilities specifically related to autonomous/automated vehicles to address the effects of automation in mixed traffic streams. Such simulator-based studies will allow us to better understand how travelers respond to automated vehicle environments, and inform the design characteristics of the PAVPG.

Access to Testing Data for Community of Practice Engagement

The CAThub built on the unique HUBzero platform will enable a new level of data sharing, data reuse, and project collaboration among established programs such as the CCAT, NEXTCAR, NEXTRANS. Currently, the NEXTRANS Center has developed modeling and driving simulator-based research outcomes. With CCAT focusing on multiple themes related to CAT and NEXTCAR addressing Class 8 trucks, we must organize Purdue's CAT-related research enterprise in terms of the diverse data generated by the various Centers. CAThub will provide the unifying data management platform for Purdue's fast-expanding CAT enterprise. This hub infrastructure has a proven track record in empowering a community to work together online, share resources, and level the playing field for traditionally underrepresented populations.

The HUBzero cyberplatform was originally developed under the direction of the National Science Foundation-funded Network for Computational Nanotechnology for the nanohub.org site, which now has over 1.4 million visitors each year from 172 countries worldwide. While nanohub.org was the first broadly successful, scientific end-to-end cloud computing environment, it has evolved well beyond online simulation to support private project areas for data management, data publication with Digital Object Identifiers, and even online education. Its impact is demonstrated by 1,700+ citations to nanohub.org in the scientific literature with nearly 26,000 secondary citations, yielding an h-index of 74. We anticipate a unique data-sharing and data-mining opportunity for engaging the automated vehicle technology stakeholders and supporting a sustainable Community of Practice.

The CAThub will provide stakeholders with key features for data management, data publication, and online community engagement. Community of Practice members will be able to create private "project" areas and invite others to join. Within each project, they will share data in a versioned repository, transition file-based data to SQL databases and publish databases as citable digital assets within the hub. Digital Object Identifiers and ORCID identifiers with author profiles will provide best practice tracking in publications and ensure data security, fidelity, backup, and mirroring. Each project includes a notes area for light documentation as well as Facebook-style messaging "wall" where project members create threads of conversation. Data then will be made available to others outside the project through a well-defined publication process that starts with a button click to initiate a new publication and receive prompts for specific files and metadata. Once the publication is submitted, it is assigned a DOI, sent on to an archiving facility, and becomes publicly available as a digital asset on CAThub (authors can also request the asset remains hidden until an embargo period has passed). After data has been published, other web sites can crawl the hub and discover the data. CAThub will track metrics that quantify the impact of each publication, including the number of downloads, number of unique users, and locations of users. These impacts are reported on the page for each publication

and also on the profile page for each author. Such metrics will help us measure the growth of Community of Practice participation.

The CAThub online community building includes capabilities for a blog, calendar, wiki pages, discussion threads, and messaging. Members can post in a question-and-answer forum, and the best answer for each question is identified by the community. It includes a "wish list" for brainstorming, whereby members can post ideas related to specific models or datasets, and other members can comment or vote on ideas and prioritize actions. Group members can keep their own Pinterest-style board for posting, following other members, and collecting information. With a built-in rating system and a means of associating peer-reviewed publications with digital assets, the Community of Practice can judge what resources are valuable and reliable.

- As part of participation in the Community of Practice, Designated Proving Grounds applicant's ability and willingness to maintain a working relationship with the Department's relevant research program offices. The application should describe this proposed relationship, including aspects such as potential participation in conferences, meetings, joint research efforts, and submission of significant activity reports to the DOT on a routine basis.

Through its role as the lead institution on the Region 5 UTC for about a decade, Purdue has demonstrated a history of research, education and outreach activities. These activities include participation in and contributions to transportation conferences and USDOT and Council of University Transportation Centers meetings twice a year; joint research activities with NEXTRANS partners from academia, industry, and government; opportunities for internships for diverse students; NEXTRANS Seminar series; annual and final project reports; and communication through newsletters, NEXTRANS website-based dissemination, and information and updates to Research in Progress and Transportation Research Information Services. In January 2018, NEXTRANS will transition from its role as the current Region 5 UTC to Purdue's Connected and Autonomous Transportation Center, and we will coalesce research, education, and outreach activities around this new center. NEXTRANS will continue its history of relationship with USDOT and will maintain a working relationship with the relevant research program offices at USDOT. Further, Purdue's DSO will coordinate the safety-related data dissemination through the CAThub and be the point of contact on the PAVPG-related activities such as testing and operation.

Commitment to Safety

- The demonstrated capability to control risks through the implementation of robust safety precautions through a published safety management plan in all proving ground testing and operations.
- Applicant demonstrates that specific safety considerations have been met over the course of operation, including safety of proving ground personnel, safety protocols when making use of public roads, and attention to safe design, deployment, and operation of automated devices.

Purdue will develop safety protocols related to the safe design, deployment, and operation of automated devices and for making use of public roads. Purdue's DSO will work with various

stakeholders involved with the PAVPG's current facilities and those involved in the design and operation of the long-term planned facilities to ensure that safety protocols are adhered to, both in the testing and operation of current facilities and the design of the long-term ones. Purdue will also leverage its partnership with Underwriters Laboratories, a global safety consulting and certification company, to ensure that the testing and operations at PAVPG meet robust safety standards and protocols.

Further, Purdue's existing research in the transportation arena routinely involves interactions of the research personnel with live traffic situations. In this context, the researchers (students, staff and faculty) are required to attend a seminar related to the safety protocols for such activities. We will leverage these protocols and develop new ones in the CAT-related context.

The PAVPG will build on a strong, existing commitment to robust safety plans as seen in the NEXTCAR project. Specifically, Purdue will be working with Cummins, Peloton, Peterbilt and NREL to complete real-world Class 8 truck testing of the connectivity/autonomy-enabled fuel savings control strategies developed during the NEXTCAR program. Peloton and NREL already have significant experience testing autonomous vehicles, both on tracks, and roadways. Cummins and Peterbilt also have extensive experience with safely testing vehicles. Purdue will continue to improve its expertise in the safe testing of autonomous vehicle technologies through this collaboration with experience industry and government partners.

Research, Application and Data Sharing

- The extent to which the State or locality in which the applicant is located can provide applicable solutions for the broader region and surrounding corridor for improved mobility through the advancement of automated vehicle technology.

Purdue's PAVPG is the outcome of needs that identified by the state government, industry, and academia. As shown in Figure 2, the State of Indiana, through the Indiana Economic Development Corporation, supports Purdue's connected and autonomous vehicle technology-related activities due to needs ranging from economic development to transportation-related challenges. Indiana has a significant focus on manufacturing and agriculture and is characterized by vast swathes of rural areas and some large urban regions. A key transportation characteristic of Indiana is that it is the "Crossroads of America" as several interstates criss-cross the state. Just as importantly, one of the main freeways through Indiana, I-65, is a commercial corridor due to its termination in the vicinity of Chicago. This commercial opportunity generates substantial semi-trailer truck traffic on I-65 and on the Borman Expressway (I-80/94) in the northwest region of the state. For example, during certain periods of the day, more than 70% of the traffic on the Borman Expressway consists of semi-trailer trucks. As a result, several of Indiana's CAT activities will focus on truck-related aspects. In this context, the Purdue-led ARPA-E NEXTCAR Center will provide leadership in the relevant CAT activities, which will entail joint research activities with consortium members such as Cummins, Peloton, ZF TRW, Wabash National, and NREL. Further, in the past, there have been concerns expressed by Indiana citizens on the significant interactions with semi-trailer trucks, and the discomfort and safety concerns thereof. Past studies have explored truck-non-truck interactions on Indiana roads; the next wave of

studies will seek to leverage CAT technologies to reduce safety and discomfort concerns related to the significant presence of trucks in the Indiana travel corridors.

Another defining characteristic of Indiana is that it is the home to the Indianapolis Motor Speedway, with a substantial focus on race cars and car-racing. In this context, safety is a key issue, and enhancing safety is a permanent goal. Through Purdue's partnership with IMS, we will leverage their extensive facilities to explore how automation and connectivity can aid in enhancing safety in motorsports.

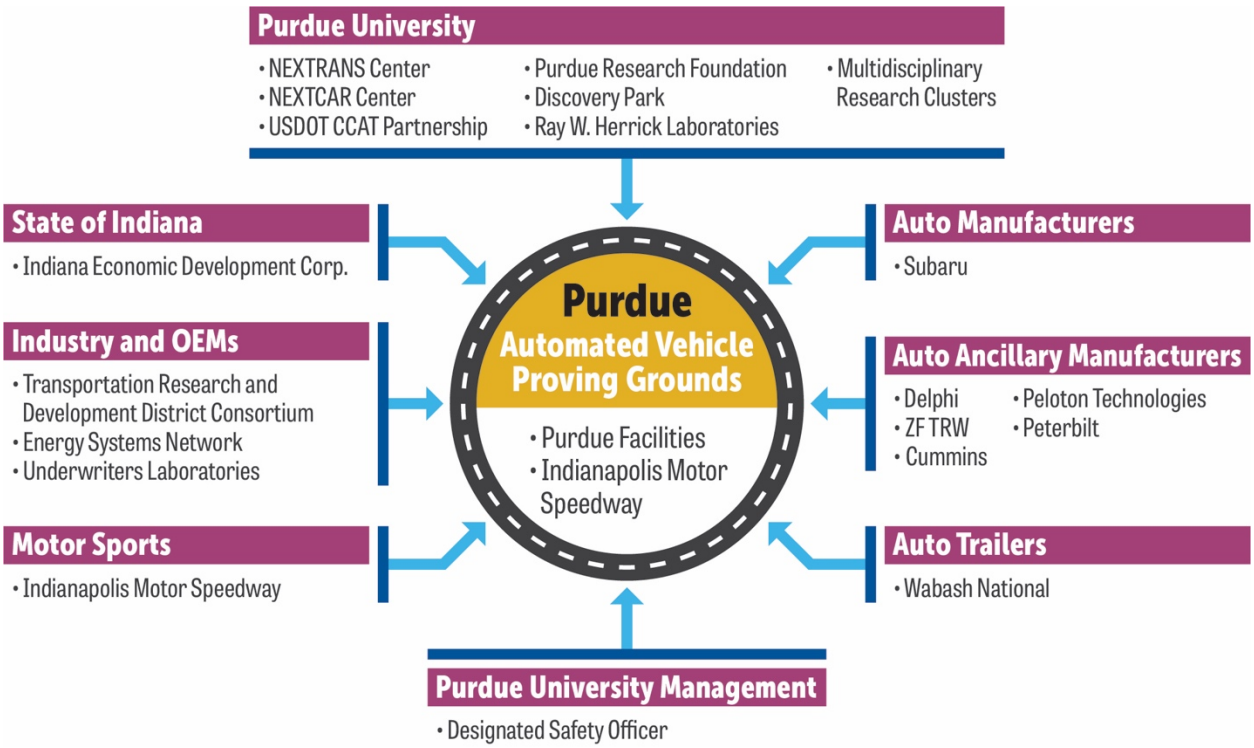

Figure 2. The Purdue Automated Vehicle Proving Grounds Integrated Partnership

As noted in different parts of this proposal, the PAVPG integrated partnership is a reflection of the synergistic goals of different stakeholder groups in the CAT space. In Figure 2, Purdue University illustrates leadership in multiple aspects related to connected and automated vehicle technologies, through Centers (NEXTRANS, NEXTCAR) and partnerships (CCAT). Further, Discovery Park, the 20-acre and $1 billion complex for interdisciplinary research and education at Purdue, enables the development of multidisciplinary research clusters in CAT. The Purdue Research Foundation is the enabling arm of research enterprise at Purdue, and directly involved with the planning and development of relevant infrastructure. Hence, Purdue Research Foundation has a key role in enabling Purdue's three-stage PAVPG plan. The Purdue University Management is responsible for identifying and designating the safety officer for the PAVPG.

Purdue's partnership with the IMS enables the leveraging of its world-renowned facilities, while focusing on the role of automated vehicle technologies in enhancing safety in motorsports. Hence, as illustrated in the figure, the PAVPG includes Purdue facilities, IMS facilities, and those developed in partnership with the large industry consortium—the Transportation Research

and Development District. This consortium consists of auto-related original equipment manufacturers and entities in the technology space related to CAT. Underwriters Laboratories has a global reputation for their safety certifications. Indianapolis-based ESN is a non-profit industry consortium focused in the energy technology sector and more recently has developed interests in the development and deployment of autonomous vehicle technologies.

Subaru-Isuzu Automotive has a large automotive manufacturing plant in the vicinity of Purdue and is a natural partner given the critical role of auto manufacturers in deploying the automated vehicle technology in the real world. Wabash National is another local Indiana firm with a national presence focused on the design and manufacture of truck trailers; hence, there is a direct interest in leveraging connected and autonomous technologies into the construction of the next generation of trailers.

The locally based unit of ZF TRW and the Kokomo-based Delphi are well-known designers and manufacturers of auto ancillary systems. Delphi in Kokomo, Indiana, has industry-leading experience in automated vehicle technologies. ZF TRW is one of the world's three largest automotive suppliers and has recently formed a group focused on commercial vehicle advanced driver assistance systems and autonomy. Both have a direct interest in leveraging the PAVPG. Cummins, Peloton Technologies and Peterbilt operate in the space of commercial trucks and further are partners in Purdue's NEXTCAR Center.

The State of Indiana will interface with the PAVPG through its economic development arm, the Indiana Economic Development Corporation (IEDC). Since the PAVPG has the potential for public-private-academia partnerships, with opportunities for economic development for the State and region, the IEDC represents the key interface with the State as part of the three-stage PAVPG plan.

- The demonstrated research and extension resources available to the applicant for carrying out activities and programs as they relate to automated vehicle advancements.

As outlined earlier, Purdue's NEXTRANS Center already performs modeling and driving simulator-based research related to automated vehicles. The associated resources include a high-performance computing cluster node, and the Purdue Driving Simulator. The unique ability of the Purdue Driving Simulator to integrate a microscopic traffic simulator in real-time with a driving simulator enables us to conduct research related to autonomous vehicles and connected vehicles in a quasi-real setting, especially as it relates to understanding how drivers and travelers behave/respond to automated and connected technologies. This core expertise will be further expanded through the new partnership with the University of Michigan in the recently awarded USDOT CCAT, with University of Michigan and Purdue being the two major partners. Thereby, we also expect to leverage University of Michigan's substantial CAT resources and learn from their experience in developing our own CAT efforts related to trucking and motorsports.

- The degree to which the applicant can disseminate results of automated vehicle research through a statewide or region-wide education program to support the national deployment of automated vehicle technology.

As a major partner in University of Michigan's USDOT CCAT Center, the new Region 5 UTC, Purdue will partner in addressing national and regional transportation goals in connected and automated transportation. This region is also the center of gravity of the U.S. automobile and trucking industry. Hence, multiple venues are available through CCAT to disseminate research results to advance the national deployment of automated vehicle technology. These include dissemination of research outcomes in specialized CAT conferences and symposiums, focused workshops and technology transfer outreach to state and local transportation personnel, creation of incubators and commercial entities through collaborative activities with private sector partners, CCAT's region-wide education program, CCAT's workforce development-related activities in connected and automated transportation, and CCAT's consortium partnership with a community college program focused on the development of CAT-related technical skills.

A major focus of the Purdue-led NEXTCAR program is the dissemination of research results. This will include the design, real-world testing data, and economic value proposition of the integrated, connectivity-enabled, vehicle-dynamic and powertrain control system for diesel-powered on-highway Class 8 trucks that will be developed during that program.

Further, as illustrated in Figure 2, Purdue's PAVPG entails substantial partnership and collaboration with the State of Indiana and many industries within the State and locally. This includes the Transportation Research and Development District Consortium championed by Indiana's industrial and manufacturing firms and the Indiana Economic Development Corporation's support of the PAVPG. Hence, we anticipate not only the research conducted through Purdue University will reach the end users seamlessly, but these Indiana and local auto-related firms will represent partners in the research, testing, and operation involving the PAVPG.

Purdue's CAThub will serve as a key resource to enable various stakeholders from the State, nation and across the globe to participate in educational and research endeavors through the "dynamic site" capabilities of the CAThub. As seen in the nanoHUB success, median time from publication of a research simulation program to classroom use is less than 6 months, for a fast-paced integration of research into educational practice. Cumulatively, nearly 30,000 students at 185 institutions have used nanoHUB simulations within their curriculum. CAThub will leverage this integrated learning management system for online education that enables instructors to drag and drop video files, PowerPoint presentations, office documents, and other instructional materials to build their own course in a self-service manner. Students will be able to enroll in courses, watch videos, complete homework assignments, take online exams, and interact with one another and instructors through a discussion forum. When they have successfully completed a course, students can claim an online badge or certificate.

Cloud-based "workspaces" accessed through CAThub will also allow students and researchers in the community to write code, test models, access powerful cluster/cloud computing resources, and deploy models for others to use. Models and data will be accessible via the web with the click of a button—without having to download or install any code and will leverage built-in plotting and visualization capabilities that are already part of the HUBzero software stack. Such computational access provides a learning environment that ensures the broadest possible participation.

- A commitment to open data and sharing performance metrics and results of objective tests.

Purdue University will continue with the PAVPG a strong track record of commitment to open data and sharing of performance metrics and results of objective tests, as illustrated in the formal agreement as part of the ARPA-E NEXTCAR program. In the PAVPG context, Purdue's CAThub will have a key role.

Demonstrated Investments

In facilitating automated vehicle testing, applicants demonstrate commitment through one or more of the following:
(1) Capital improvements to the proving grounds to advance automated vehicles;
(2) Authorization for the proving grounds, either through State legislation or regulation, to address regulatory challenges associated with higher levels of automation;
(3) Testing or deployment underway to determine automated vehicle technology feasibility.

As stated earlier, Purdue has a three-stage strategy for proving grounds for automated vehicle technology-related testing and deployment. In the first stage, Purdue will partner with Indianapolis Motor Speedway to leverage its facilities for exploring automated vehicle technologies from a safety perspective. In the second stage, a 1.5-mile facility is being explored for testing of automated vehicle technology in the vicinity of Purdue University. The large-scale third stage will involve a partnership with an industry consortium and the State of Indiana to develop CAT infrastructure.

Readiness

(1) Designated facility is open for testing, or the ability of the applicant to demonstrate that the facility will be open for testing, by January 1, 2018.
(2) The facility supports testing by multiple users, or the data generated by the proving ground is shared openly to the public.
(3) Designated facility provides a Designated Point of Contact.
(4) If making use of public roads, the applicant demonstrates that it has engaged with any affected communities and can show that it is actively working with those communities to address any concerns.

As shown in Figure 3, Indianapolis Motor Speedway (IMS) has an extensive set of existing private facilities that would provide the PAVPG its first stage facilities. Through partnership with the IMS, the data generated by Purdue's automated vehicle technologies related testing will be made available to the public through Purdue's CAThub. Purdue will partner with IMS to identify a Designated Point of Contact for these facilities.

For the second- and third-stage plans, Purdue and its partners, illustrated in Figure 2, will involve relevant stakeholders in the planning stage, if such facilities would affect specific communities.

Figure 3. The Indianapolis Motor Speedway Facilities

Adherence to Laws, Regulations, and Federal Policy

- The degree to which the application addresses how the automated vehicle testing facility will adhere to all state and local laws and federal regulations.
- If making use of public roads, the applicant demonstrates adherence to those primary subject areas outlined in the National Highway Traffic Safety Administration's (NHTSA) policy for automated vehicles (Federal Automated Vehicles Policy: Accelerating the Next Revolution in Roadway Safety) for any testing or deployment of L3 -L5 systems on public roads.

Purdue will work with the IMS and other members of its integrated PAPVG partnership at various stages to ensure that the PAVPG facilities adhere to all state and local laws and federal regulations. Also, Purdue will also draw on the expertise of PAVPG partner Underwriters Laboratories to ensure that these laws and regulations are being satisfied.