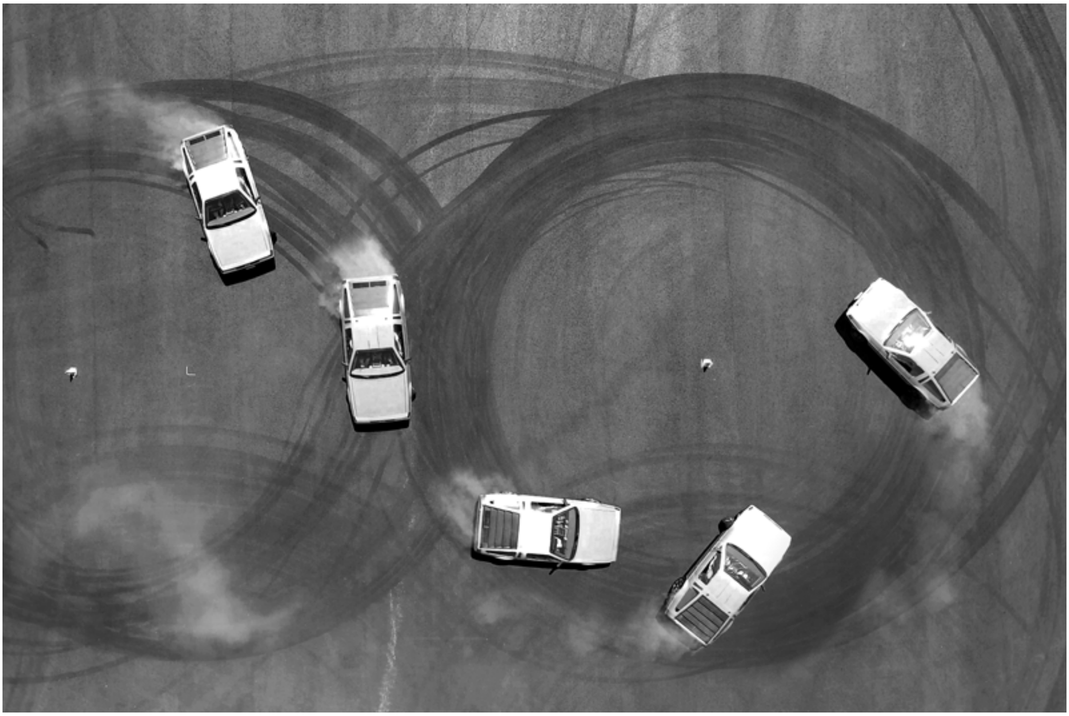


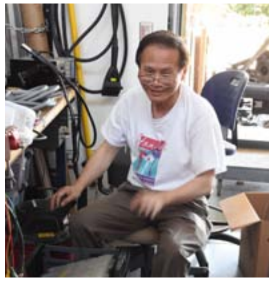
CARS

# 2017/18 Highlights

2017/18
Highlights















PACCAR



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# An Update From CARS

## For the last three years the CARS program has produced an annual review of our activities and perspectives of researchers on the future of mobility and of the industry.

This *Highlights* document is a living history of our community read by local mobility labs, hiring managers and CEOs of automakers, suppliers and community members. We are pleased to share with you new focus areas of research, spotlighting the efforts of CARS faculty members, and reviews of some of the events that bring our CARS community together throughout the year.

We are privileged to have the support of talented faculty at Stanford. In March 2017 we were happy to welcome back faculty director Chris Gerdes from a year of public service as the Chief Innovation Officer for the U.S. Department of Transportation. Chris is joined by four new faculty co-directors who help lead new and innovative research on the future of mobility: Mykel Kochenderfer, Marco Pavone, Per Enge and Allan Reiss. We are also pleased to welcome back Larry Cathey to lead work in our simulator and mobility platforms.

Thanks to the support of our affiliates, CARS has kicked off five broad, new areas of research, initiated two new mobility classes in 2017, hosted three Open Garage Talks, three transportation-focused workshops, an automotive and mobility career night, and hosted leadership from the Departments of Transportation from four countries.

With this year's *Highlights* document we'd like to share some of the findings of these research efforts, to welcome new community members, and to look forward to educating the next generation of transportation and mobility innovators. We'd like to dedicate these highlights to Per Enge who passed away April 2018. We will miss his warmth, enthusiasm and deep technical expertise on GPS navigation systems. Per led the Stanford GPS Lab and worked with CARS to develop a new class and textbook on Electric Vehicles. He inspired us all with his dedication to his students and contributions to the Stanford community.

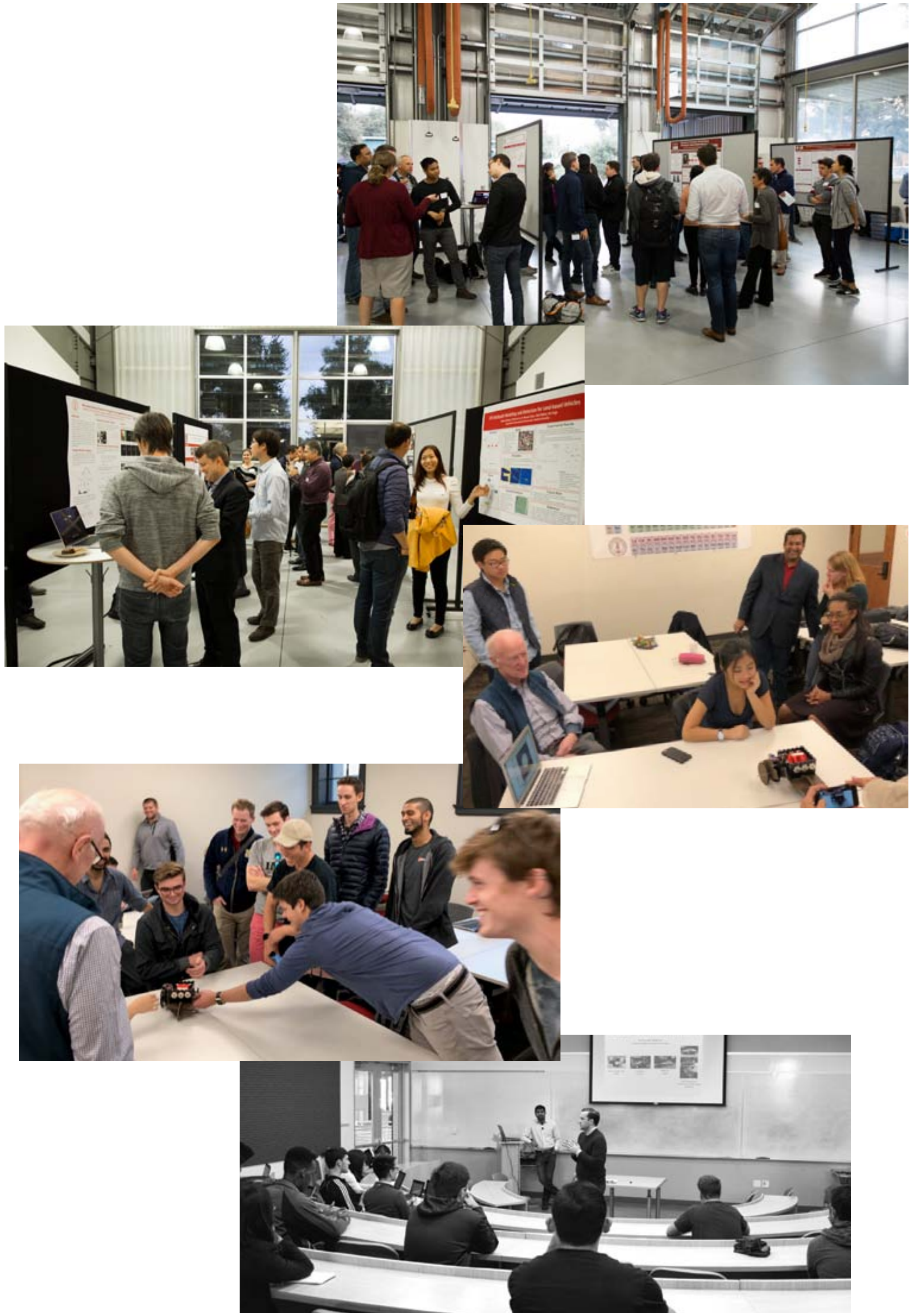
# A Great Community Comes Together

# About Our Community

**CARS creates new opportunities for faculty, students and affiliates to become engaged in the future of transportation.**

With the rise of automation, new powertrains and shared mobility, a new generation of students is entering Stanford with the knowledge that work they undertake on campus has the potential to remake an entire socio-technical system. Whether their objective is to launch a new startup, contribute to academic knowledge or to write a new legal framework, a common thread is the desire to conduct work that will make an impact on the world.

Researchers look to industry participants to find new problems that need solutions, and applications for novel technologies invented on campus. One of the ways that CARS affiliates support new avenues of research is by supplying students and faculty with real-world data, allowing projects that have immediate relevance and reveal challenges in dealing with noisy data, unknown constraints and sensor limitations.



# The Classroom & Beyond

**Many Stanford students aspire to careers in transportation, and the CARS program embraces the role of preparing these students for the next stage of their lives, be it in a startup, automotive manufacturer, or government policy-maker.**

While not all students conduct research in transportation, all of them use transportation systems every day, and these systems are a rich source of relatable examples that students may use to understand social concepts such as externalities.

Transportation is a profoundly social enterprise: one which affects our ability to access employment and see our family and friends. It is also one of the most highly regulated and studied systems in the world. CARS faculty and staff have recognized the need to prepare students for the responsibilities that come with the design and engineering of these social systems. In response to this need, CARS is proud to support the launch of two new classes, ME267 (Ethics and Equity in Transportation Systems) and ME182 (Electric Transportation).

Instructors of ME267 use real-world examples from the ride-hailing space, design of infrastructure, control of automated vehicles and emissions regulations to illustrate concepts such as economic externalities and the need to consider values of a variety stakeholders. During the course of the quarter, students design a new bridge layout, develop an experiment designed to evaluate equity in a transportation system, and write an emissions policy to promote the adoption of electric vehicles in a developing country. Through the course of these assignments, students are also exposed to the laws that grant travelers fundamental rights, such as the Americans with Disabilities Act (ADA) and the Civil Rights Act.

The objective of ME182 is equally ambitious: over the course of ten weeks the teaching team shares virtually all the key concepts of electric vehicles with students including energy conversion, storage, the fundamental physics of motors, and the economics of a transition to an electric fleet.

# Workshops

**Introduced in 2015, our workshop series is a chance to share research insights into topics ranging from ride sharing platforms, vehicle interiors for the future to unconventional mobility.**

The half-day format of panels and academic presentations provide an informal forum for discussion and sharing of recent research innovations. Our hope is to bring an interdisciplinary perspective to these topics bringing in researchers and experts from industry, academia, and government. Thank you to all our affiliates and partners that have participated either as speakers or attendees for the 2017 workshops: *Doing the Hard Work of Mobility* and *Mobility from the Inside Out*.

In *Doing the Hard Work of Mobility* we looked at the changes in transportation and specifically into the world of mobility services. This transformation after 100 years of a traditional sales and ownership model impacts both the demand and supply sides of the automotive business. In this workshop we explored how mobility services support the various needs of users, ridesharing drivers, carsharing entrepreneurs and policymakers to move us from today into the future.

Affiliates and designers were invited to showcase new concepts at our *Mobility from the Inside Out* workshop in June related to vehicle interiors for automated vehicles of the future. With the evolution of car sharing and automation, cars are becoming personal devices that can allow occupants to be more productive. With carsharing we wanted to explore how vehicles adapt to each new user and adapt between passengers that choose to cohabitate in a space versus those that do so out of convenience. Attendees experienced prototype vehicle interiors and new material concepts.

We hope you will be able to join us as we explore other topics in 2018.

# Open Garage Talks

**Every quarter, we throw open the doors to the Automotive Innovation Facility for our Open Garage Talk series.**

We host notable speakers in the mobility/transportation realm and frequently draw over 200 attendees. Our goal is to bring the Stanford and larger Bay Area automotive community together to learn and to spark new ideas. Students also have the opportunity to engage in open discussion with the speakers prior to the talk.

In past years we have featured designers, professional racers, student groups, and other noteworthy figures in the automotive/transportation realm. In 2017 we were fortunate to have Padmasree Warrior, CEO of Nio featured at our first Open Garage Talk of the year discussing *The Here & Now of Electric Vehicles*. In May, Stefano Domenicali, CEO of Automobili Lamborghini S.p.A. joined us for *The Future of the Enthusiast*. Michelle Christensen, NSX Lead Exterior Designer, and Ted Klaus, NSX Global Development Leader were featured in *The Secret to the Best Products: Design Something Impossible to Make* in November.

Please check cars.stanford.edu for upcoming Open Garage Talks.

This year's new solar car, Sundae, takes shape at the AIF.

The Stanford Solar Car Project team at the unveiling of the latest solar car.

# Transformative Student Experiences

## Ranging from classes to student international exchanges, seminars to infrastructure support, CARS provides support to a range of student activities.

In 2017, the Stanford Solar Car Project had their build cycle prior to competing in the 2017 Bridgestone World Solar Challenge held in Australia. The Automotive Innovation Facility (AIF) was transformed into a fabrication and build facility as the new solar car, named Sundae, took shape. The solar car team, an undergraduate student club whose home base is the AIF, provides a challenging hands-on engineering project and an opportunity for the students to manage the design, build and racing of a brand new solar car from the ground up every 2 years.

Larry Cathey was brought on board as our Vehicle Research Platform Manager in summer 2017. Leveraging his 30 years of experience as an automotive research engineer which includes 20 years experience with ground based real-time visual simulation,

Our new Vehicle Research Platform Manager, Larry Cathey, was brought on board in summer 2017.

Stanford students Matt Brown, Tim Wheeler and Jeremy Morton along with Jan Timo Wendler and Robert Graubohm in Braunschweig, Germany.

A visit by the German Minister of Transportation and Digital Infrastructure during a visit in February

Larry assists students with experimental design, technical support and integration activities. These students represent a cross-section of departments: from mechanical engineering, aeronautics and astronautics, the medical school, communication and computer science.

For the past several summers, CARS has sponsored a select group of students to attend a summer exchange program at TU Braunschweig. The class provides an opportunity for students to work with a diverse group of participants from different academic backgrounds and cultures to learn a wide variety of industry tools, learn how to communicate and organize as an effective team, and to present to a realistic management team.

In 2017, we were fortunate to host several CEOs, overseas ministers of transportation, designers, and R&D leaders. With these opportunities, we organize a student-focused discussion to spark new discussions and lines of thought.

# Turning Ideas Into Reality

**CARS is possible thanks to the dedication of talented faculty and students at Stanford.**

**Transportation is inherently a multidisciplinary field of research: it is so complex and interconnected that even the best engineers in the world cannot progress in isolation. CARS supports projects that originate from unlikely partnerships, both within the School of Engineering and beyond in Medicine, Philosophy, and Law. CARS research is led by five key faculty members: faculty director Chris Gerdes, and co-directors Per Enge, Mykel Kochenderfer, Marco Pavone and Allan Reiss. Together they conduct research in areas that are core to the future of transportation: Decision making and planning under uncertainty, planning and decision making for autonomous robotic systems, cars and brains, cyber safety for transportation, and ethical programming of automated vehicles.**

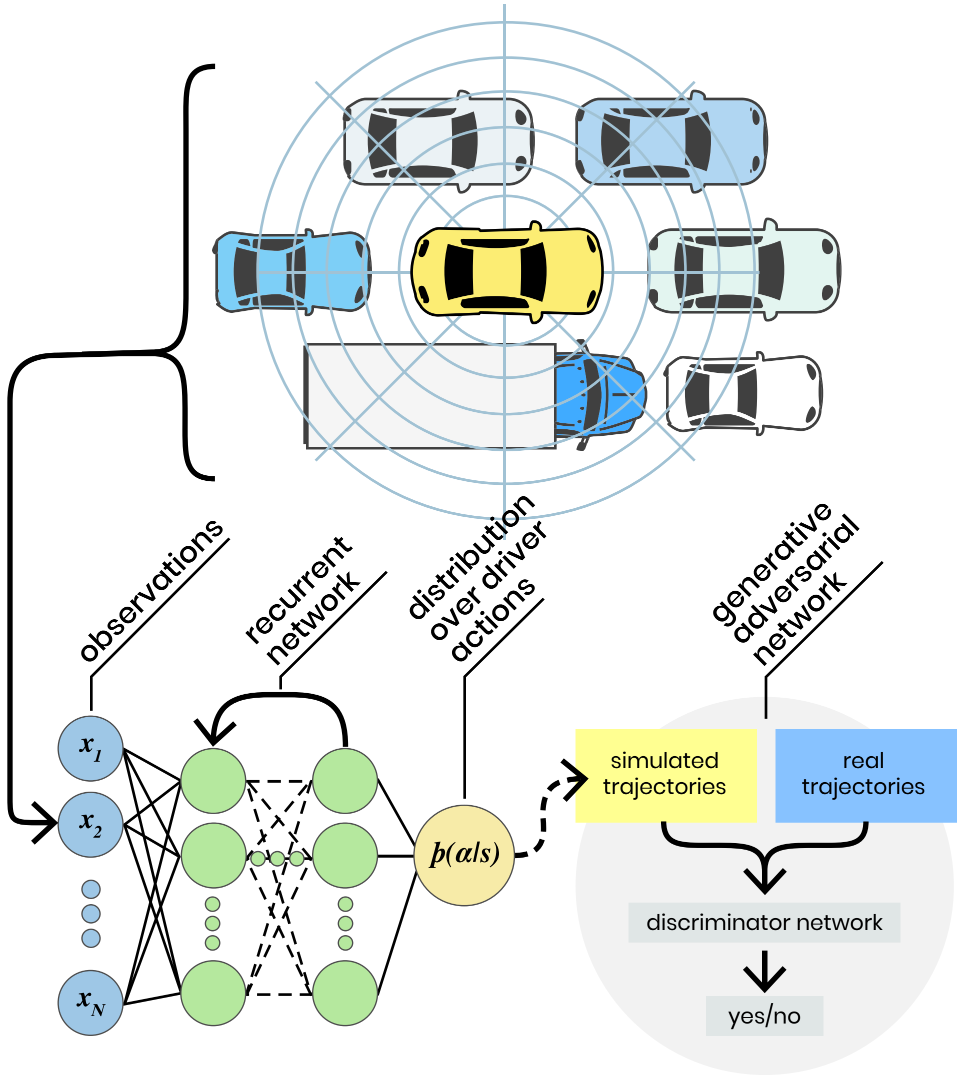


**Figure 1**: Visualization of Driver Modeling Methods. Using observations of the state of the world, we train neural networks to predict the likely driver actions. This can be improved with generative adversarial networks, which compare the simulated trajectories from the generative model with real-world trajectories. The goal is to train a model that is good enough to fool the discriminator network.

# Decision Making & Planning under Uncertainty

**Mykel Kochenderfer**
Assistant Professor, Aeronautics and Astronautics
Director, Stanford Intelligent Systems Laboratory
Co-director, Center for Automotive Research at Stanford

The Stanford Intelligent Systems Laboratory (SISL) solves decision-making and planning problems in safety critical applications like aircraft collision avoidance and autonomous vehicles. Our research focuses on designing systems that can safely and effectively plan and execute tasks when there is uncertainty in the current state of the system or world, the underlying model, and/or the effect on actions.

To validate driving systems in simulation, we need accurate driver models that capture the stochastic nature of human actions. Using recurrent neural networks to capture the nuances of human behavior, we can learn relevant features for predicting driver acceleration and intent at a variety of intersections and conditions. This approach shows improved and more consistent performance over greater distances. We can significantly improve the efficiency of interactive maneuvers (e.g. changing lanes) without compromising safety by modeling the internal

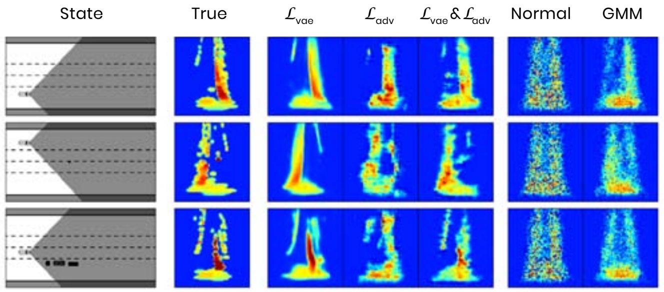


**Figure 2**: Comparison of Learned Radar Models. As shown, by integrating adversarial networks, the resulting output more accurately captures the fundamental effects of radar.

state of drivers as a hidden state in a POMDP (Partially Observable Markov Decision Process). We also model driver behavior over longer time horizons using generative adversarial learning. Using LiDAR-like features, we obtain extremely good performance, and avoid some of the disadvantages of traditional supervised and imitation learning approaches.

We use the driver models described above to develop simulation tools for improving validation of autonomous vehicles. One of our recent approaches is to use deep learning to capture stochastic models for automated vehicle sensors, such as radar. Deep neural networks are powerful tools that allow for real-time simulation, but may exhibit unexpected behavior in scenarios that are not well presented in the training dataset. We have developed a framework called Adaptive Stress Testing that will find the most likely failures, without the need for validation with millions of simulated driving hours.

To capture the complexities of urban driving, we use guaranteed control frameworks like model-predictive control to provide trajectory optimization and low-level control. We then train a deep neural network to optimize high-level decisions. To model the navigation of intersections under uncertainty, we use a POMDP and solve for near optimal decisions using a Monte Carlo tree search, and in this way we can tune the rewards to trade off between efficiency and risk, while showing improvement over open-loop policies. Estimating model parameters (e.g. friction) is crucial in autonomous planning and control, and we have developed a Bayesian approach, leveraging the Monte Carlo tree search, to optimize for vehicle control while simultaneously estimating parameters. Taken together, these three examples demonstrate how our main research goal of improving decision-making for planning and control has important implications for the future of autonomous driving.

*Research described above is sponsored by Ford and Toyota; Bosch and SAIC.*

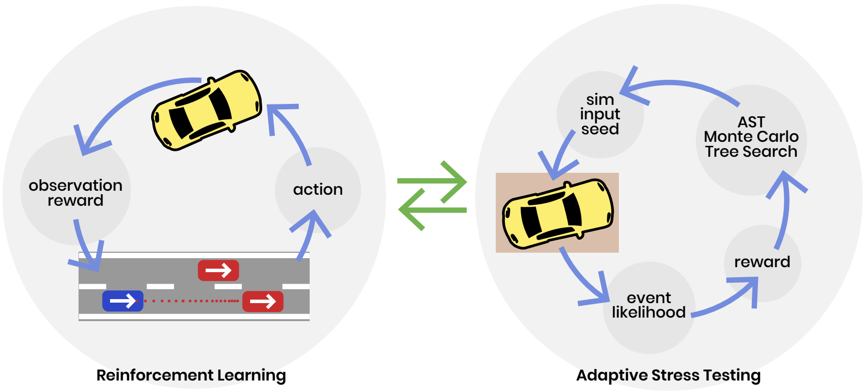


**Figure 3**: Visualization of the Adaptive Stress Testing Pipeline. After training a policy using standard learning techniques, we apply Adaptive Stress Testing, which provides the most likely failure cases. Using these as training examples, we can update our policy to be robust to these low-probability events.

# Planning and Decision Making for Autonomous Robotic Systems

**Marco Pavone**
Assistant Professor, Aeronautics and Astronautics
Director, Autonomous Systems Laboratory
Co-director, Center for Automotive Research at Stanford

The goal of the Autonomous Systems Laboratory (ASL) is to develop methodologies for analyzing, designing, and controlling autonomous systems, in particular self-driving cars, autonomous aerospace vehicles, and future mobility systems. The lab combines expertise from control theory, robotics, optimization, and machine learning to develop the theoretical foundations for networked autonomous systems operating in uncertain, rapidly-changing and potentially adversarial environments. We use these theoretical insights to devise practical, computationally efficient and provably correct algorithms for field deployment.

Our projects on motion-planning for agile robotic systems include devising methods for safe transfer of control policies from simulation environments to the real world (e.g., to grasp complex objects), studying the theoretical foundations of risk-sensitive learning and decision making, and developing new techniques to merge formal methods with stochastic optimal control and deep learning for high-confidence implementation on safety-critical systems. We are applying our research to the problem of interactive decision making for self-driving cars.

Specifically, endowing autonomous cars with the ability to predict the evolution of their surroundings is essential for safe, reliable, and efficient operation. Prediction is especially important in scenarios where self-driving cars must interact and “negotiate” with human drivers to mitigate misunderstandings which may lead to dangerous situations. Quantifying the relative likelihoods of multiple, possibly highly distinct futures enables us to plan autonomous car strategies that are cognizant of how a human may respond and which take information

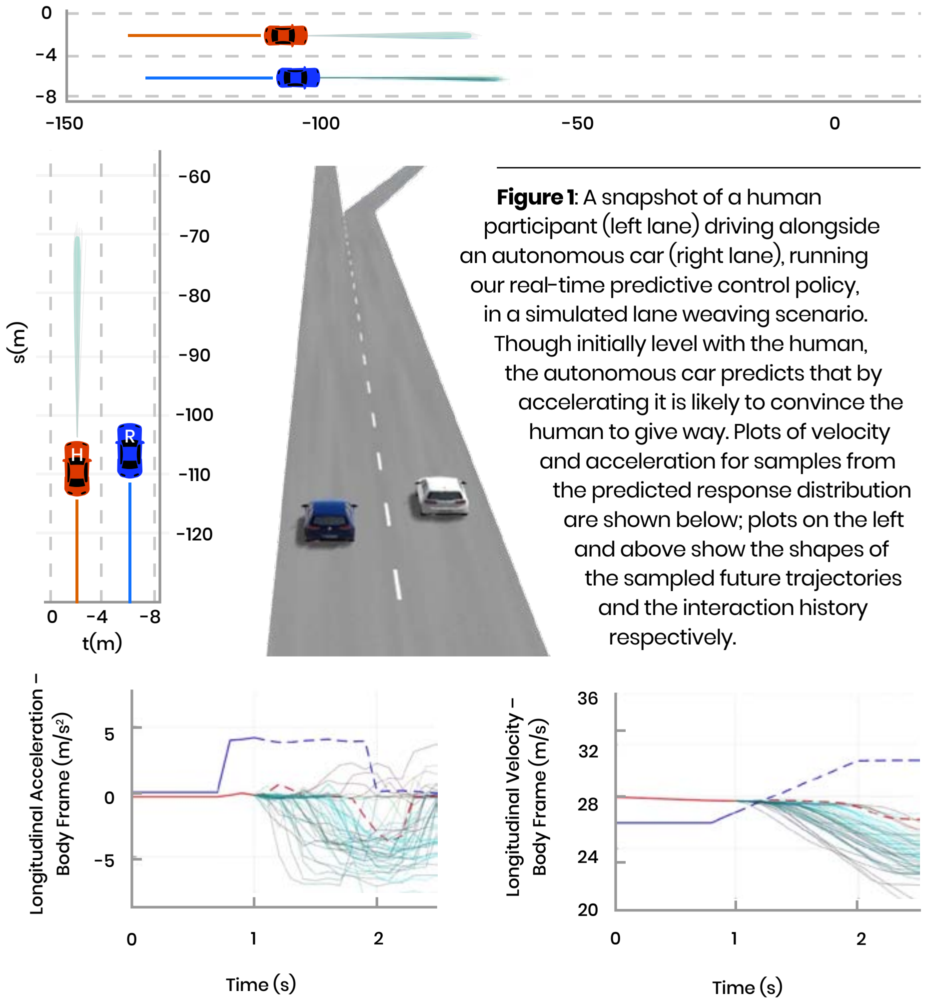


**Figure 1**: A snapshot of a human participant (left lane) driving alongside an autonomous car (right lane), running our real-time predictive control policy, in a simulated lane weaving scenario. Though initially level with the human, the autonomous car predicts that by accelerating it is likely to convince the human to give way. Plots of velocity and acceleration for samples from the predicted response distribution are shown below; plots on the left and above show the shapes of the sampled future trajectories and the interaction history respectively.

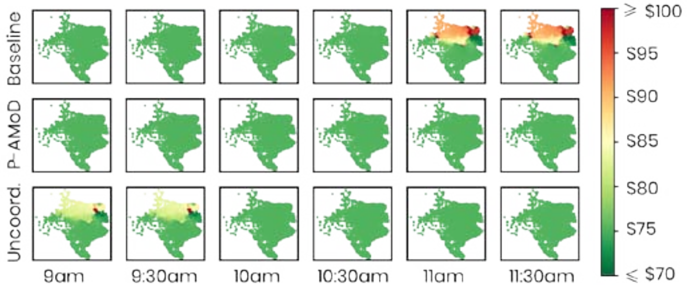


**Figure 2.** Electricity prices [$/MWh] in Texas. In the baseline case, no cars are present. In the Power-in-the-loop AMoD (P-AMoD) case, the operations of the power network and of the AMoD system are jointly optimized. In the uncoordinated case, the AMoD system does not account for its impact on the power network. By leveraging their battery capacities and acting as mobile storage units, the EVs are able to reduce congestion in the power transmission network: this results in lower prices in the Dallas-Fort Worth region, and hence lower electricity expenditure.

seeking actions to disambiguate human intent (**Figure 1**). Utilizing our flexible driving simulator platform and the steer-by-wire capabilities of the Stanford Dynamic Design Lab's research vehicle X1, we are developing an experimental pipeline from data gathering through model/control synthesis to human-in-the-loop simulation and ultimately to reality – our aim is to demonstrate algorithms that apply equally well on road as in simulation.

*Research on interactive decision making is sponsored by Toyota and the Office of Naval Research.*

Our research on Autonomous Mobility-on-Demand systems (fleets of self-driving cars offering on-demand transportation) hold promise to reshape urban transportation by offering higher quality of service at lower cost than private vehicles. While large numbers of EVs can significantly increase electricity prices and threaten the stability of the power network, autonomous EVs provide a unique opportunity for joint traffic and energy production management. Idle vehicles can be strategically routed to charging stations in order to either absorb excess power at times of low demand (by charging) or inject power at times of high demand (by discharging).

Our research builds analytical tools and algorithms to model and control this interaction. We designed a joint model that captures the coupling between AMoD systems and the power network, and leveraged it to optimize the operations of both systems to maximize social welfare. A pricing mechanism aligns AMoD system and generator operators interests with the social optimum, enforcing the socially-optimal solution as a general equilibrium.

We studied a hypothetical AMoD system in Dallas and its impact on the Texas power network. Our results (**Figure 2**) show that coordination between the AMoD system and the power network can reduce the overall energy expenditure compared to the case where no cars are present (despite increased demand for electricity) with savings of $182M/year compared to an uncoordinated scenario. This suggests that the societal value of AMoD systems spans beyond mobility: properly coordinated, AMoD can deliver significant benefits to the wider community by helping increase the efficiency of the power network.

*Research on AMoD systems is sponsored by the Toyota Research Institute (TRI) and the National Science Foundation (NSF) under CAREER Award CMMI-1454737.*

# Cyber Safety for Transportation

**Per Enge**
Vance D. and Arlene C. Coffman Professor, Aeronautics and Astronautics
Director, Stanford GPS Lab
Co-director, Center for Automotive Research at Stanford

In the Stanford GPS lab, we are focused on a multi-disciplinary cyber safety effort, combining aeronautics, computer science, biology, electrical engineering, mechanical engineering and physics, to combat the threat posed to autonomous vehicles by navigation jamming and spoofing GPS (Global Positioning System) and GNSS (Global Navigation Satellite System) signals.

Navigation jammers are simple and already commonplace: they use strong radio signals to overwhelm (jam) the radio signals used for navigation and surveillance, preventing these signals from being received. In contrast, spoofers are complicated, and more dangerous. They replace the authentic navigation signals with counterfeit signals that misdirect the navigation system without detection.

Our work to date has focused on the detection of spoofing attacks on satellite navigation systems like the Global Positioning System. **Figure 1** shows a typical GPS antenna on the left that has a diameter of 5 cm or so. Importantly, it is sensitive

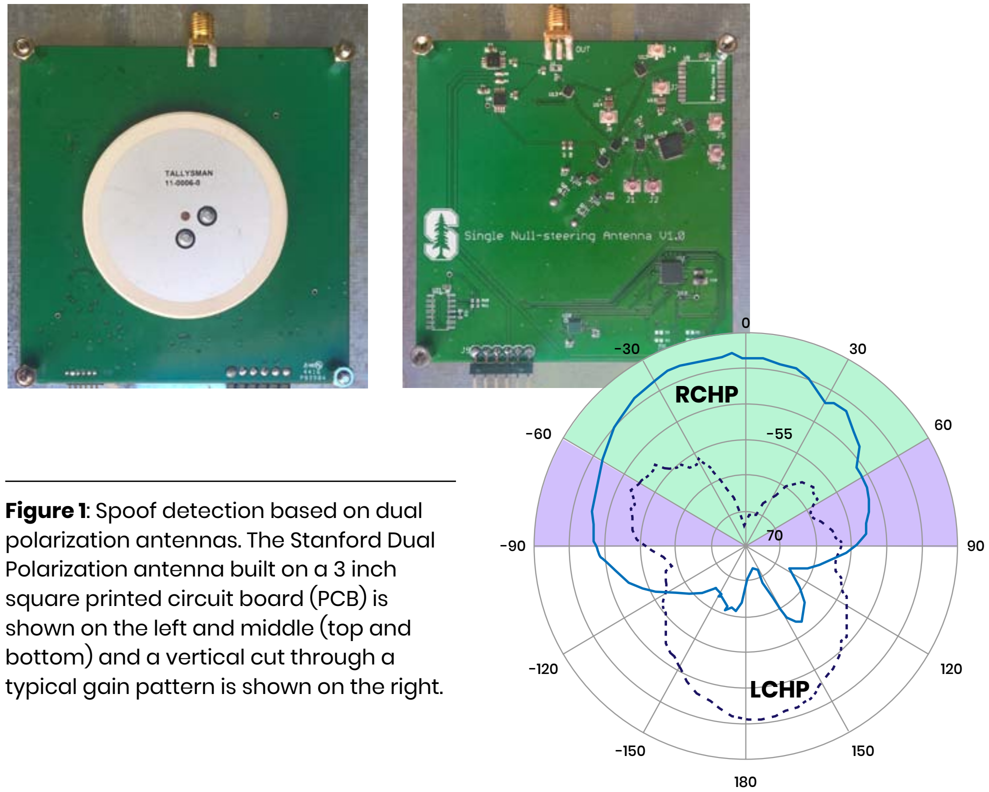


**Figure 1**: Spoof detection based on dual polarization antennas. The Stanford Dual Polarization antenna built on a 3 inch square printed circuit board (PCB) is shown on the left and middle (top and bottom) and a vertical cut through a typical gain pattern is shown on the right.

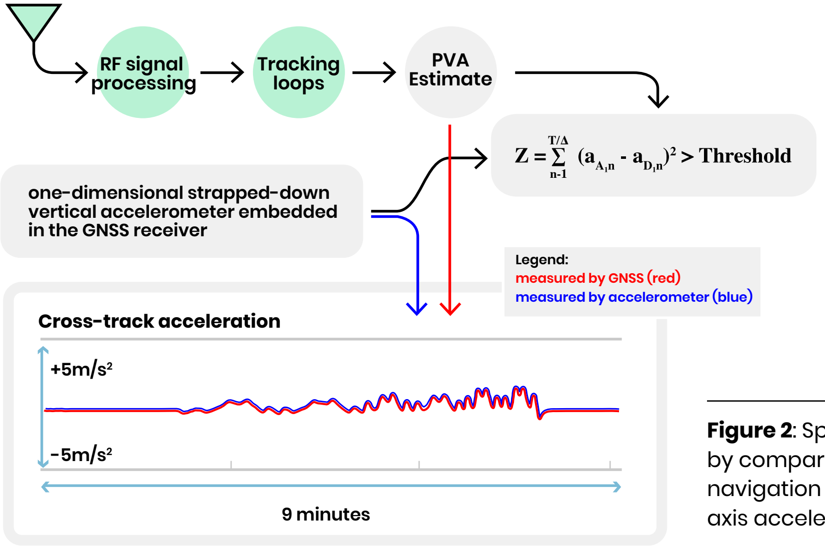


**Figure 2**: Spoof detection by comparing satellite navigation to a single axis accelerometer.

to two types of received wave. One wave has right hand circular polarization (RHCP), which is the wave radiated by the authentic GPS satellites. The other wave has left hand circular polarized (LHCP), which a normal GPS receiver should not ever see. Spoof detection compares the two. If the wave is predominantly RHCP, it can be classified as an authentic satellite signal. If the received wave is a mixture of RHCP and LHCP, then it can be classified as a counterfeit signal coming from the side of the vehicle rather than from above.

We are also investigating spoof detection comparing the cross-track acceleration of an automobile when one measurement is derived from GPS and the second measurement is made by a single axis accelerometer embedded in the onboard system. GPS estimates the cross-track acceleration by taking advantage of its high quality Doppler rate measurements. The single axis accelerometer is strapped down to the vehicle in the cross-track direction. As shown, the red (GPS) and blue (accelerometer) curves agree remarkably well in this very early driving trial (**Figure 2**).

Cyber safety for transportation requires the type of technical work performed in the Stanford GPS lab to toughen the navigation receivers with new satellite signals, digital message authentication, intelligent antennas and inertial sensors. Safety against jammers and spoofers will also require us to augment current navigation with completely independent sources of time and location, preventing automated vehicles being denied navigation, or maliciously misdirected.

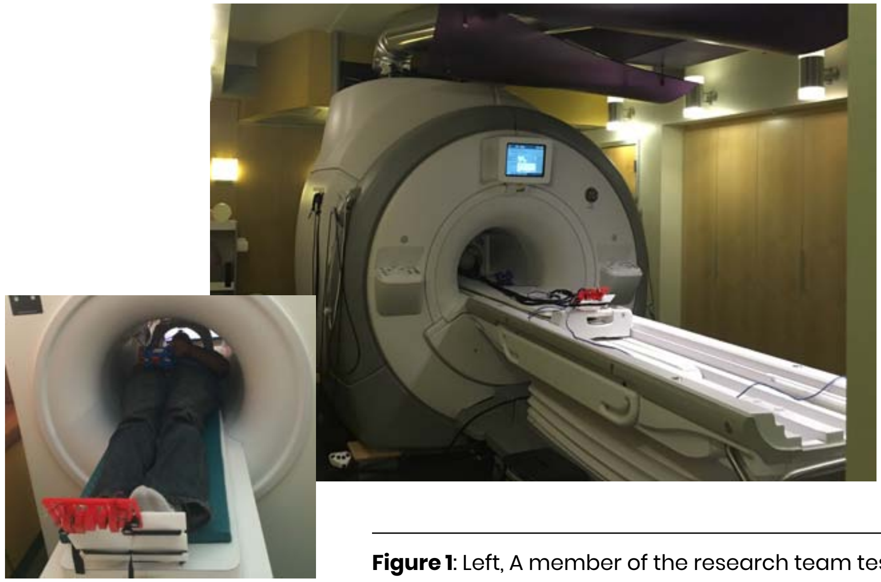


**Figure 1**: Left, A member of the research team tests the controllers in the MRI bore. Above, the MRI setup.

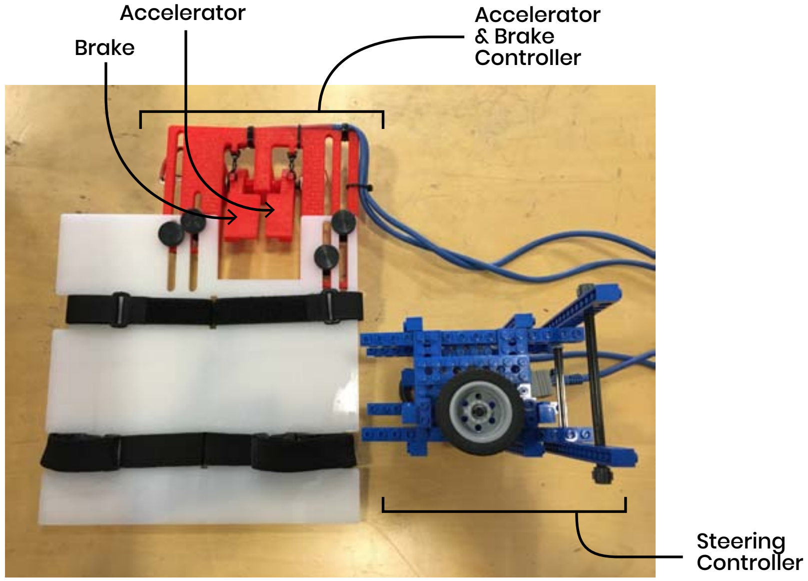


**Figure 2**: MR-safe driving simulator controllers, designed and built in-house.

# Cars & Brains

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**Allan Reiss**
Howard C. Robbins Professor, Psychiatry and Behavioral Sciences
Director, Center for Interdisciplinary Brain Sciences Research
Co-director, Center for Automotive Research at Stanford

Cars and Brains (CAB) is a collaboration between the Center for Interdisciplinary Brain Sciences Research, led by Dr. Allan Reiss, and the Dynamic Design Lab, led by Dr. Chris Gerdes. Our research focuses on identifying the brain regions and circuits involved in driving, and investigating the neural signatures of safe driving performance; information that is important for the design of autonomous systems that support, rather than distract or confuse the driver.

We use the safe, non-invasive, and ultra-portable imaging technique of functional near-infrared spectroscopy (fNIRS), which measures the same proxy for neural activity as fMRI (functional magnetic resonance imaging, see **Figure 1**). Our systematic research program includes simultaneous fNIRS and fMRI imaging during simulated driving, using a MR-safe steering controller (developed in-house, see **Figure 2**) to control a simulation of a vehicle being driven on the highway. We have found strong correlation between the "gold standard" fMRI signal, and the fNIRS signal, which gives us confidence in our interpretation of the fNIRS recordings we make during on-the-road studies. The simultaneous fMRI and fNIRS recordings have also allowed us to develop and define robust fNIRS signal processing practices, for example assessing wavelet-domain

**Figure 3**: A participant (behind the steering wheel) wearing eye-tracking glasses and fNIRS cap beginning the task in our experimental, steer-by-wire vehicle X1.

motion-artifact correction, and comparing different methods for removing noise. fMRI allows us to visualize deep-brain activity (which fNIRS cannot measure) and determine its correlation with cortical activity (which fNIRS can measure).

Moving from the simulator to on-the-road studies, we have expanded on previous work studying how drivers adapt to a change in vehicle handling, using fNIRS and a suite of physiological measures to investigate the changes in brain activation that allow drivers to successfully adapt to reversed steering control, using our experimental, steer-by-wire vehicle, X1 (**Figure 3**). These studies have also demonstrated that analyzing complementary driver data, for example head motion and heart rate, improves our analysis and interpretation of the fNIRS signal in a real-world environment.

To extend our studies beyond the task of basic vehicle control, we have most recently used our full-cab, 270°-screen driving simulator to investigate the effect of different levels of interaction with other traffic users, and with an in-car navigational device, affect driver mental workload and performance.

Moving forward, we are interested in the neurobiological underpinnings of skilled driving performance. For example what differentiates a professional driver from an average driver, and whether we can use this information to improve a driver's performance at the limits of handling. Intriguingly, our results to date suggest that individual brain states and personality traits may be predictive of a person's driving style and performance, and this gives rise to the possibility of tailoring automated vehicles and interfaces to an individual user. With our knowledge base, hardware, and collaborative research program, we are uniquely positioned to answer these questions in the coming years.

# Driving the Future Of Mobility

CARS supports work that propels us into the future of mobility and which explores new regions of research beyond what would be possible with conventional programs. Through CARS, students and faculty are exploring social issues around future mobility systems including questions of risk, minimizing negative outcomes from both everyday decisions in a conventional driving environment, to more unusual ones such as evacuating vulnerable populations from a natural disaster.

CARS researchers are also investigating novel sensing technologies. The GPS Lab leads students in developing new GPS antennas that minimize the potential for interference (either accidental or malicious) in vehicle location information. Prof. Gordon Wetzstein leads work in adapting the way vehicles use laser-based LiDAR sensors, offering the promise of sensors that are robust to visual obstructions that could mask dangers in the environment.

Thanks to the support of CARS affiliates, this body of work continues to grow. We continuously solicit feedback from CARS affiliates and share the progress of this work in detail through CARS events including webinars, research symposiums and workshops.

**Figure 1:** Experiment of speed control algorithm developed using Value Sensitive Design. The autonomous vehicle drives at a reasonable speed around the occluding vehicle and successfully yields to the pedestrian within crosswalk because it accounts for safety, legality and mobility.

**Dynamic Design Lab**

# Ethical Programming of Automated Vehicles

**Sarah Thornton**
Graduate Student, Mechanical Engineering

**Jason Millar**
Interdisciplinary Ethics Fellow
McCoy Family Center for Ethics & Society

**Chris Gerdes**
Professor, Mechanical Engineering

Automated and connected vehicles are introducing new ethical challenges to the world of automotive engineering and policymaking. Replacing human drivers with automated systems and artificial intelligence requires engineers and policymakers to confront a number of ethical questions during the design phase that would traditionally be left up to the driver. For example, should an automated vehicle be able to break the law, by crossing a double yellow line to get around a parked car? And how exactly should automated vehicles (and pedestrians) behave at crosswalks to balance human values like safety, mobility and legality?

Answering these, and other, ethical questions is becoming an increasingly important aspect of designing automated and connected vehicles, which frames one of our primary research questions: How do we empower and equip engineers to integrate ethics into the design of automated vehicles?

Our research is focused on providing engineers with ethically-informed design frameworks and practical tools to help them integrate ethics into their design work. We successfully demonstrated how a Value Sensitive Design (VSD) approach can practically inform engineers in the task of programming an automated vehicle to navigate a pedestrian crosswalk (**Figure 1**). VSD provided a useful framework for clarifying the various values associated with different practical design options (**Figure 2**). We have also begun piloting and validating our design tools through a series of interactive design workshops meant to engage a variety of engineering teams.

This work underscores our interdisciplinary approach, which combines ethics, engineering and policy expertise to explore the many ways that automated vehicle design is, can and should be, shaped by human values. We are motivated by the belief that we make better technology when it aligns with our ethical expectations and values.

**Figure 2 :** Simulation of speed control algorithm developed using Value Sensitive Design. The autonomous vehicle drives at a tolerable speed around the occluded pedestrian crosswalk because it accounts for safety, legality and mobility.

**Stanford Intelligent Systems Laboratory**

# POMDPs to the Rescue: POMDP Planning for Disaster Evacuation

**Chelsea Sidrane**
Graduate Student, Aeronautics and Astronautics

**Mykel Kochenderfer**
Assistant Professor, Aeronautics and Astronautics

Natural disasters such as Hurricane Katrina or the Northern California wildfires can't be prevented. However, the evacuation strategies used during these disasters are integral to saving many human lives. Implementing effective evacuation strategies is therefore an important matter of study (**Figure 1**). Modeling the environment in which a disaster takes place is difficult because of significant uncertainty (**Figure 2**). It is difficult to predict where evacuees will congregate for pickup, especially when typical communication methods may be unavailable, roads may become impassable unexpectedly, and the cost of solving these logistics problems sub-optimally is the loss of human life. To address this problem, we are investigating the use of methods from artificial intelligence and humanitarian logistics to the optimization of routing problems relevant to such

**Figure 1:** The city is modeled as a graph. In this example, one node represents the vehicle depot, one node represents the shelter, and the remainder of the nodes represent pickup points where people are waiting. The numbers on the nodes represent the number of people waiting there. The green node is the current location of the bus.

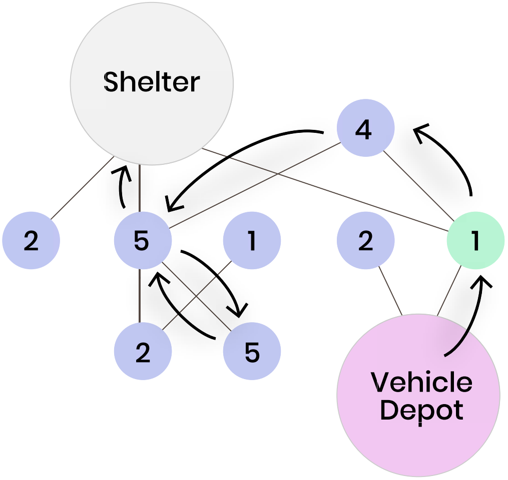
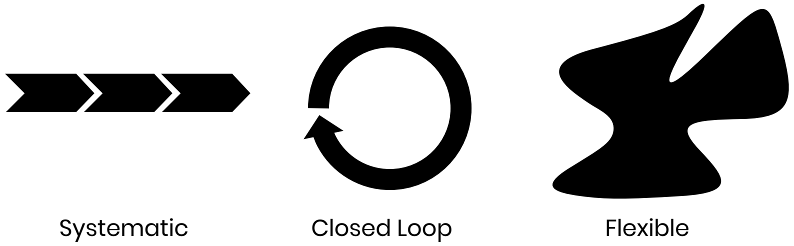
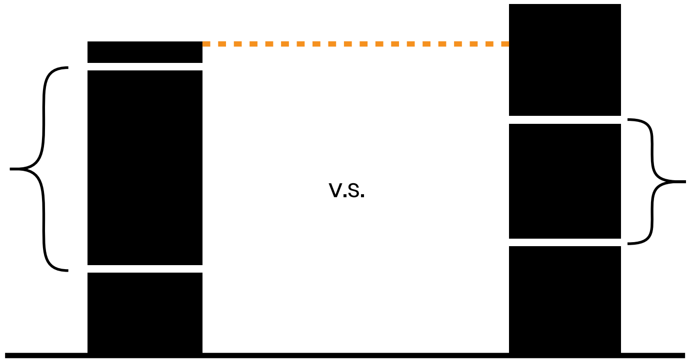


**Figure 2:** Markov Decision Processes provide a systematic, closed loop, and flexible way to model the stochasticity present in an evacuation scenario.



disaster scenarios. This project is focusing on evacuation routing in a more realistic model of the environment using traditional linear programming methods, Markov decision process models solved exactly using factored techniques, and approximate techniques that use neural networks. When using approximate algorithms, the safety of the solutions produced will also be assessed using frameworks from formal methods. The solutions produced using these techniques can be used to improve evacuation and relief operations. Even if not implemented directly, examining the solutions produced will provide insight into which factors – number, frequency, and destination of relief vehicles -- could materially improve evacuation outcomes (**Figure 3**).

**Figure 3:** The project explores different definitions of optimality. For example, does minimizing the maximum wait time for any group of people produce significantly different routes than does minimizing the total time it takes to pickup all evacuees?



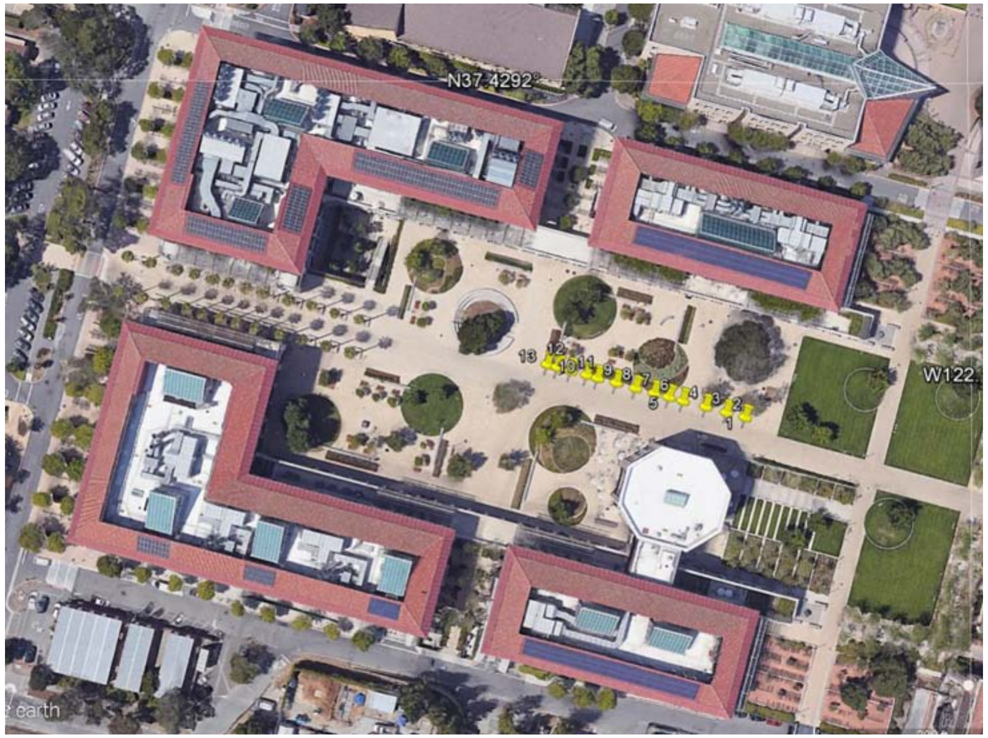


**Figure 1**: GPS data collected at 13 locations on the Stanford University Engineering Quad.

**Stanford GPS Lab**

# GPS Multipath Modeling & Detection in Urban Environment

**Shiwen Zhang**
Graduate Student, Aeronautics and Astronautics

**Per Enge**
Professor, Aeronautics and Astronautics

GPS multipath refers to the phenomenon when the satellite signals are reflected by buildings before reaching the user receiver. Such reflections can cause significant errors in the user navigation solutions. Multipath is a significant source of error in urban environments. Identifying and reducing the effect of multipath would enable GPS and the other satellite navigation constellations to contribute to high integrity railway control and autonomous vehicles operating in urban environments.

Our work focuses on the detection and mitigation of multipath error for ground vehicles in an urban environment. The multipath detection algorithm uses a 3D building model and a ray-tracing algorithm to predict the multipath effect at the estimated position. In addition, a sensitivity analysis on the building model is performed to estimate the confidence level of the prediction. Satellite exclusion is then executed based on the final prediction.

**FIgure 2**: Position error at each testing location.

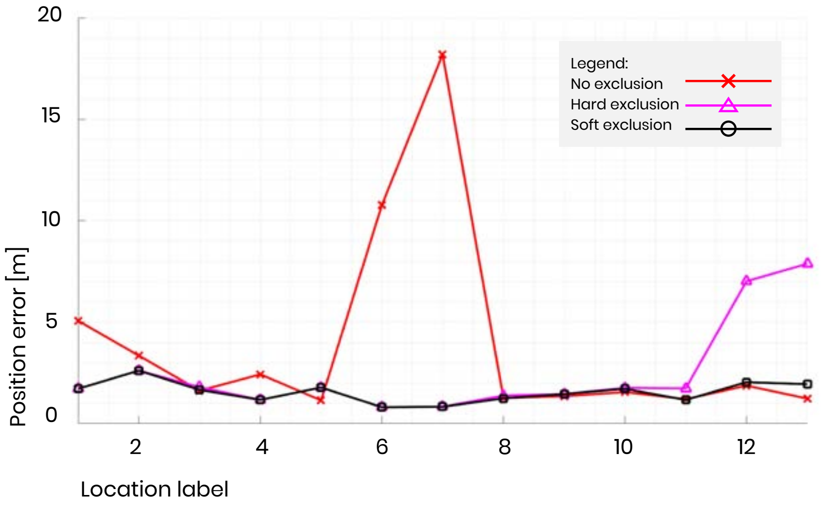
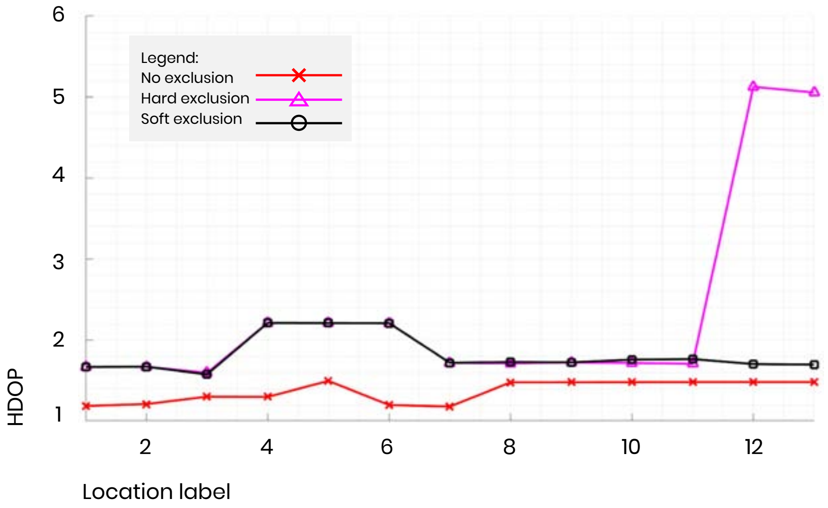


**Figure 3**: Horizontal dilution of precision (HDOP) at each testing location.



Field testing of the algorithms has been performed on the Engineering Quad at Stanford University. GPS data were collected at 13 different locations on the Engineering Quad (**Figure 1**). Three exclusion algorithms were implemented and experimental results were compared among the three algorithms. A “no exclusion algorithm” uses all received signals to calculate the position solution; a “hard exclusion algorithm” excludes signals based on the model prediction. And a “soft exclusion algorithm”, which is the most promising algorithm, performs exclusion based on the confidence level of the model prediction. Position errors at each location were plotted for the three algorithms (**Figure 2**). It can be seen that multipath induced large errors on the position solution for the no exclusion algorithm. Both the hard exclusion and soft exclusion algorithms improved the position solution when multipath was present. The soft exclusion algorithm prevented the hard exclusion algorithm from too aggressively removing signals that leads to worse position accuracy due to bad satellite geometry (**Figure 3**).

Future work will focus on the benefit of dual frequency signals and multi-constellations. Additional detection and mitigation algorithms such as residual checking will also be investigated.

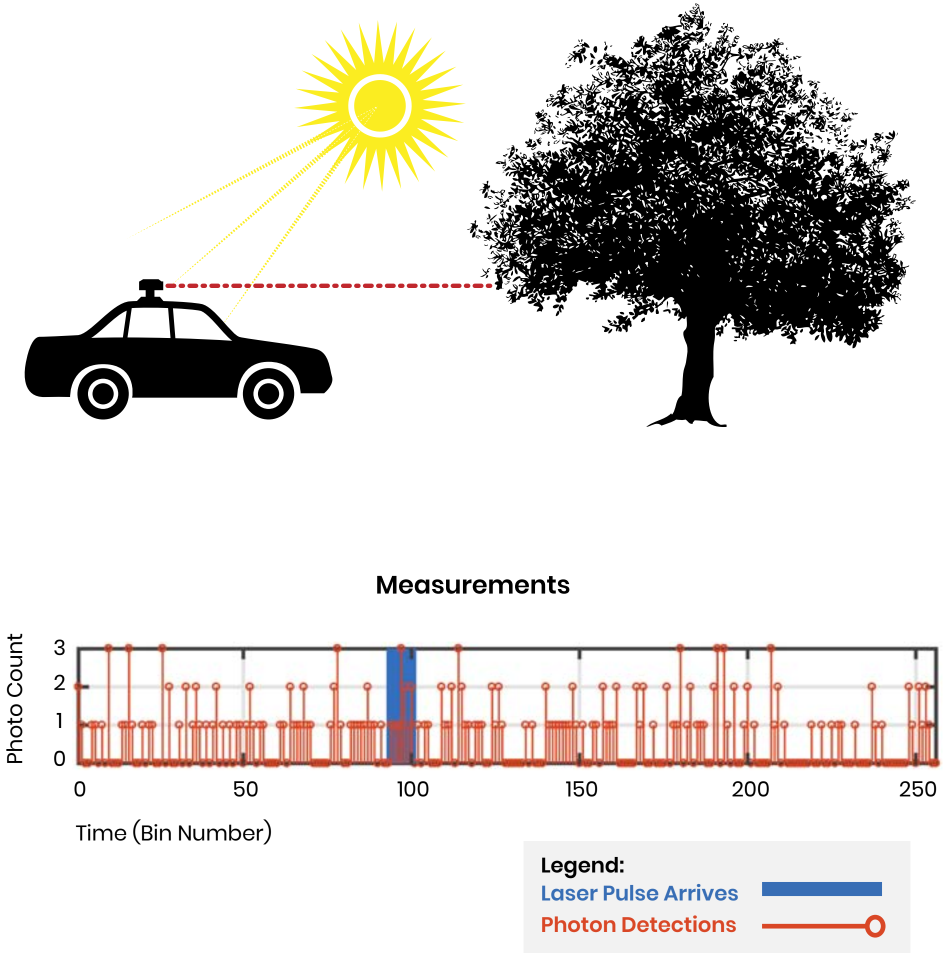


**Figure 1:** Sample histogram of photon events recorded by a single-photon avalanche diode (SPAD) in a LiDAR system. In the case where the laser signal is weak compared to ambient light, detected photons from the laser pulse (blue area) are difficult to distinguish from detected photons from ambient light.

**Stanford Computational Imaging Lab**

# Single-Photon LiDAR with Deep Sensor Fusion

**David Lindell**
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**Matthew O'Toole,**
Postdoctoral Scholar, Electrical Engineering

**Gordon Wetzstein**
Assistant Professor, Electrical Engineering

Single-photon avalanche diodes (SPADs) are an emerging sensor technology which measures the time of arrival of incoming photons with resolution on the order of tens of picoseconds. In a LiDAR application, SPADs are paired with pulsed lasers to estimate depth by recording the time it takes for a pulse of light from a laser to travel to a point of interest and return. By rapidly pulsing the laser (typically at MHz rates), measurements are repeated many times for a given point and a histogram of photon arrival events is compiled, enabling depth estimation. Given their extreme detection sensitivity and implementation in highly-scalable CMOS technology, SPADs have potential to become widely adopted in LiDAR technologies, especially for the autonomous vehicles space.

In sensing regimes where photon events recorded by the SPAD are dominated by background or ambient illumination rather

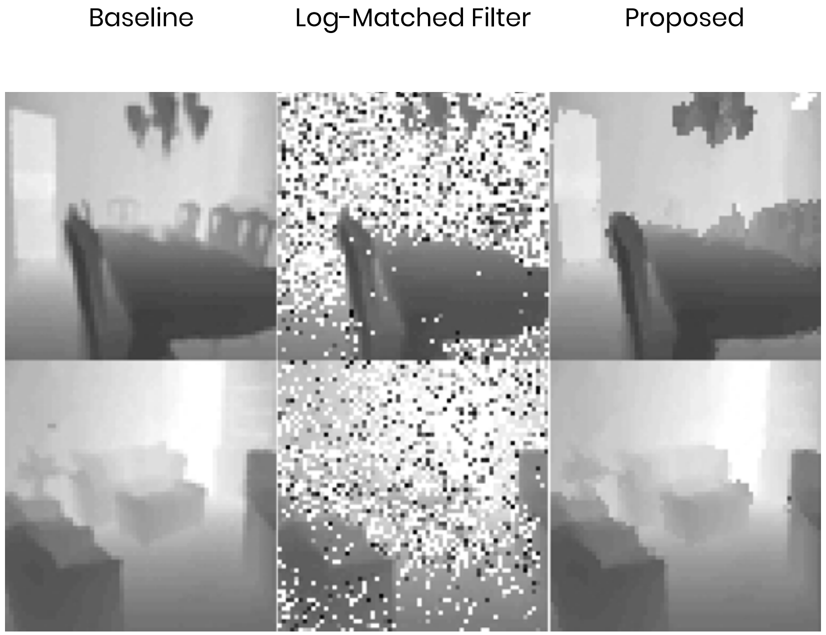

**Figure 2:** Comparison of depth map reconstructions using the conventional approach (a log-matched filter) and the proposed deep sensor fusion approach. The proposed approach uses both the intensity image and the SPAD measurements to reconstruct a depth map of superior quality to the naive approach.

than the laser signal (**Figure 1**), the time of arrival of the laser signal must be disambiguated from noise events in order to estimate distance reliably. The disambiguation problem can become challenging when operating any LiDAR system in ambient light at low power, at long range, or when scanning the system very rapidly such that any point in a scene is actively measured with only a few low-power laser pulses. As a result, 3D-reconstruction quality may degrade.

Our proposed system is designed to achieve robust, high-resolution distance estimates in ambient light with low-power lasers at a 15 Hz frame rate. We adopt a sensor-fusion approach which leverages the photon-efficiency of SPAD sensors and the high-resolution imaging capabilities of conventional intensity sensors (**Figure 2**). Our signal-processing framework uses deep convolutional neural networks and machine learning to combine an intensity image with the SPAD measurements in order to capture high-resolution details and inform the denoising and depth-detection process.

**Biomimetics & Dexterous Manipulation Lab**

# A Steering Wheel Skin Stretch Display for Enhanced Driver Situational Awareness

**Chris Ploch**
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**Mark Cutkosky**
Professor, Mechanical Engineering

Improvements in AI, sensing, and communication are giving “smart” cars increased situational awareness and ability to take part in driving decisions. It is an open question how the driving interface will evolve as these technologies progress. We are exploring using skin stretch haptic feedback, a currently unused channel of communication that could play a role in future interfaces. The lateral skin stretch is delivered to the driver’s hands through a mechatronic steering wheel with an embedded, rotating ring, providing analog magnitude and direction information (**Figure 1**). On-road testing has shown that skin stretch navigation cues are more accurate and less distracting than audio cues for already distracted drivers (**Figure 2**). We are now preparing to utilize Stanford’s driving simulator to test the ability to inform drivers of road irregularities (like an impending collision or ice patch) quickly and intuitively using skin stretch.

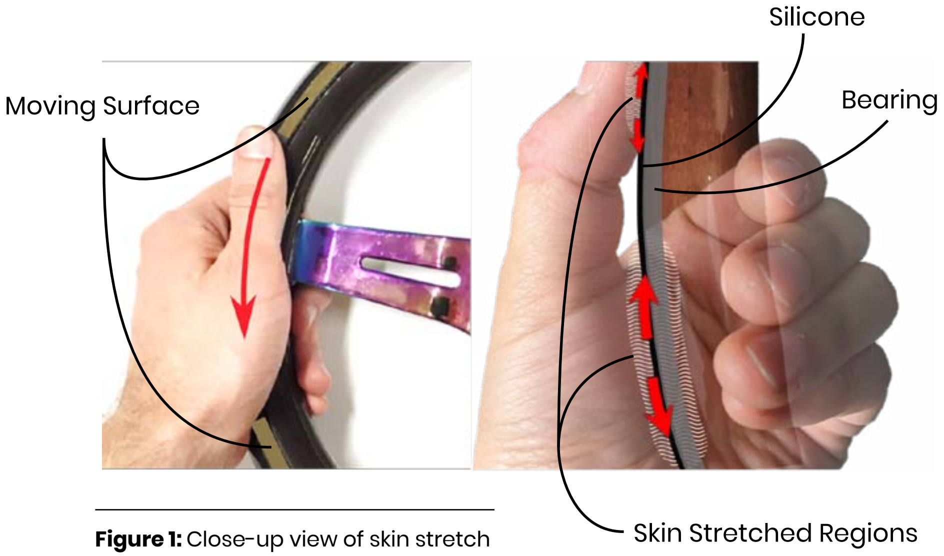

**Figure 1:** Close-up view of skin stretch produced by the steering wheel

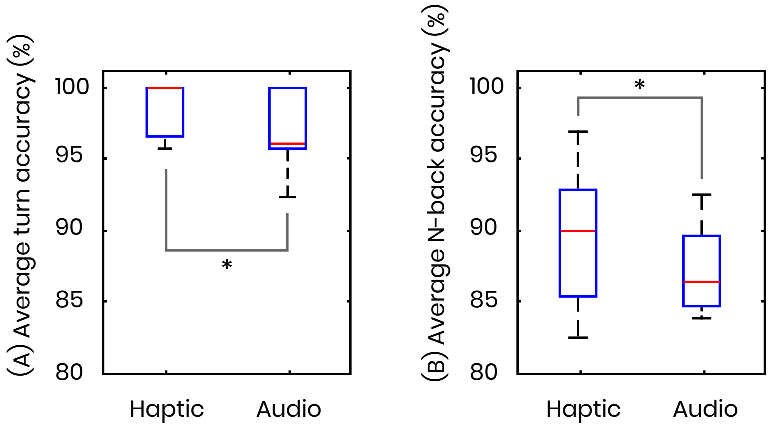

**Figure 2:** Skin Stretch vs. Audio Navigation Cue Performance. (A) Average turn accuracy (B) Average accuracy in secondary distraction task (N-back)

**Center for Design Research**

# Putting the Human at the Center of Automation

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Executive Director

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**Mishel Johns**
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**David Miller**
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**Wendy Ju**
Executive Director

The Center for Design Research (CDR) seeks to understand how humans will interact with automation and increasingly automated vehicles. CDR's research has focused on topics that include: prototyping and testing how a robotic, transforming steering wheel affects performance during transitions of control; understanding drivers' brain activity during manual versus automated travel; exploring how drivers from different cultures shift their attention between foreground and background features of the passing environment; driving performance during transitions of control that involve secondary tasks with varying degrees of engagement; and measuring and comparing drivers' evolving situation awareness of road hazards in both simulated and on-road environments. The driving simulator at Stanford is used for these human-in-the loop, human-machine interaction (HMI) driving studies (**Figure 1**). The simulator's toolset collects objective driving behavior data directly from the simulator, as well as data streams from eye trackers, cameras and other physiological sensors that we employ to understand human responses to myriad circumstances in the simulated environment

**Figure 1:** Stanford Driving Simulator with 270° wrap-around screen, 5 projectors and full vehicle at the Automotive Innovation Facility.

Small-scale driving simulators are increasingly incorporated in studies that involve multiple participant drivers who interact within the same environment (**Figure 2**). These laptop-based simulators interoperate with the large simulator, so we can have up to 6 participants simultaneously controlling their own vehicles within a single virtual environment, encountering the same traffic control devices and ambient traffic (**Figure 3**). The multi-user simulator helps us run experiments that focus on differences between (a) human operated and automated control environments, (b) individual versus group driving behavior, and (c) alternative cultural or regional settings. We can then infer differences in driving styles and interactions based on the aggregate data set. We are also conducting experiments to understand cultural differences in driving based on the driver's experience, culture, or country of origin. To support these studies, each portable simulator, along with its steering wheel and pedal set, can be packed into a case and shipped or carried to remote global locations for use by local participants. One study, currently underway in Japan, employs eye tracking to learn how drivers perceive, attend to, and react to (visual) environmental details in different ways.

The simulation tools at the Automotive Innovation Facility are an important instrument for student research at Stanford in autonomous vehicle technology drawing researchers from not only mechanical engineering but also the school of medicine and computer science. We continue to develop studies and expand the technical capabilities around the small-scale multi-user simulator and the large simulator.

**Figure 2:** Prototyping/Training Simulator

**Figure 3:** Graduate students testing laptop simulators

**NanoEnergy Lab**

# Machine Learning in Powertrains

**Rui Xu**
Graduate Student, Mechanical Engineering

**Hai Wang**
Professor, Mechanical Engineering

We are examining the feasibility and defining the scope of a possible onboard, on-the-fly optimization strategy for future, AI-enabled vehicle powertrain systems. Specifically, the project will provide estimations for fuel saving and pollutant emission reduction that can be achieved by implementing a “smart” powertrain strategy. This would replace “single-point optimization” (and design compromises) by real-time optimization, and can adapt to a particular driver in a particular region, climate, local emission regulations with respect to fuel/energy consumption and drive performance. Hybrids present another layer of design complexities yet they also offer additional advantages with respect to energy system optimization.

At a detailed level, we are exploring whether powertrain systems can utilize machine learning algorithms to achieve real-time optimization of individual-system performance with respect to a range of internal and external parameters. Internal features such as battery, electric motor/generator and range extender/petrol engine can be adapted to the external features such as driver behaviors, local and real-time factors to achieve prescribed performance enhancement as outlined in the next page. The project will also examine the question concerning the feasibility, and specifically, the roles of autonomous driving in facilitating the implementation of smart powertrain systems.

## Machine Learning in Powertrain Systems

### External Features ($x_Y$)

**Driver behaviors**

1. Driver temperment
2. Typical (daily) drive cycle
3. Autonomous?

**Local and real-time factors**

1. Local climate cycles
2. Terrain over daily drive cycle
3. Weather (eg. temperature, humidity)
4. Emission regulation
5. Traffic conditions
6. Fuel (octane rating, fuel composition)
7. Driving mode (starting, cruising, accelerating, decelerating, braking)

### Targets ($Y$)

1. Energy efficiency
2. Drivability
3. Emissions (particlates, $NO_x$ and HCs)
4. Noise level
5. Torque
6. Power

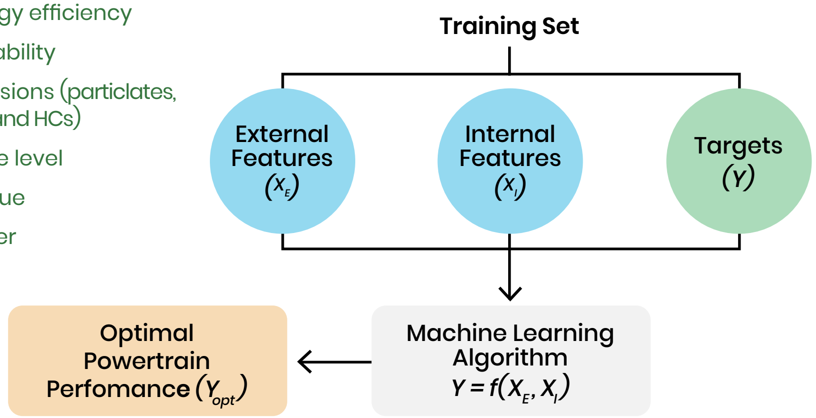
### Internal Features ($x_I$)

**Battery, electric motor/generator**

1. RPM of the electric motor
2. Battery temperature
3. Battery charge level
4. Regenerative braking (on/off)
5. RPM of the electric generator
6. Architecture (sequential/parallel)

**Range extender/petrol engine**

1. Compression ratio
2. Fuel/air ratio
3. Fuel injection timing
4. Ignition timing
5. Engine RPM
6. Engine temperature
7. EGR, Exhaust gas recirculation
8. Power splitter ratio



# Thank You

Established in 2008, CARS is a unique community which brings together academic researchers, students, as well as industry and government experts. Our industry partners provide the program with the resources to advance education and research in the automotive and mobility fields. The success of this community inspires us to further cultivate this model and develop more and deeper exchanges between academia, industry and government. We are grateful for our affiliate support, and Susan and Craig McCaw. These partnerships form the foundation as we work towards improving vehicle safety systems and creating new mobility models.

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## 1953-2018

**Vance D. and Arlene C. Coffman Professor**
Stanford School of Engineering

**Cover Image:** MARTY executes a 'Figure 8' manuever, transitioning from drifting left at 40° of sideslip to drifting right at 40° of sideslip in 1 second.

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