CONTENTS

An Update From The CARS & Revs Team ...........................................1

A GREAT COMMUNITY COMES TOGETHER

About Our Community .....................................................................5
Open Garage Talks ........................................................................7
The Classroom & Beyond ...............................................................9
Workshops ..................................................................................11
Stanford Solar Car Project ..............................................................13

ENVISIONING MOBILITY IN THE COMING DECADE

Safety ..........................................................................................17
Energy & Efficiency .......................................................................27
On-Demand ..................................................................................33
Humans & Their Machines ............................................................39
Data as Change Agent .................................................................47
AN UPDATE FROM THE CARS & REVS TEAM

For the past two years, the CARS and Revs programs have produced an annual review of our mobility activities. *Highlights* has become a great living document of our community, read by local R&D labs, hiring managers, and CEOs of the major automakers and suppliers.

With our 2016 Highlights, we decided to look forward. We put one simple prompt in front of our students and researchers:

**What changes do you want to see in the world of mobility in the coming decade?**

The question forced our community to think about the future they want to inhabit and how their current work aligns with that view. The document you hold in your hands is reflective of those answers and is a great time capsule of how some really smart people are thinking about — and working toward — the future.

Across all the responses we find safety is paramount to our researchers. Whether the approach is semi or full autonomy, at the heart of this work is a desire to make our roads more secure. Some are tackling the future of transportation through new hardware, new software, new policy, or perhaps entirely new business models.

Within our community at Stanford, we see the growth of a new face of mobility — and this growth is inherently multi-disciplinary. Being a great product designer in a new mobility world requires a relationship with policy makers, while being a computer scientist requires an understanding of the ethics, and so forth. The future of the vehicle will be built by those blending many skills and perspectives.

As it turns out, the future of transportation is going through a reinvention by creators who are reinventing their own operating beliefs. What does it mean to be a mobility leader in 2016, in 2026, or 2066? Use this issue of Highlights to peer into the future.
A GREAT COMMUNITY COMES TOGETHER
ABOUT OUR COMMUNITY

CARS and Revs support numerous opportunities for members of the community to become engaged in the future of transportation. One key initiative is in the development of informed policy for transportation at a state, national and international level. This year has brought enormous advancement to the regulation of autonomous vehicles, and the Stanford community has led efforts to ensure that the regulation brings the best knowledge from industry and research. The Automotive Innovation Facility was the site for two major policymaking events this year with the National Highway Traffic Safety Administration in April, and with the United Nations Economic Commission for Europe in October. CARS and Revs Director Chris Gerdes spent 2016 on leave as the Chief Innovation Officer of the U.S. DOT and will be back on campus early 2017. Stanford faculty and students continue to support the development of Automated Vehicle policies around the globe by sharing the insights gleaned from original research developed on campus.

Engagement through CARS and Revs is not just an outward facing exercise. Both programs support the participation of the next generation of researchers that view Stanford as an aspirational institution, or incoming students who are looking for inspiration in their studies. JR Hildebrand joined the community this year as a “racer in residence” supporting students on the track in testing of full-scale cars, and joining the Freshman Sophomore College (“FroSoCo”) in the development of small scale models as an extracurricular activity. The Automotive Innovation Facility is a beacon for budding researchers, and students from area elementary, middle and high schools frequently tour the facility and join presentations by members of the Stanford community.
OPEN GARAGE TALKS

One of the most successful of our community events, the Open Garage Talk series brings in luminaries to share their experiences and inspire students.

In keeping with the name of the event, these are open to the public and have become popular with many different areas of interest. It’s not atypical to see Stanford researchers, auto industry engineers and startup founders chatting in the happy hour period beforehand. Each event we host at the Automotive Innovation Facility includes a special, closed-door meeting between the speakers and a handful of Stanford students. If you’re in the area during the year, please join us for our next Open Garage Talk.

2016’s Open Garage Talks included speakers such as Patrick Dempsey, Patrick Long, Larry Burns, Rick Wagoner, and Josh Giegel. We were lucky to have moderators Diego Rodriguez and Perry Klebahn with us, too.
Coursework is one of the core functions of any academic institution and CARS and Revs continue to grow and diversify the automotive and mobility-focused classes available to students. While we sometimes find that this learning happens within the confines of a classroom, mobility learning often extends well outside the walls of Stanford.

Examples of this are everywhere within our community. Whether it is a group of ME200 students taking part in the Pebble Beach Concours d’Elegance or students from Stanford Solar Car Project and Dynamic Design Lab on a field trip of a lifetime to Williams F1 in England, we believe the classroom can extend beyond a physical space. In addition to touring their manufacturing facilities, students spent two days discussing aerodynamics, composites, vehicle dynamics, program management and vehicle integration, and instrumentation with Williams engineers.

Back at campus, our ME302 series draws from a cross-section of students—not only engineering, but also business, law, and the humanities. This multi-disciplinary group strengthens the new face of mobility. Revs Executive Director Reilly Brennan led ME302C, a new course on mobility entrepreneurship where students gained firsthand insight into the challenges of launching a new business. CARS Executive Director Stephen Zoepf led ME302A together with guest lectures from transportation researchers at Stanford, sparking collaboration opportunities between faculty and students. Jan Becker will join us as a lecturer for ME302B, teaching the fundamentals of Driver Assistance and Automated Driving.

For 2017, several new courses are under development by CARS and Revs including Electric Transportation, which will teach the basic engineering principles behind batteries, motors, and electric vehicles, and the policy and economic issues surrounding their use.
WORKSHOPS

Our workshops form a key point of engagement and interaction between affiliates, Stanford faculty and students, and others in the vibrant Silicon Valley community. In many ways these workshops are a philosophical extension of the courses that CARS and Revs sponsored over the last number of years, and we found the experience rewarding for both internal and external partners.

In April we hosted our first workshop on In-Vehicle Notifications, bringing together innovation from the mobile device community with the focus on the driver and how they interact with a multitude of data and messages now present within the vehicle. In June we hosted our Unconventional Mobility workshop and a showcase of novel compact vehicles that have been unavailable in the United States outside controlled demonstrations. Users of other unconventional devices took the opportunity to outline the barriers to adoption and use of vehicles that defy classification in conventional categories. Transportation planners, policymakers and administrators described the challenges in creating safe and effective policies for licensing, allocation of urban space and development of new visions of transportation. In September, the CARS and Revs community came together again to engage in a detailed discussion of sensors, automation and engineering choices in our Driving Constraints workshop. The event created a dialogue between two important communities: vehicle manufacturers and developers seeking to improve the function and accessibility of automation, and faculty from Stanford’s school of Electrical Engineering and Computer Science seeking new challenges for the evolving capabilities of sensors.
The Stanford Solar Car Project (SSCP) is one of America’s top solar car teams and competes in the biannual World Solar Challenge (WSC) across the Australian Outback.

Entirely student-run, SSCP builds vehicles that push the limits of high-efficiency transit, renewable energy, and the associated technologies required to successfully integrate these concepts. Students on the team build solar cars to share their enthusiasm and educate themselves and the community through hands-on engineering. The team is currently about halfway through the design of their 2017 car, which will compete in the most challenging iteration of WSC that has ever been held: the amount of solar cells we can use has been restricted to just half of what it was in the first race, and other rules continue to drive engineering ever closer to a regular car. The project strives to build reliable and ever-improving cars not only to represent cutting-edge work at Stanford, but also to allow students to tackle competitive engineering challenges while still undergraduates.
ENVISIONING MOBILITY IN THE COMING DECADE
SAFETY

Across our entire community, researchers viewed safety as the #1 priority for mobility’s future. The benefits of autonomous vehicles might be found in increased productivity, decreased energy consumption or rest during commute hours, but our community believed those gains are only valuable if we’ve solved for the near 1M global road deaths each year. The contributions to safety come from numerous sources, such as improvements in sensors, algorithms, validation and verification techniques. Research conducted by our faculty and student body addresses all of these areas, and includes efforts focused at both fully autonomous vehicles and shared control scenarios. Throughout these efforts is a theme of transformation: where we are today, and how achievable near-term goals can bring us closer to a safer world of future mobility.

What changes do you want to see in the world of mobility in the coming decade?
Mobility is undergoing rapid changes as autonomous driving, vehicle connectivity, and ride-sharing services are being introduced.

However, with these new systems come daunting validation problems. Thoroughly testing a self-driving car in the real world would take billions of driving hours in order to properly build confidence and establish trust.

My research has been focused on overcoming these validation difficulties. I would like to see the automotive industry establish a system of shared safety data. Inspired by the Aviation Safety Information Analysis and Sharing (ASIAS) program in civil aviation, sharing information would allow us to develop better models of human drivers, roadways, rare events, driving conditions, and of the impact of autonomous vehicles. It would let us establish and track safety metrics, maintain a safety feedback loop, and help with the standardization of safety systems. Most importantly, an automotive ASIAS would encourage a culture of safety and would in turn lead to a tangible improvement in efficiency and lives saved.

I’d like to see cars in the near future with shared human-computer control.

Computers must become better than most humans in adverse conditions, and computers should be able to take control in such situations. In the more distant future, I envision vehicles capable of full autonomy. The fully autonomous car presents significant benefits to passenger safety and offers improved mobility for those unable to drive today’s vehicles. My research focuses on mechanical design of drive-by-wire vehicles. These by-wire systems will grow to be more prevalent as shared control becomes integrated into production vehicles.
Just like humans, sensors on autonomous vehicles are susceptible to limitations. LiDARs (or laser scanners) sense objects around the vehicle with high accuracy and resolution, but have limited field of view and range.

My current research connects control and perception together to navigate in scenarios where the sensors lack perfect knowledge. For example, determining how to maneuver safely when a pedestrian crosswalk has a large vehicle parked in front. By harnessing information, or rather lack of information, from the LiDARs atop Trudi, a fully automated hybrid Ford Fusion, the control algorithm can intelligently adjust the vehicle's speed and path to safely traverse an occluded pedestrian crosswalk. It is important to address the limitations of the sensors in the development of control and perception algorithms to ensure the safe operation of autonomous vehicles in all conditions.
JOHN ALSTERDA
Mechanical Engineering, PhD 2020

In the coming decade, I’d like to see vehicles predict and prevent accidents more effectively.

The newest accident avoidance features available from major manufactures are encouraging, but their vehicles’ ability to sense the environment, plan intelligent paths, and follow them safely are still quite immature. My research aims to help evolve the current strategy, towards the navigation of stable paths on roads among predictable agents.

MAXIME BOUTON
Aeronautics and Astronautics, MS 2016

I would like to see 100% safe roads where autonomous vehicles are able to anticipate human error in complicated situations.

Autonomous vehicles will have to leave highways and face more complicated situations such as urban intersections. My research focus is about how can we scale up the current AI techniques to dense traffic scenarios.
JONATHAN GOH
Mechanical Engineering, PhD 2018

Electronic Stability Control (ESC) systems are standard on cars today, and help to keep a car within the stable handling limits imposed by friction. However, when maneuvering to avoid an obstacle during an emergency scenario, it is sometimes helpful to purposefully exceed these limits, albeit temporarily.

I work on developing control algorithms that will allow autonomous vehicles to robustly understand and drive in these fast and unstable regimes, with the goal of improving road safety in even the most extreme of scenarios. This work is currently manifest in MARTY, the world’s first – and only! – autonomous drifting electric DeLorean.

JOHN SUBOSITS
Mechanical Engineering, PhD 2018

Through optimal trajectory planning and control, I solve problems related to autonomous driving near the limits of a car’s capabilities.

Modelling the stability and performance limits of vehicles more accurately while balancing the complexity of models and algorithms with the quality of the results is an important part of this work. Currently, I am working to give Shelley, the Dynamic Design Lab’s autonomous race car, the ability to rapidly regenerate its racing line to adapt to changing conditions. By continuously testing how close the car is to exceeding the performance of the best human drivers and professional racers, my teammates and I hope to give autonomous cars the ability to avoid collisions whenever physically possible.
ENERGY & EFFICIENCY

While researchers feel strongly that the desire for improved safety is a key motivating force in their work, forthcoming technological changes in vehicles will bring about equally significant evolutions in how we use them. If autonomous vehicles become more expensive due to their increasingly complex suite of sensors and hardware, how can we share their use across a 24-hour period to drive down costs, lessen the load of a congested urban core and find greater efficiencies? Themes of quality of life permeate researchers’ desires: improved air quality, more efficient usage of precious urban infrastructure, and more effective use of a passenger’s time to tasks other than driving.

What changes do you want to see in the world of mobility in the coming decade?
30% of the US energy use is consumed by transportation, overwhelmingly that is oil as it is energy dense and a liquid that is easy to move by tank and pipeline.

Electric vehicles will reduce the dependence on oil and the attendant pollution, but even electrification doesn’t fully ameliorate the negative effects of transport, as there is still urbanization to consider. In Western Europe, even small cities are more dense and have good public transport, drastically reducing energy use, and also reducing home energy use and land use as a whole. Additionally, more compact communities are more cohesive, there is more social interaction, and the people tend to live longer, healthier lives—especially when they can walk or bicycle to where they are going. The Netherlands, Denmark, and Germany have amazing pedestrian and bicycle infrastructure, with bicycles and pedestrians preferred over vehicle transport in many cases—this is the vision I have for the US.

I would like to see autonomous vehicles utilized in such a way that reduces the footprint transportation leaves on the environment.

If cities do not need parking infrastructure and have a smaller surface area, if we have fewer cars on the road by using them as a shared resource, and if each vehicle can operate more smoothly and efficiently than human drivers, then this could have a huge positive impact on our environment. First, however, we need these autonomous cars to be reliable to even unpredictable events on the road. I work on developing a control framework that is robust to both model and environmental uncertainty. My research focuses on improving a vehicle’s ability to intelligently modify its behavior to reduce the uncertainty associated with occluded sensors.
As self-driving technology gains adoption in our cities, new mobility modes will emerge.

Personal vehicles, which sit idle more than 90% of the time, will be largely replaced by self-driving taxis, which can offer on-demand transportation with quality of service comparable to private cars and much lower cost of ownership. Commuting to and from work will become a far more pleasant experience: commuters will be able to watch a movie, read a book or catch up on their Facebook feed as the self-driving car brings them home.

Over time, robo-taxis will change our cities' infrastructure. Self-driving vehicles do not need parking spaces in the city center: valuable blocks will be repurposed for homes and businesses, mitigating the need for long commutes and making our cities more affordable. My research focuses on autonomous mobility-on-demand, and in particular on congestion-aware routing and pricing of networks of self-driving vehicles.
What changes do you want to see in the world of mobility in the coming decade?

ON-DEMAND

If vehicles become a shared asset among multiple people (or, perhaps, within a municipality or affinity group such as a workplace or campus), how will we receive a maximum benefit given the variability of our day? On-demand models seek to give us a vehicle when we need it and never when we don’t (goodbye, parking). Researchers see continued themes of integration: both integration of hardware and software, integration of personal transportation modes with public transportation, and integration of the transportation infrastructure with other social systems. Students see the power in leveraging devices and software to bring about changes in large-scale socio-technical systems.
Envisioning Mobility: On-Demand

CHRISTOPH MEYER
Graduate School of Business, MBA 2017

I am hopeful that we can create a world where we no longer individually own vehicles.

I am excited about a world where urban spaces are returned to pedestrians and where we can more efficiently use our transportation assets to have less of an impact on the environment. I also hope to see a world where we can seamlessly integrate different modes of transportation. I believe transportation is similar to energy in which there is no silver bullet: this is an ‘all of the above’ scenario and I hope we can coordinate these different modes.

RAMON IGLESIAS
Civil Engineering, PhD 2019

I would like to see mass adoption of electric, autonomous mobility-on-demand systems (E-AMoD).

Such systems have potential to greatly reduce our carbon emissions, improve air-quality within urban centers, increase travel safety, make commuting more affordable and more accessible, and build the foundation for new services that are currently impractical (like cloud computing was to web development). At the Autonomous Systems Laboratory, we are working on algorithms for controlling large fleets of autonomous vehicles. Current research avenues include the issue of rebalancing/repositioning vehicles according to anticipated demand while minimizing the impact on traffic congestion, the coordination of autonomous fleets with public transportation, and the potential interactions between autonomous electric fleets and the power grid.

I am hopeful that we can create a world where we no longer individually own vehicles.
In the next decade I want to see the rapid acceleration of the replacement of vehicle miles travelled using individually owned human driven vehicles with those using shared fully autonomous electric vehicles. I want to see this growth in autonomous electric mobility on demand usher in a decentralized “Autonet” that gives rise to the massive innovation and value creation similar to what is being built on the Internet. The Autonet won’t consist of proprietary vertically integrated services like AOL but open robust technology and commercial stacks that allow innovation with massive leverage and value to consumers. With 55 employees WhatsApp was able to create a messaging network that provided better communications for hundreds of millions of smart phone users. I want to see the Autonet emerge where less than 100 engineers can create the next Uber in a few months that provides a cheaper, better or more enjoyable form of transport for billions of people or packages.
Students and researchers feel that developing future transportation systems is a profoundly empathetic endeavor, and bringing mobility to someone who lacks access today is an admirable goal. These could be persons with a disability, or even drivers unable to pass today’s driving test requirements due to their age (both young and old). Some researchers view their work as improving the sensing or decision-making capabilities of humans, while others view their objective as removing driving responsibility from the human entirely. The way that we put these vehicles into the hands of users will be critical, and understanding how consumer perception impacts the early rollout of autonomous vehicles is of utter importance.
The world of personal transportation is changing rapidly today, both in terms of the cultural significance of the automobile and in terms of the availability of ride-sharing services, and the next wave of change will likely be due to vehicle automation.

Automakers have been quick to introduce many driver-support features, but the critical point in technology adoption and utility to the user will be when drivers are allowed to sit back and engage in other activities and not have to ‘supervise’ the automated vehicle.

Interestingly, some state governments have been quick to legislate and allow such systems, possibly due to interest from the industry and due to the huge lifesaving potential. Most people I have interacted with are extremely optimistic about the technology, but it is critical that we not allow accidents that can turn public opinion and set the field back by years. I work on developing systems that allow drivers and automated vehicles to collaborate in the task of driving. I anticipate that this will be most relevant in situations where a driver might choose to intervene while an automated system is active, or in transitions of control where a gradual transfer of responsibilities might be preferable to a sudden full switch. Technology adoption and utility to the user will be when drivers are allowed to sit back and engage in other activities and not have to ‘supervise’ the automated vehicle.

For a society in which personal mobility is strongly focused on cars, I’m excited about the potential of autonomous vehicles to bring mobility to those who cannot — or can no longer — drive a vehicle. In addition, I’d like to see autonomous driving features on the streets with the goal of improving road safety.

My current research is focusing on estimating the friction between the four tires of an autonomous car and the road, and developing a control framework that is explicitly operating the vehicle at the peak of the tire force potential. It is exciting to develop these systems for a real vehicle and collecting data at a race track every month. This is a great test case for demonstrating the value of such algorithms for preventing road departures and avoiding obstacles.
I am currently working on a neurological adaptation study, which involves brain imaging during dynamic driving tasks. Our team is developing and executing experiments that provoke neurological response to unexpected driving events in order to correlate handling of sudden dynamic changes with activity in different regions of the brain.

We use functional Near Infrared Spectroscopy (fNIRS), a mobile imaging method, to measure brain activity. In order to verify the data from this relatively new technology, we concurrently collect functional Magnetic Resonance Imaging (fMRI) data during our experiments. Ultimately, we analyze driving data and brain data to determine whether, and to what degree, adverse driving conditions and performance correlate with increased neurological activity. The results of our research will lead to a better understanding of how well humans are able to adapt to sudden changes in driving characteristics on the neurological level.
I would like to see mobility solutions tailored to the safety, convenience and comfort of many different populations, to better reflect the heterogeneity of road users and their needs.

In addition to the clear opportunities that automated vehicles and shared mobility systems offer to the aging population, those with disabilities, and those without the financial security to own a personal vehicle, I am excited by the prospect of designing automated solutions that cater to people's differing "styles" as operators, or passengers, of automated vehicles rather than producing a "one size fits all" solution. My research, studying the brain activity of people as they use or interact with automated driving systems, investigates the brain activity patterns that underlie the differences in the way different people operate various automated driving systems. I am also interested in how different user's mental workload increases when confronted with a novel system, and how this workload changes over time, as the user learns to adapt to the new system.
Data as Change Agent

Data might be the new ‘oil’ of the future of transportation. How we use it will impact nearly all parts of the vehicle stack, from urban planning, safety and vehicle R&D. How will we collect that data and use it efficiently? How will we be safe keepers of this data, and conversely how will we push hard to make sure we obtain the maximum amount of data for the most good? Future mobility business models will hinge on the ways that data factors into partnership agreements, user conditions, and the provision of service. Researchers are already recognizing the importance of data gathering in their own work and developing strong stewardship habits that will serve them in their professional careers.

What changes do you want to see in the world of mobility in the coming decade?
I am interested in seeing how advances in machine learning and control in automated driving lead to the increase in mobility as well as safety. Big data will play a role in the future of automated driving and how we can use this data to make automated vehicles perform better over time is still an open question. I am also interested in how conventional models and control techniques can be augmented by the data gained by intelligent vehicles and how this can be used to increase safety. Currently I am working on using model based and machine learning techniques to learn the longitudinal dynamics of Shelley, the DDL’s autonomous Audi TTS, and in this work, I have learned the importance of data and learning in constructing models that compare or perform better than simple physics based models.

I hope our means of transportation will get smarter in the next decade, through wider use of sensory systems and increased connectivity. I’m convinced this will lead to increased safety, a more efficient use of our time on the road, the rail or in the air and faster, more efficient traffic flow especially in congested situations. This development goes hand in hand with a higher trust in algorithms and the sensors they base their decisions on. To help ensure that we can do so with a clear conscience, I am currently working on improving the safety, accuracy and integrity of the position information we get from satellite navigation systems such as GPS.
THANK YOU

Thank you to our affiliates, donors and collaborators for your continued support and for making 2016 a banner year for our programs. In particular we would like to thank our affiliate partners, the Revs Institute, Miles and Parker Collier and Susan and Craig McCaw.
Cover Image: At our Open Garage Talk series, we welcome members of the Stanford community and beyond into the Automotive Innovation Facility. Pictured on the cover is a good representation of the building’s energy - it has served as both a gathering and realization space, drawing in people of all types. During November’s Open Garage Talk event, featuring Hyperloop One’s co-founder Josh Giegel (MS ’08), visitors gathered around Shelley, Stanford’s autonomous race car. The community congregates to hear from notable people from the automotive world who share their views on design, product development, regulation, business, and life.