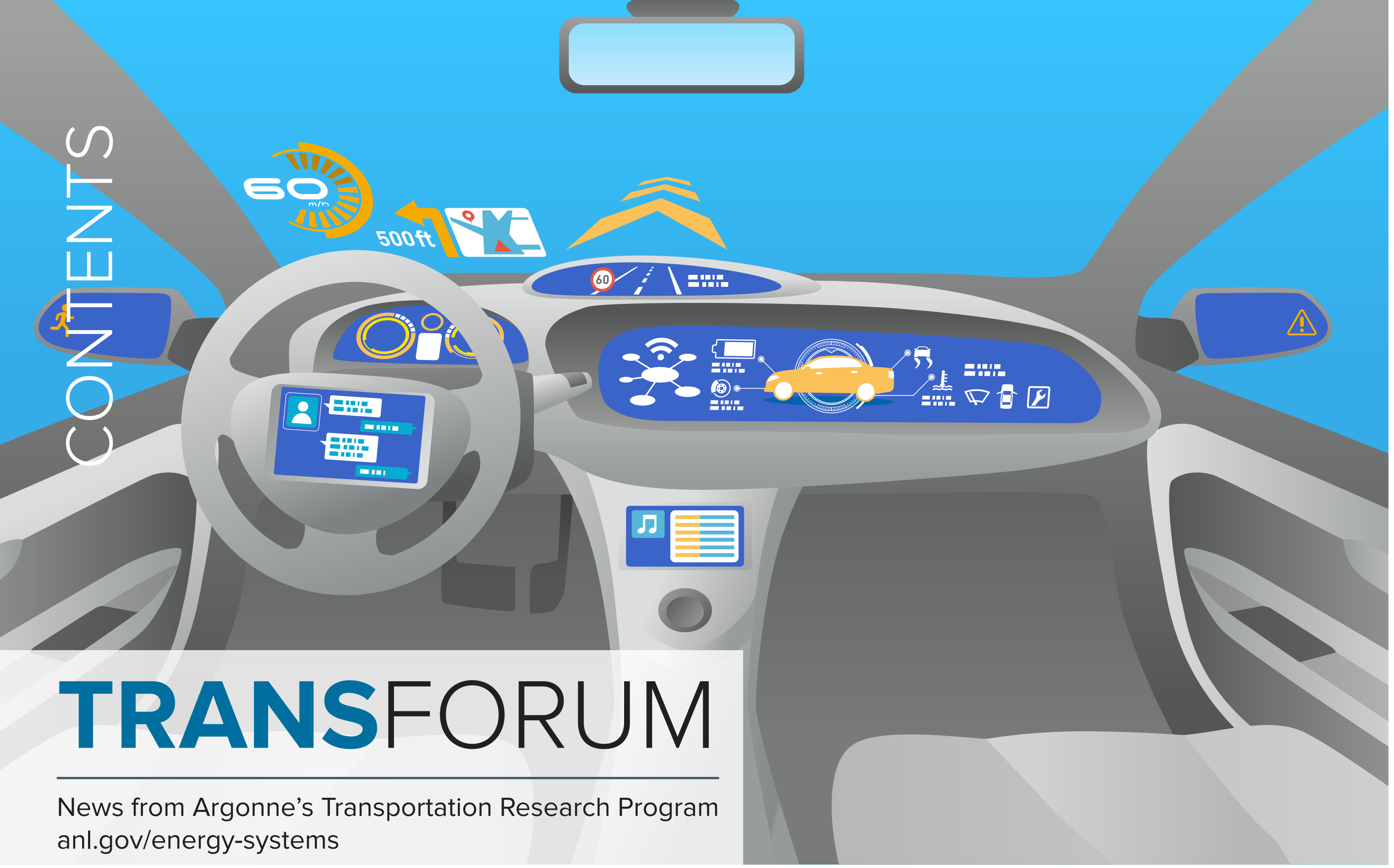
Argonne
NATIONAL LABORATORY

SMART MOBILITY

A special issue of **Trans**Forum – News from Argonne's Transportation Research Program



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Driving Toward a More Mobile Future

America's love affair with the automobile is well-known. From the early days of the Model T Ford to today's electric vehicles and hybrids, Americans have long favored four wheels when it comes to taming the country's vast territory.

With an aging infrastructure and an ever-increasing population of drivers, however, the honeymoon may soon be over.

The crumbling state of our roads and the surging number of vehicles on America's highways and byways is more than just an inconvenience for commuters. It is a serious threat to America's culture of auto-enabled mobility.

Consider the numbers: the cost of time lost to congestion alone adds up to $120 billion annually, and automobile accidents add up to $87 billion[1] each year.[2] Not to mention the increased carbon dioxide (CO_2) from tailpipes that exacerbates climate change. And soon, unprecedented stringency in efficiency regulations will require rapid technology discovery, adaptation and deployment.

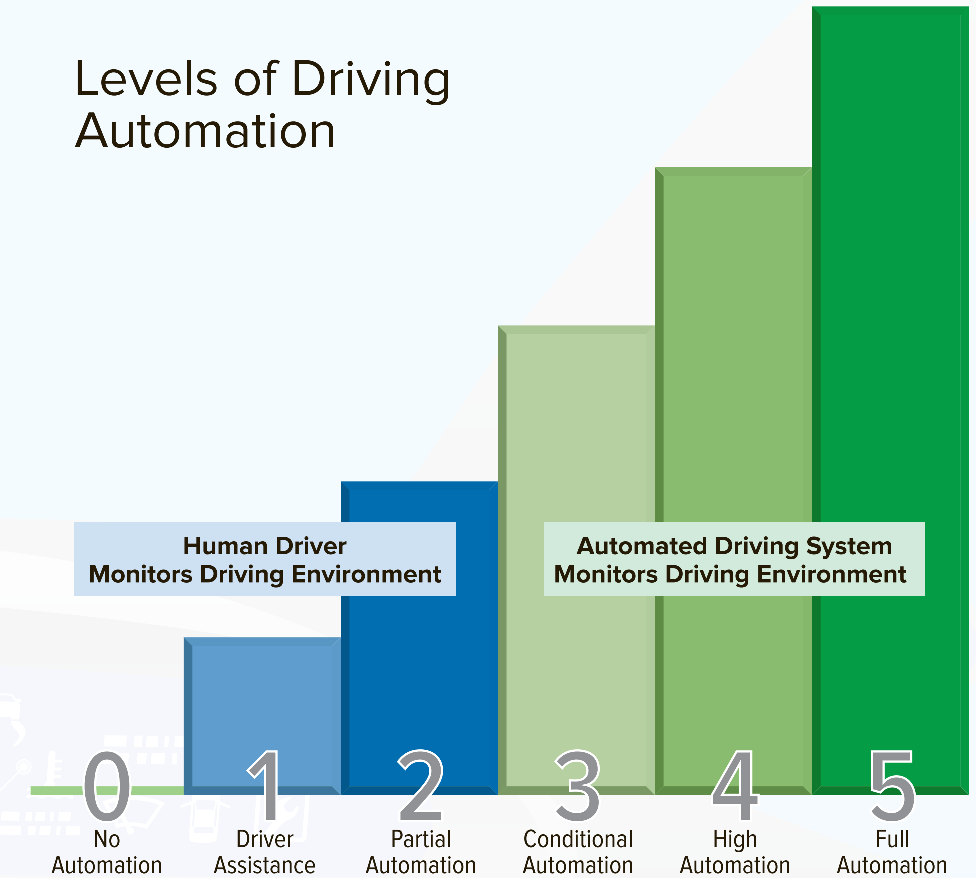
If America's population is to continue to move largely by car, a paradigm shift is in order. And few alternatives hold the promise of Connected and Autonomous Vehicles (CAVs), a term that encompasses a wide range of technological and infrastructure innovations that will enable largely self-operated automobiles to communicate with their surrounding environment for maximum mobility, safety and energy efficiency. CAVs are among the most transformational technologies introduced in decades and present new opportunities for mobility, American infrastructure and transportation business models.

> CAVs are one of the most transformational technologies introduced in decades.

The term "connected" refers to the vehicles acting in concert via computer applications that increase efficiency; just as humans are connected by way of the Internet and smartphones, so too will tomorrow's vehicles share common communication platforms.

"Autonomous" implies a range of computerized functions that take responsibility away from the driver, from today's cars that feature "driver assistance," a minimal level of automation that merely helps human drivers perform the task at hand, to tomorrow's "full automation" marvels in which cars themselves perform all driving tasks under all conditions.

The evolution will occur in stages, and Argonne National Laboratory will be front and center every step of the way.



Source: SAE International and J3016

Summary of Levels of Driving Automation

SAE Level	Name	Narrative Definition	Execution of Steering and Acceleration/ Deceleration	Monitoring of Driving Environment	Fallback Performance of Dynamic Driving Task	System Capability (Driving Modes)
Human driver monitors the driving environment						
0	No Automation	The full-time performance by the human driver of all aspects of the dynamic driving task, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	Driver Assistance	The driving mode-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the human driver perform all remaining aspects of the dynamic driving task	Human driver and system	Human driver	Human driver	Some driving modes
2	Partial Automation	The driving mode-specific execution by one or more driver assistance systems of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the human driver perform all remaining aspects of the dynamic driving task	**System**	Human driver	Human driver	Some driving modes
Automated driving system ("system") monitors the driving environment						
3	Conditional Automation	The driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task with the expectation that the human driver will respond appropriately to a request to intervene	System	**System**	Human driver	Some driving modes
4	High Automation	The driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task, even if a human driver does not respond appropriately to a request to intervene	System	System	**System**	Some driving modes
5	Full Automation	The full-time performance by an automated driving system of all aspects of the dynamic driving task under all roadway and environmental conditions that can be managed by a human driver	System	System	System	**All driving modes**

Source: SAE International and J3016

In short, think cars that drive themselves, at least to some degree, communicating with each other, traffic lights and even homes to ensure maximum traffic flow, minimal energy usage and reduced pollution.

CAVs will be a critical component of advanced mobility, in which automobiles communicate not only between themselves but also with the wider transportation ecosystem. The United States Department of Energy (DOE) is facilitating this transportation transformation via its Systems and Modeling for Accelerated Research in Transportation (SMART) Mobility Initiative, of which CAVs are an integral part.

In fact, CAVs, in addition to decision science, multi-modal transportation, urban science and vehicles and infrastructure, have been identified by the DOE as essential to an advanced mobility future. And because CAVs require innovation across the R&D spectrum, their development will both assist and evolve alongside the wider SMART Mobility platform.

The road ahead

Because the SMART Mobility Initiative will require innovation on a grand scale—from individual automobile components to the entire transportation ecosystem—the challenge requires broad vision and wide collaboration.

Argonne has established itself as a key partner in the march toward a carbon-efficient, sustainable transportation system. To help usher in the next era of transportation, Argonne researchers have developed a set of tools that will prove indispensable in tackling the challenges posed by next-generation transportation.

For instance, the POLARIS traffic model gives researchers a glimpse into how individual behaviors and overall traffic flow affect one another, providing realistic models for a range of situations, from rush hour to emergency evacuations. And Autonomie©, a vehicle modeling and simulation tool, is the DOE standard for assessing the fuel consumption and performance of advanced vehicles.

But cars and trucks are only part of the equation. CAVs require interaction not only between vehicles, but with the surrounding infrastructure. Argonne researchers have developed a modeling and simulation platform to help urban planners understand transportation and energy demands in an effort to design more mobile and efficient cities at scale, from 200,000 to 10 million residents.

> Argonne is emerging as an epicenter of smart mobility innovation.

All of these challenges will rely heavily on Argonne's expertise in fundamental areas such as advanced vehicle systems, sensors, cybersecurity, resilient infrastructure and the electric grid.

Sensors, for instance, will be instrumental in the advancement of both automation and communication between vehicles and infrastructure. Argonne recently received a $3.1 million award from the National Science Foundation for its contribution to the Array of Things (AoT), a research project that seeks to install 500 sensor nodes to monitor and gather data in real time on Chicago's environment, infrastructure and activity. AoT has been touted as an important step toward creating a "smart city," boosting data-driven public policy and community engagement.

Other Argonne capabilities such as cybersecurity, codes and standards and automotive testing will also be imperative in realizing the potential of CAVs.

These capabilities, in concert with Argonne's top-tier facilities such as the Advanced Powertrain Research Facility, Leadership Computing Facility and Advanced Photon Source, will be instrumental in evolving American mobility across the transportation and urban science sectors.

In the end, the data generated at Argonne will be instrumental in helping policymakers plan for the future of mobility, a future that will almost certainly redefine America's relationship with the automobile.

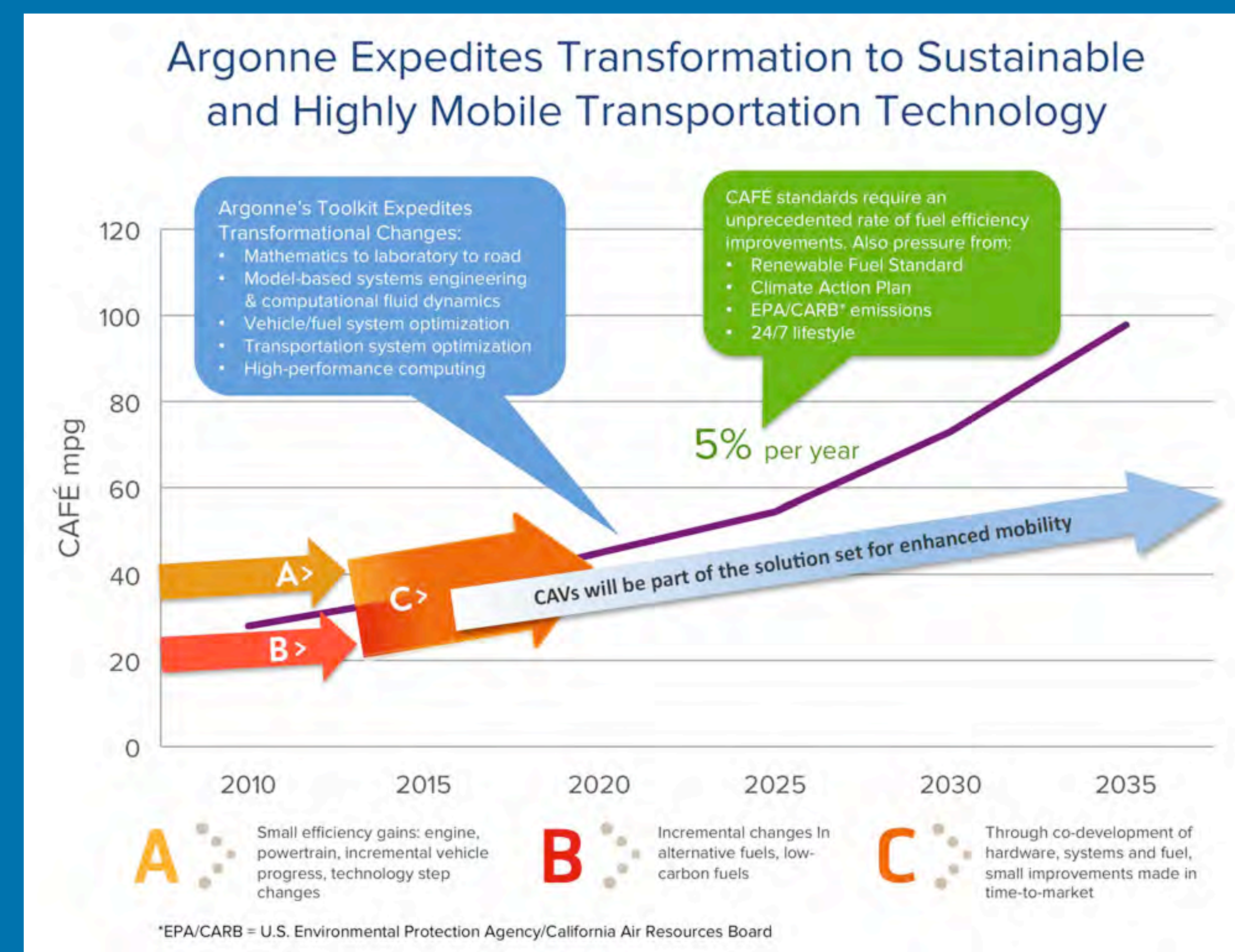
[1] National Economic Council. "An Economic Analysis of Transportation Infrastructure Investment." July 2014. Available at https://www.whitehouse.gov/sites/default/files/docs/economic_analysis_of_transportation_investments.pdf.

[2] U.S. Department of Transportation, National Highway Traffic Safety Administration. "The Economic and Societal Impact of Motor Vehicle Crashes, 2010." May 2015 (revised). http://www-nrd.nhtsa.dot.gov/Pubs/812013.pdf.

Mobility and **Energy Sustainability**

CAVs represent a transformational technology and a potential mobility sea change. Not only will they improve traffic flow and enhance safety, but they will also boost energy efficiency. The government's Corporate Average Fuel Economy (CAFÉ) standards require an unprecedented rate of fuel economy improvements, requiring industry and suppliers to adopt a faster development cycle for innovation, development and integration.

While vehicles and fuels have historically been developed independently for efficiency, a joint approach may allow for more rapid innovation and optimization. Argonne has the facilities and expertise necessary to enable the coming transportation transformation via CAVs and its wider vehicle efficiency platforms.



Transportation as a System

Research by the U.S. Department of Energy's (DOE's) national laboratories, including Argonne, suggest that better use of transportation assets and their role in the broader transportation system could help meet national energy and greenhouse gas objectives.

Today's System:

- Vehicle-level focus
- Independent
- Unconnected
- Subject to human behavior and decisions

Tomorrow's System:

- System-level focus
- Connected
- Automated
- In concert with other vehicles and infrastructures
- Operates across modes
- Managed human behaviors and decisions

Argonne is exploring numerous untapped efficiency improvements across the transportation ecosystem. The laboratory is quantifying the energy impact of connected and autonomous vehicles (CAVs), identifying and developing CAV-enabled opportunities and informing policy and research on CAVs and smart mobility.

Decisions, Decisions

The advent of connected and autonomous vehicles (CAVs) will see no shortage of new technologies aimed at transforming transportation. While some will likely succeed and others fail, to truly understand their potential and their impacts on the larger transportation system, researchers need to understand how people respond and react to them, preferably in real time.

By understanding the driving public's relationship with innovation, researchers can help policymakers plan for the future—planning that is essential to the success of CAVs and their integration into the U.S. Department of Energy's (DOE's) SMART Mobility Initiative, which is based on behavioral and decision sciences.

Like most big R&D questions, however, it's easier said than done. In order to understand the relationship correctly, researchers need to watch thousands of drivers make decisions on the fly, over and over again, under a range of conditions. Only then can they begin to understand how people react to various technologies and situations, and how those reactions, in turn, affect the larger transportation system as a whole.

While, in reality, such extensive observation presents an obvious logistical nightmare, it's an exercise well-suited to computation.

As one of the world's foremost research institutions in the field of decision science, Argonne's experience in modeling decision-making processes dates back to the 1990s. It is now a recognized leader, thanks to both its fundamental expertise and world-class computing capabilities.

As CAVs and other aspects of smart mobility ramp up, this combination of expertise and computing capability will be critical to realizing the potential of these transformational technologies.

"Our expertise in high-performance computing (HPC) and agent-based modeling gives us the ability to model phenomena at unparalleled resolutions," said Chick Macal, a senior systems engineer at Argonne. "These capabilities allow us to push the frontiers of large-scale, innovative applications."

POLARIS predicts how individuals' decisions influence transportation.

Take POLARIS, an agent-based model that simulates traffic flow to predict how individuals' decisions influence transportation.

With POLARIS, researchers can change road conditions spontaneously and quickly visualize the impact on traffic flow and infrastructure. For instance, do you want to see where people go if they know there is an accident on a major thoroughfare? Or how they react to a lane closure? What about connected vehicles moving in concert on automated cruise control? POLARIS can do all that, and much more. Everything from the houses people purchase to the cars they drive to the routes they take to work can be computed, thanks to this unique modeling and simulation framework.

The heart of POLARIS is its agent-based architecture. Because the environment affects peoples' decisions, which in turn affect the rest of the ecosystem, the POLARIS team wants to know how and why people make the decisions they do. "POLARIS models all sorts of behaviors," said Ann Schlenker, director of Argonne's Center for Transportation Research. "This is a chain of decision making, a major simulation of human behaviors as they apply to transportation."

The tool will be essential for crafting the policies needed for cities like Chicago to adapt to CAVs and smart mobility—from emissions to parking to urban sprawl to car sharing, CAVs will inevitably alter the way in which tomorrow's cities approach transportation challenges.

"This type of traffic forecasting will be critical to determining how people will react to increased automation and connectivity in their vehicles," said Schlenker.

And as CAVs' technologies evolve, POLARIS will likewise increase in complexity.

"Survey data will be essential to better understand individual decision-making, a process that is especially difficult to model," said Joshua Auld, a computational transportation engineer in the systems modeling and control group that is leading the CAVs effort, adding that people often make an ill-informed decision, which adds an additional layer of complexity.

The survey data will be paired with traffic flow data from local and state vendors to align future forecasts with real-world conditions. Step-by-step, POLARIS will greatly assist researchers in understanding how the adaptation of CAVs will transform transportation and assist DOE's wider SMART Mobility Initiative.

"CAVs will come about in unexpected ways," said Schlenker. "Ultimately, POLARIS will help policymakers to mitigate negative impacts CAVs might have while providing a glimpse into the future of human transportation."

This research was funded by the Federal Highway Administration (U.S. Department of Transportation) and Argonne National Laboratory.

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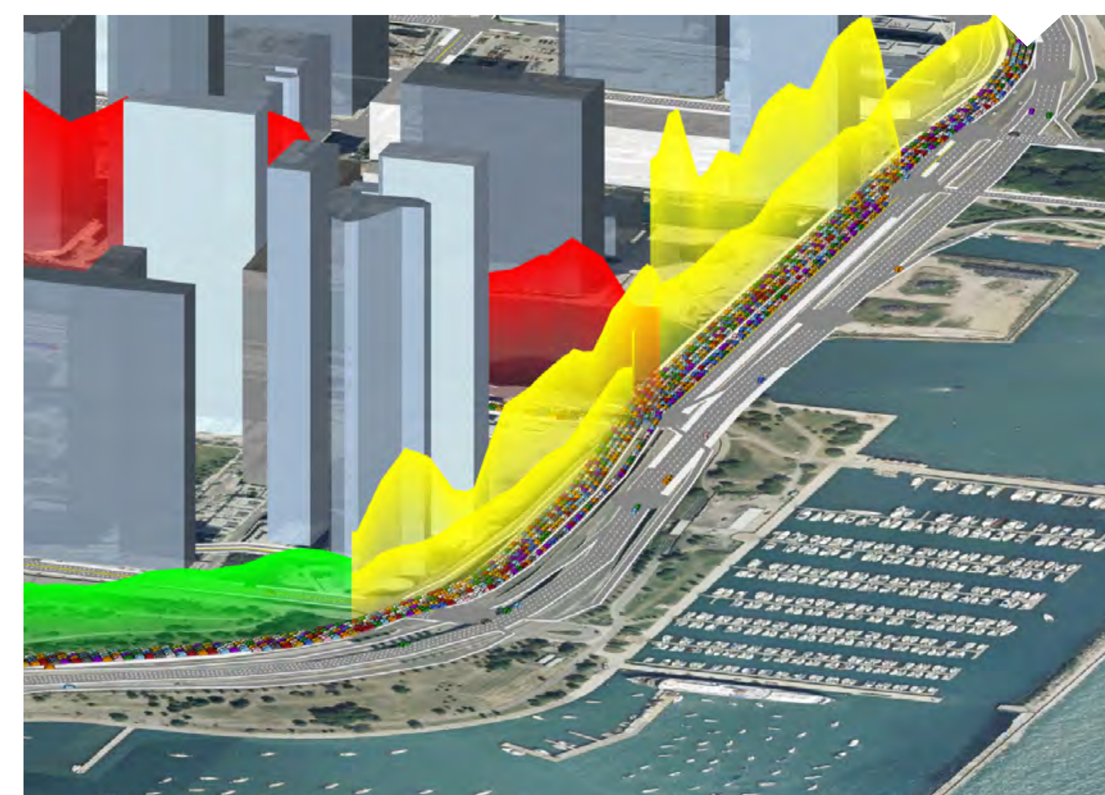
A POLARIS simulation of traffic flow in downtown Chicago.



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Calculating **Consumption**

Connected and autonomous vehicles (CAVs) reside at the intersection of three critical avenues that will decide the future of transportation: safety, mobility and energy. Argonne is tackling all three head on.

Because they will be largely self-operating, CAVs will decrease and eventually eliminate the human error variable, reducing the need for traditional safety protocols such as medians and yellow lights that are built around human reaction times. CAV safety will be more technological in nature, such as securing on-board computer systems from malicious cyber attacks.

Argonne's POLARIS Transportation Systems Model has already begun to address traffic flow (and much more) with promising results, demonstrating that mobility and efficiency can go hand-in-hand.

But of particular importance to policymakers is energy—automotive technology represents a unique opportunity to help rein in CO_2 levels and reduce our dependence on fossil fuels, especially as the country moves toward advanced mobility. Therefore, measuring the energy impact of CAVs is essential for policymakers to understand the implications of this promising technology and plan accordingly.

In response to this immense challenge, a team led by Argonne's Aymeric Rousseau has developed a system simulation tool known as Autonomie that allows energy consumption prediction for a wide range of transportation technology scenarios, all of which are of interest to DOE's SMART Mobility Initiative.

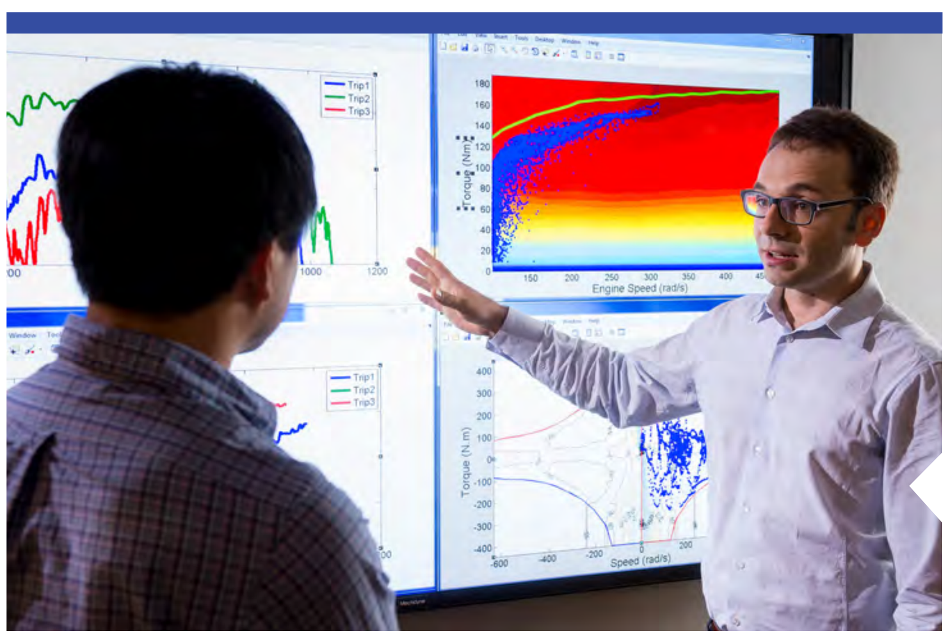
"We want to give concrete numbers on efficiency, and information to planning agencies so they know where to invest in infrastructure and how best to conduct future research," said Rousseau.

While calculating energy consumption is nothing new for the transportation community, the results produced by Autonomie are. Past research has used very simple equations (car × distance = output) to calculate what in reality is a much more complex problem: different types of cars with different weights, engines and various technologies all moving at different speeds under different conditions.

"Not all vehicles and drivers are created equal," said Rousseau.

Far from using one generic value for the myriad types of cars on the road, Autonomie can model energy consumption for every conceivable vehicle type and technology. Hybrid? Plug-in Hybrid? Gas? Diesel? 5-Speed? 9-Speed? You name it, Autonomie can calculate it. In fact, Autonomie currently boasts high-fidelity models for more than 300,000 vehicle configurations.

And because CAVs will be more energy efficient, predicting their impact on energy requires foresight. For instance, vehicles will be lighter and more powerful in 2020 than those on the road today, making their energy consumption vastly different. Multiply that times hundreds of thousands or millions of cars and the energy portfolio for the nation begins to look very different.



Researchers Dominik Karbowski (right) and Namdoo Kim examine data from recent Autonomie simulations.

Autonomie accurately predicts CAVs' energy consumption.

To better predict the evolution of automotive energy consumption, the Autonomie team works with other specialized groups at Argonne, such as the Energy Systems Analysis team, and other national laboratories, to estimate market changes and adoption by consumers. With CAVs, and advanced mobility in general, the technological changes will be massive, from materials to batteries to computer systems. Autonomie will be critical in planning for their arrival, beyond individual automobiles to the wider, nationwide transportation system.

For instance, the team has developed an algorithm that can model the effects of Ecosignal, an advanced mobility technology in which cars communicate with traffic signals to reduce energy consumption and improve flow.

"If the light is turning red, Ecosignal will tell the car to stop injecting fuel," said Rousseau. "Even though this will only save a couple of seconds of fuel for a single car, it starts to add up when you calculate it for an entire system."

Autonomie has already been successfully linked with Argonne's POLARIS traffic flow model to understand the energy and mobility impacts of a dedicated lane for tractor trailers, and future research will likewise pair it with Argonne's GREET and BatPaC tools, providing researchers with unprecedented resources with which to tackle the future of CAVs and energy.

While promising, however, these enhanced, coupled models will require massive amounts of computing power. Fortunately Argonne is home to the MIRA supercomputer, where researchers will be able to run hundreds of thousands of scenarios in a single day, with simulations containing between 50,000–100,000 vehicles each.

While calculating the energy impact of CAVs and other advanced mobility technologies is no easy task, there are few, if any, better places equipped to do the job than Argonne. After all, no one said predicting the future would be easy.

This research was funded by the U.S. Department of Energy's Vehicle Technologies Office.

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GREET

To fully evaluate energy and emission impacts of advanced vehicle technologies and new transportation fuels, the fuel cycle from wells to wheels and the vehicle cycle through material recovery and vehicle disposal needs to be considered. Argonne has developed a full life cycle model called GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) that allows researchers and analysts to evaluate various vehicle and fuel combinations on a full fuel-cycle/vehicle-cycle basis.

BatPaC

The recent penetration of lithium-ion (Li-ion) batteries into the vehicle market has prompted interest in projecting and understanding their potential for performance and affordability. To accurately project both performance and associated costs for a range of Li-ion technologies, Argonne researchers have developed BatPaC, the only public-domain model that captures the interplay between design, manufacturing and cost of Li-ion batteries for transportation applications.

A Model **Marriage**

The potential of CAVs is matched only by the challenges they pose in technology development. Even if the technologies are successfully developed, however, researchers need to be sure they will pay off in terms of increased mobility and reduced energy usage in urban environments.

Luckily, Argonne National Laboratory specializes in tackling the big questions. This means not only teaming researchers from dissimilar fields, but also ensuring that their tools work together seamlessly as well.

It's a tall order, and one that was recently achieved with impressive results by a team of Argonne researchers seeking to validate a unique approach to measuring mobility and energy efficiency in a transportation system.

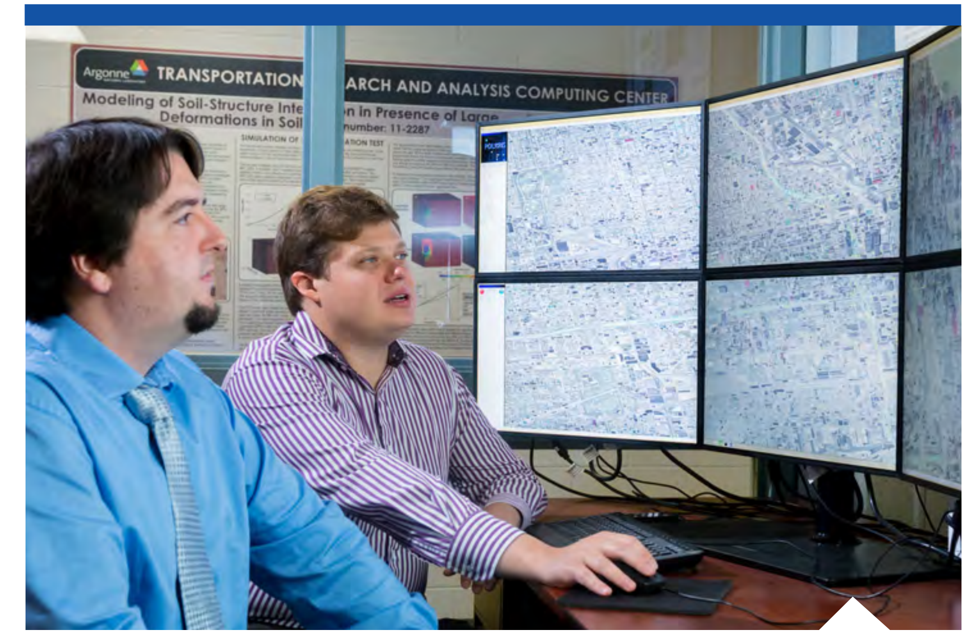
By combining Argonne's high-fidelity traffic flow model known as POLARIS with the laboratory's Autonomie powertrain simulation tool into a platform known as the Transportation Energy Systems Model, researchers have made significant progress toward understanding the impacts of CAVs in major metropolitan areas, a discovery critical to DOE's SMART Mobility Initiative.

Argonne's modeling tools have found that a dedicated lane for tractor trailers on automated cruise control could produce energy savings of up to 40 percent.

"The fact that our tools were able to communicate is great news for the future of CAV research," said team member Vadim Sokolov. "This type of joint modeling will be critical as the research advances and systems are collectively optimized."

Specifically, the group leveraged POLARIS to model the traffic flow for three different scenarios: "unmanaged traffic," where cars and trucks are free to change lanes, as is the case today; managed truck traffic, in which all tractor trailers are relegated to a single lane; and managed truck traffic with automated cruise control, which allows the tractor trailers to essentially accelerate and brake in unison while maintaining the optimal distance between vehicles for maximum fuel efficiency.

The researchers used Autonomie to calculate the energy consumption of the different classes of vehicles which, when coupled with speed and grade profiles and fleet mix estimates from Argonne's Energy Systems Analysis team and other national laboratories, allowed the researchers to produce the energy output for the system as a whole and for the individual classes of vehicles. In all 17,500 vehicles were simulated on the heavily traveled Interstate 90 corridor between downtown Chicago and O'Hare International Airport, a stretch of approximately 11 miles.



Argonne's Joshua Auld (left) and Vadim Sokolov explain a visualization of their joint POLARIS/Autonomie simulation that examined the energy and mobility impacts of a dedicated lane for tractor trailers in one of Chicago's busiest traffic corridors.

The findings: A dedicated lane for tractor trailers on automated cruise control could produce energy savings of up to 40 percent for the trucks alone and 18 percent for the system as a whole, a significant chunk of change when it comes to transportation efficiency.

New tool helps define impact of CAVs in cities.

Perhaps more important, however, is the validation of modeling energy output for an entire transportation ecosystem, information critical for policymakers to weigh the pros and cons of advanced mobility innovations as we enter the next era in transportation.

The new simulation framework also allows researchers to assess a large number of scenarios in just a matter of hours, an invaluable tool for modeling future scenarios in various cities. While this type of research has been done before, said Sokolov, Argonne's approach is unique due to its scale and level of fidelity.

Next, the researchers are aiming higher, incorporating a greater number of vehicle types and simulating the entire city of Chicago. "There is a process for parallelizing it," said Sokolov. "It could easily be scaled up for a larger system."

Funding for POLARIS is provided by the Federal Highway Administration (U.S. Department of Transportation) and Argonne National Laboratory, while funding for Autonomie is provided by the U.S. Department of Energy's Vehicle Technologies Office.

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The Computing Component

For centuries, scientific research was governed by two pillars, and two pillars alone: theory and experiment.

With the advent of the computer age, however, a third pillar has emerged: simulation.

Today's most powerful computers are capable of performing thousands of trillions of calculations per second, making it possible to mimic many of nature's most complex processes with a startling degree of accuracy. Simulation has increasingly been shown to save both time and money, precious commodities in the R&D universe.

When it comes to designing and sorting through prototypes, the traditional research route of theory and experiment can be prohibitively expensive and time-consuming. Simulation, however, can easily weed out the weak and provide data for enhanced experiments aimed at arriving at a final, optimal design.

Argonne researchers have at their disposal MIRA, an IBM Blue Gene/Q system capable of 10 quadrillion calculations per second and currently ranked as the 5th-fastest computer in the world. With MIRA's raw computing power, researchers can optimize complex models and simulate a wide spectrum of technologies of interest to DOE's SMART Mobility Initiative, including CAVs.

> Argonne's high-performance computing power optimizes and accelerates CAV research.

But when the data from the MIRA simulations must be mined and processed, researchers turn to the laboratory's Cooley cluster, which converts computational data from MIRA into high-resolution visual representations. And understanding big data will be instrumental in the development and adaptation of CAVs and other advanced mobility innovations. Techniques such as visualization, data mining and data querying will be instrumental in turning the mountains of data generated by an increasingly connected and automated transportation ecosystem into usable knowledge.

For most current application-level datasets, however (including many used in transportation), smaller, more dedicated resources may be more suitable.

Enter Argonne's Transportation Research and Analysis Computing Center (TRACC) User Facility, established in 2006 to facilitate simulation-based design and analysis for improvements in transportation efficiency, economics and safety, all of which CAVs could potentially transform.

The User Facility's Zephyr and Phoenix clusters provide research teams with unprecedented tools for tackling traffic modeling and simulation; emergency transportation planning; infrastructure analysis; and structural mechanics, to name a few, and will provide a vital platform with which to eliminate weaker mobility technologies.

TRACC staff work side-by-side with users to optimize their tools and get the most bang for their computing buck.

And that's good news. The third pillar of research will be critical in Argonne's quest to ensure both the adoption of CAVs and the evolution of smart mobility.

Funding for TRACC is provided by the U.S. Department of Transportation, while funding for MIRA is provided by the U.S. Department of Energy's Office of Science.

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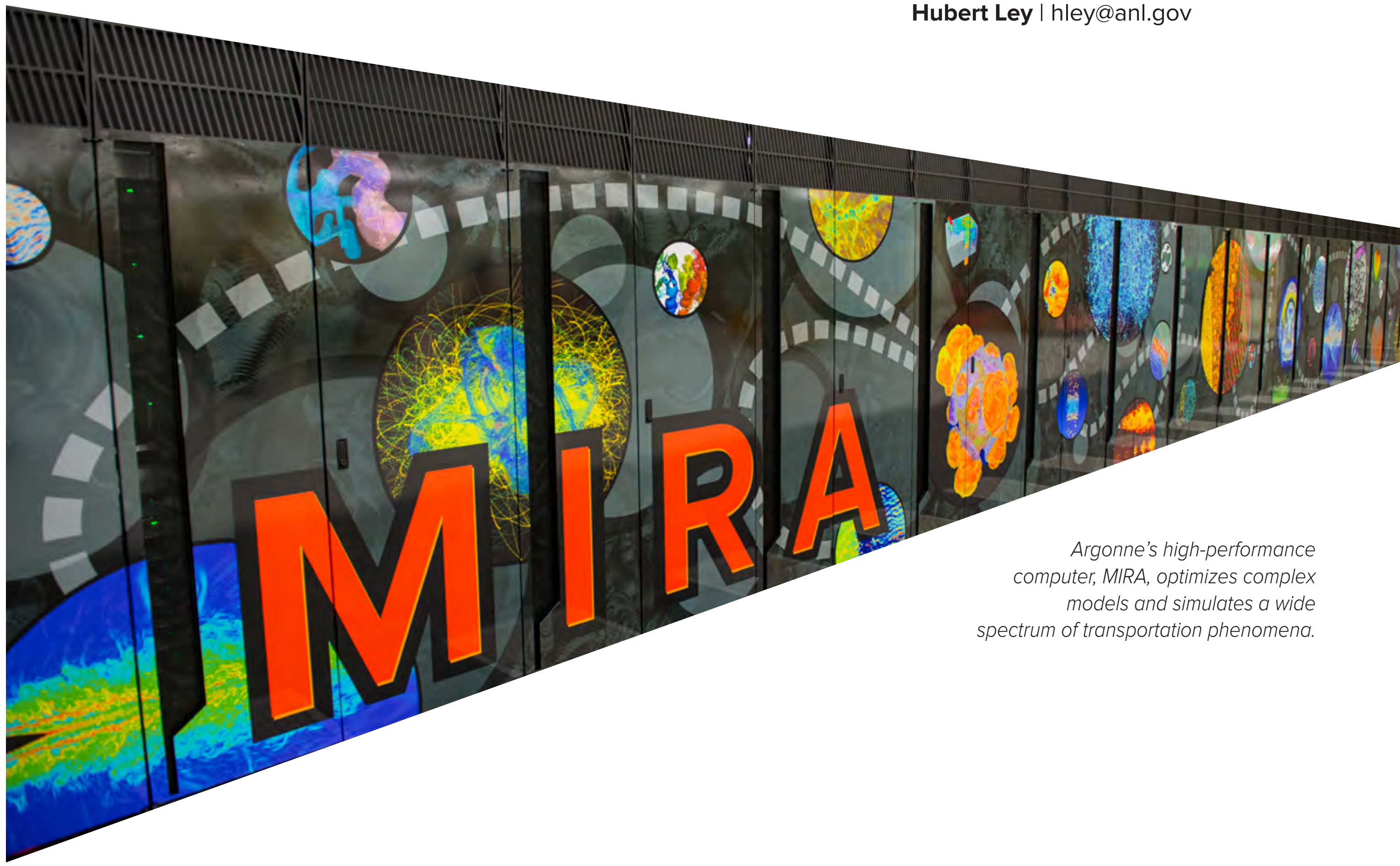

Argonne's high-performance computer, MIRA, optimizes complex models and simulates a wide spectrum of transportation phenomena.

Testing, **Testing**, 1, 2, 3

Technology has come so far, and progressed so fast, that it's easy to take for granted.

But rest assured most every modern marvel, from microwaves to smartphones to contact lenses, are the result of years of research and rigorous testing; after all, Bluetooth® technology didn't just appear out of thin air.

Cars and trucks are no exception. As vehicles become more advanced and eventually enter the era of CAVs—that is, cars that largely drive themselves and communicate with one another and the surrounding infrastructure for maximum mobility and efficiency—there will be no shortage of revolutionary technologies.

Expediting these technologies to the marketplace as quickly as possible will be critical to realizing the potential of CAVs.

However, before they can simplify our lives, new technologies need to be tested and optimized, a process that can be both expensive and time-consuming. Luckily for CAV supporters, Argonne has a well-established track record of vehicle technology analysis, energy consumption assessment and standards/test procedure development.

The centerpiece of Argonne's automotive assessment effort is the Advanced Powertrain Research Facility (APRF), where via emulation, researchers conduct vehicle benchmarking and testing activities that provide data critical to the development and commercialization of next-generation vehicles, including codes and standards.

"We are a codes and standards lab," said principal research engineer Eric Rask.

> Expediting these technologies to the marketplace will be critical to realizing the potential of CAVs.

The laboratory has contributed greatly to testing best practices, including measurement of fuel economy and emissions for hybrid-electric vehicles; development of advanced mobility technologies will require even more Argonne involvement.

"We are leveraging our expertise and experience in a broad range of codes and standards to guide CAV and advanced mobility standards under development," said Rask.

The APRF's detailed instrumentation know-how and powerful data analysis capabilities reveal valuable insights for system improvements, and by emulating and simulating a range of potential CAV technologies, the APRF facilitates innovation rapidly and safely.

Because reduced use of energy is a major driver for CAVs and advanced mobility adoption, the APRF will be instrumental in guiding which technologies hit the streets and which ones end up on the R&D cutting room floor.

For instance, different technologies will perform better under different conditions; what works for automated cruise control on a conventional car might not be optimal for a hybrid vehicle, and vice versa. Understanding which technologies will work best requires robust testing under myriad conditions in order to sort out the best performers for actual production and implementation.

Among the APRF's more unique capabilities is the evaluation of vehicles and components under extreme hot and cold temperature conditions (from 20°F to 95°F) via its Environmental Test Cell. This controlled environment allows researchers to validate performance targets for battery packs, drivetrain components, control strategies and accessory loads across a range of temperatures and duty cycles; quantify the impacts of air conditioning and heater/defrost operation on energy consumption and vehicle performance; identify vehicle-level control solutions to mitigate temperature-related impacts; and generate cold and hot operational characteristics and data to be integrated into Autonomie, Argonne's energy modeling and simulation tool.

And because the APRF has a lengthy track record of assessing both innovative and traditional vehicles, any testing of new technologies would be compatible with testing performed on existing technologies. In other words, the playing field would be level.

"The benefits of any technology vary dramatically over usage and driving style.... We would need to assess these technologies in a similar way or at least understand the differences," said Rask. "For example, an adaptive cruise system might work only at higher speeds, so we would not necessarily be able to apply a benefit across the board, such as in city driving. When looking at a full portfolio of technology options, one needs to be sure they are evaluated consistently, that your procedures are as technologically neutral as possible."

At the end of the day, there will be numerous technologies with the potential to transform the way we get from point A to point B. Quantifying their benefits is a tall order, yet one Argonne is well positioned to tackle.

The APRF will be a large part of that equation.

Funding for this research is largely provided by the U.S. Department of Energy's Vehicle Technologies Office.

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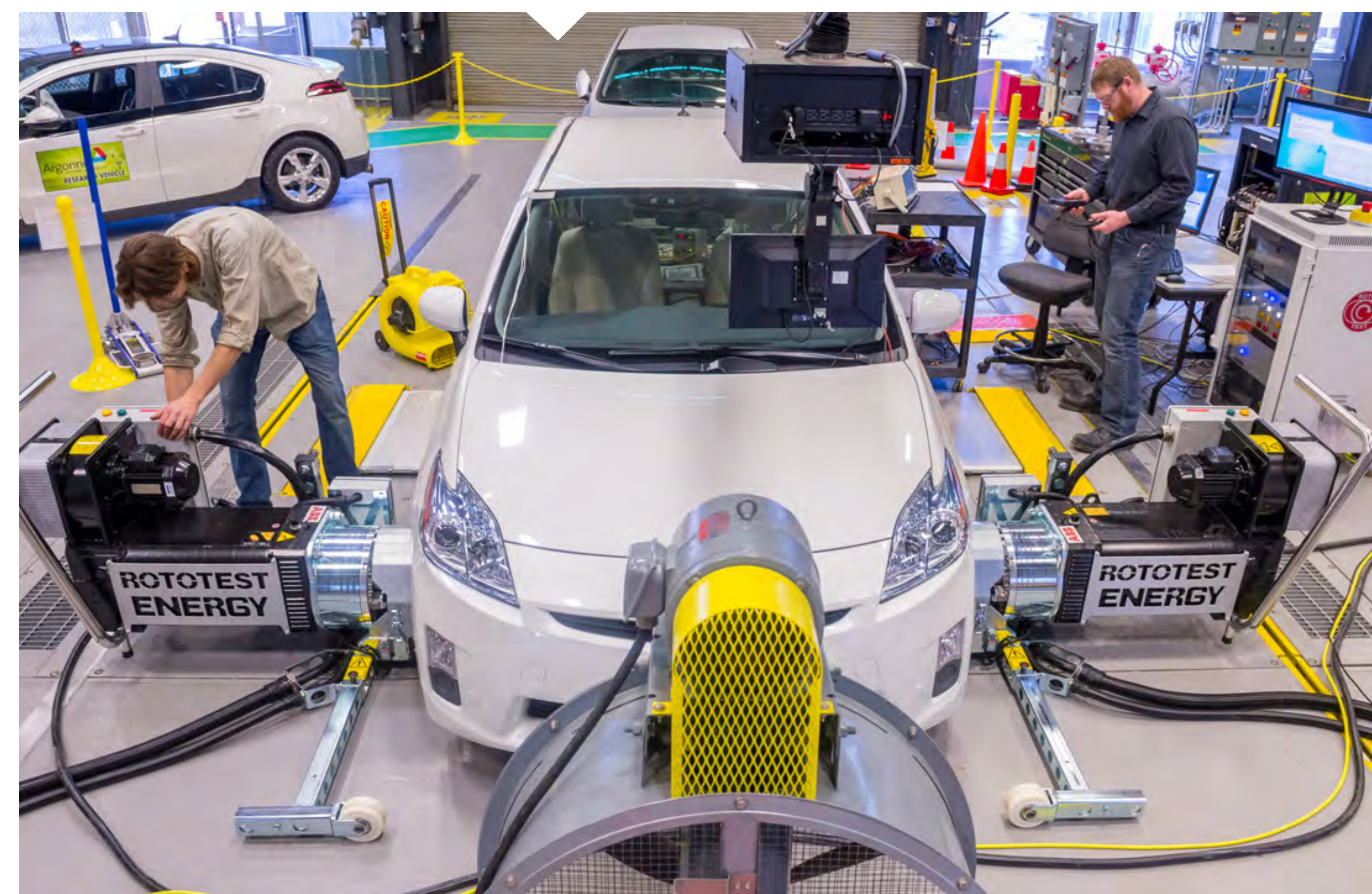
Argonne's Zach Stauber (left) and Kevin Stutenberg test a hybrid vehicle on a chassis dynamometer system in the laboratory's Advanced Powertrain Research Facility.



Sensor Essentials

If the future of transportation truly lies with self-driving vehicles that communicate with each other and the surrounding infrastructure for maximum safety and energy efficiency, then few technologies will be as critical as sensors as cars evolve essentially to be able to see, think and act on their surroundings.

These technological marvels will be the eyes, ears and voice of next-generation vehicles, navigating densely populated metropolises, dodging obstructions in the road and communicating with buildings and traffic signals to ensure that the entire transportation ecosystem is functioning as smoothly and as safely as possible.

While current automobiles employ up to 100 sensors, next-generation automation will likely see that number double in the most advanced vehicles. Getting these sensors to work in adverse conditions, respond quickly and be manufactured cheaply, however, is a major obstacle in the evolution and adaptation of CAVs.

When it comes to automated, or self-driving vehicles, sensors will be absolutely essential to their navigation. Safety will be paramount, and that safety will largely be sensor-dependent. The same paradigm applies to connected vehicles; sensors will play a major role in collision avoidance and spacing, both of which require sensor-based communication.

The heart of Argonne's sensor development expertise is in national security: think detection of nuclear, chemical, and biological agents during transport, for instance. In its quest to develop next-generation sensors for CAVs, Argonne is casting its net far and wide across the laboratory.

> The laboratory will lead the evolution of sensors for advanced mobility via motion sensors and data streaming/analysis.

"The key will be bringing the laboratory's sensor expertise together," said Eric Rask, a principal research engineer at Argonne.

By leveraging the success of Argonne's existing sensor research, such as the Waggle platform, which records urban environmental data in real-time, researchers have a base with which to begin filling the gaps related to CAVs, urban design and infrastructure.

Essentially, said Argonne principal mechanical engineer H.T. Chien, the laboratory will lead the evolution of sensors for advanced mobility on two fronts: motion sensors and data streaming/analysis.

The laboratory's experience with millimeter-wave and microwave sensors in the arenas of chemical and explosive detection will be critical for CAV motion detection, as they are less affected by weather and have longer ranges than traditional automotive sensors.

And as more cars become automated and further connected both to each other and the surrounding infrastructure, the amount of data being sent and stored will multiply exponentially via networks of sensors providing information instantaneously.

Argonne is already testing the waters of these "real-time everything" environments with the Array of Things, a pilot sensor program (in which Argonne is a partner) to measure pollutants and efficiency in Chicago. While largely focused on public health, the network of deployed sensors will be an invaluable test bed for future networks focused on advanced mobility.

Of course, the vehicle must understand all of this enhanced data, and quickly. Because sensors are used for a variety of functions, and some are better than others at specific tasks, they will all be listening and talking, so to speak, simultaneously. Refining this Babel-esque binary into a single, comprehensible data stream helps make the network of sensors greater than the sum of its parts; analyzing the data from different sensors in concert can give a vehicle a much more comprehensive picture of its surroundings and will help a vehicle select routes and optimize controls.

"Sensor fusion" will be critical to the ability of CAVs to both navigate their environment and better respond to their surroundings, and to the success of a transportation ecosystem that is becoming increasingly connected.

"Sensors will be a longer-term effort with multiple iterations. Essentially, we will act as advisors on the transportation side to the lab's existing sensor efforts," said Rask.

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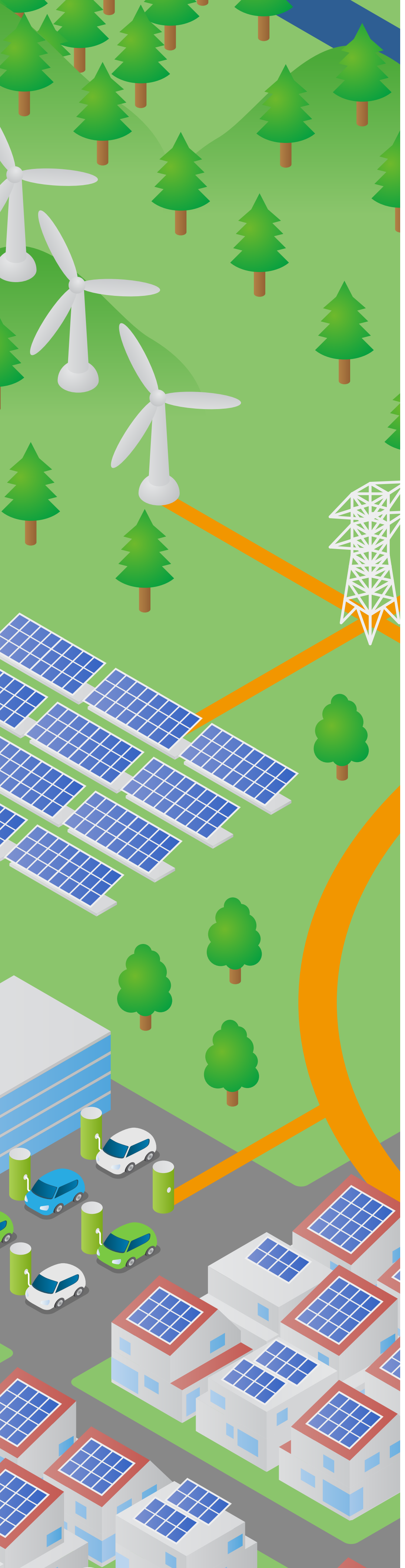
Artist rendering of Array of Things nodes mounted on city streetlight poles. The Array of Things is an an "urban sensing" instrument, measuring data on cities' environments, infrastructure and activities in order to scientifically investigate solutions to urban challenges ranging from air quality to urban flooding. Credit: Douglas Pancoast & Satya Mark Basu, School of the Art Institute of Chicago/Array of Things.



Growing the **Grid**

Believe it or not, a great deal of transportation is invisible.

Whereas cars and trucks traverse vast expanses via highways and byways, electrons depend on the intricate network of transmission lines that make up America's electric grid for transport from solar farms and power plants to our homes and businesses.

And just as CAVs have the potential to transform our interstates and avenues, they likewise could revolutionize the way in which we generate, store and distribute power, a revolution that will play a central role in realizing DOE's SMART Mobility Initiative.

While America's electric grid is one of the great marvels of modern engineering, it is also a rapidly aging relic of the era of consolidated power. In the past, energy was largely centralized via large coal and nuclear power plants; today, renewables are changing that landscape. Because wind and solar can generate power on-site, they are slowly but surely transforming the grid from a centralized network to one that is more distributed.

And because a large portion of tomorrow's cars and trucks will almost certainly be electrically powered, they also will serve as mobile energy storage and assist in the further decentralization of power. "Current doesn't have to begin at a central generator anymore, as it has for years," said Mike McElfresh of Argonne's Infrastructure Protection Center. "Now it can go in all directions."

Today's grid is essentially zero storage; power is instantaneously generated and then distributed or lost to excess capacity. But CAVs and other advanced mobility components such as urban science and infrastructure have the potential to change that.

Essentially, CAVs will grow the grid by becoming an extension of it—that is, with a little help from Argonne.

> CAV adaptation could help transform our power grid.

For example, Argonne is leading the charge in working with SAE International to develop new standards for electric vehicles. These standards will be critical in accelerating the adoption of electric vehicles and CAVs and providing vendors and manufacturers with clear guidelines in order to make their products compatible and usable across the marketplace.

And by coupling the grid to Argonne's agent-based behavioral models to better understand how people interact with the grid, researchers can further optimize charging infrastructures for electric vehicles. These efforts will help to maximize both CAV adaptation and grid efficiency by developing a realistic representation of when and where travelers encounter charging infrastructure; an accurate understanding of how charging opportunities affect drivers' vehicle adoption, use and charging decisions; and an optimized grid operation which provides users with ideal charging time, rate and location based on travel needs and system operational needs.

"Vehicle-to-grid allows power in both directions and represents real storage," said McElfresh, adding that this capability will have a major impact on the larger grid itself, particularly when it comes to "valley filling" and demand response.

Demand peaks in the early evening and then falls off later at night, creating a "valley," and generating too much power can lead to negative pricing. But if drivers of electric CAVs primarily charge their cars at night they can increase the baseload, or "fill the valley," and stabilize the grid while making the overall system much more flexible. And flexibility is critical to adapting to the future of electricity production and generation.

Argonne editor Madonna Pence plugs in her electric vehicle after arriving home for the day. Argonne staff are conducting research into vehicle-to-grid communication that, one day, will enable power to flow from the grid to her car, and from her car to the grid.

For consumers, this presents a particularly enticing possibility: electric CAVs could possibly lead to power arbitrage, in which CAV owners buy energy at night, when the price is down, and sell it back during peak times, turning a profit.

But first the grid must be tweaked to take advantage of the more distributed nature of modern power and of CAVs. "The use of power is going down in the U.S.," said McElfresh. "How do we build a fancy new grid when the market is in decline?"

By growing the grid, CAVs will prove to be an integral part of the solution. And a next step in the march toward smart mobility.

This research was funded by the U.S. Department of Energy's Office of Electricity Delivery & Energy Reliability.

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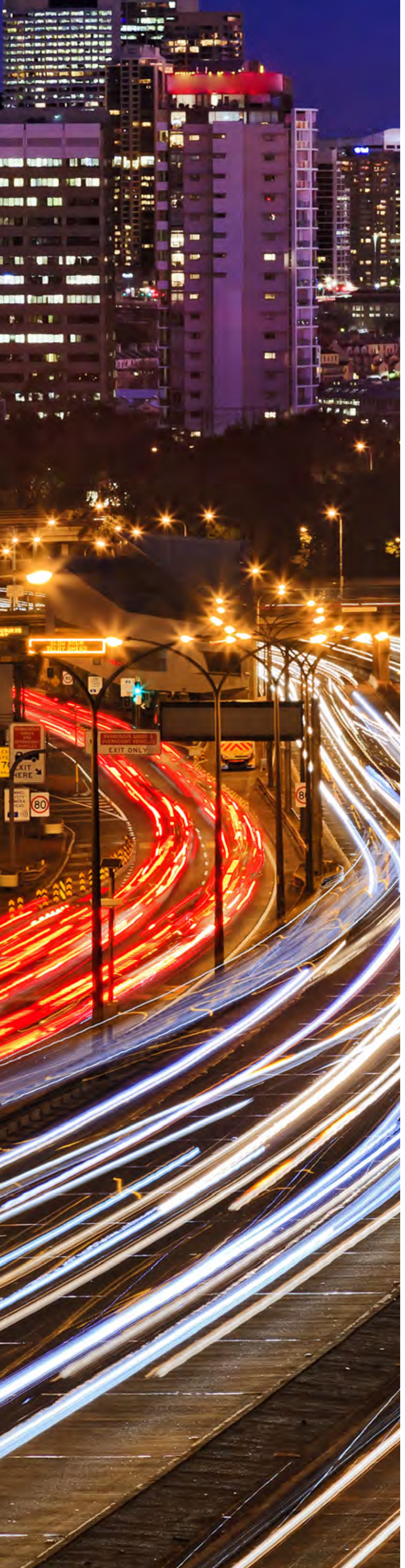

Enhancing Urban Efficiency

Buildings are among the earliest hallmarks of civilization, monumental representations of art and culture. We not only live and work in them, but marvel at the place they populate, somewhere between beauty and function.

Old, new, wood, brick, stone or stucco—few things play a more important role in the human experience than do buildings.

On average, Americans spend upwards of 90 percent of their day in, you guessed it, some sort of building. Think about it: every form of transportation exists to move people and goods from building to building, from where they live to where they work, shop, etc. Buildings are the largest consumer of energy in the world, and therefore nearly every aspect of water and utility design is based on these centers of domesticity and enterprise.

This reliance on structure means that in order to enhance urban and residential efficiency, researchers need advances in science and engineering tools with which to understand the connections between buildings, people and transportation. Furthermore, they need to predict how technologies will affect those connections.

And that's exactly what Argonne has set out to do. By increasing energy efficiency and enabling communication between buildings and the grid, the laboratory is getting a head start when it comes to next-generation urban design, an effort that will include electric and connected and autonomous vehicles (CAVs) and the urban science pillar of DOE's SMART Mobility Initiative.

America is setting its sights on rebuilding the Rust Belt, repurposing old manufacturing plants and designing new large-scale urban systems, all of which will impact how CAVs are designed and operated.

CAVs will revolutionize the way we interact with buildings in profound ways.

Argonne is currently working on a large-scale understanding of the interconnections of buildings, transportation systems, utility infrastructure and social dynamics to develop tools for planning and assessing various urban environments in the laboratory's push toward advanced mobility. And CAVs provide the perfect platform with which to better understand the intersection of buildings and transportation.

In order to make the best use of limited resources, design cities with the least environmental impact and provide the highest support for human comfort and productivity, CAVs modeling and incorporation will be critical.

CAVs will revolutionize the way we interact with buildings in profound ways. For example, vehicles will communicate with one another to maximize mobility—imagine a CAV switching from fuel to battery after realizing it's only a few miles from its destination (something already occurring today in many advanced vehicles), or a building telling a vehicle when to plug in and supply energy to the building itself.

The latter scenario will be critical for reducing peak power demand. Moreover, CAVs will rely on plug-in hybrid and electric power supplies and will provide proxy energy storage for surrounding buildings and the larger grid.

"Essentially, parking lots could one day serve as both a charging station for electric vehicles and provide a local power source for buildings to combat peak power demand, when energy is at its most expensive such as early in the evening," said Argonne principal building scientist Ralph Muehleisen. "There will be more and more electric vehicles with ever more powerful batteries, which means, in the end, more storage availability."

In fact, with enough local renewable power and electric CAVs acting as energy storage devices, buildings could provide the storage necessary to fully integrate renewables with coal and nuclear, both lowering peak demand and providing a cleaner energy source for areas far beyond the parking lots where they plug in. And because the vast majority of solar power will be created via solar paint, panels or other technology, electric CAVs will provide the perfect storage platform for one of the most promising renewable energy alternatives. This arrangement will break the century-old constraint of matching instantaneous electricity generation with instantaneous electricity demand.

The plug-in hybrid and electric power supplies of CAVs have the potential to provide proxy energy storage for surrounding buildings and the larger grid.

Imagine a future in which an electric CAV is included with the price of an apartment, doubling as both your vehicle and portable storage for the building. You might not get the same car every time—the computer systems inside the cars themselves will decide which ones stay and charge and which ones provide transportation—but you will have one when you need one, and the building will have its energy storage when it needs it most.

This enhanced storage capability has emergency implications as well, specifically for extended backup power. Take Hurricane Sandy, for instance; aside from emergency vehicles there were virtually no cars on the roads. Stationary electric cars could provide local power when the infrastructure is down, said Muehleisen, adding that today's largest automotive batteries can store enough energy to power a single-family home for a week if conserved properly.

Whatever the final relationship, there is little doubt that CAVs will greatly transform the way we interact with the buildings that we inhabit, and vice versa.

This work was supported through a Cooperative Research and Development Agreement with McCaffery Interests.

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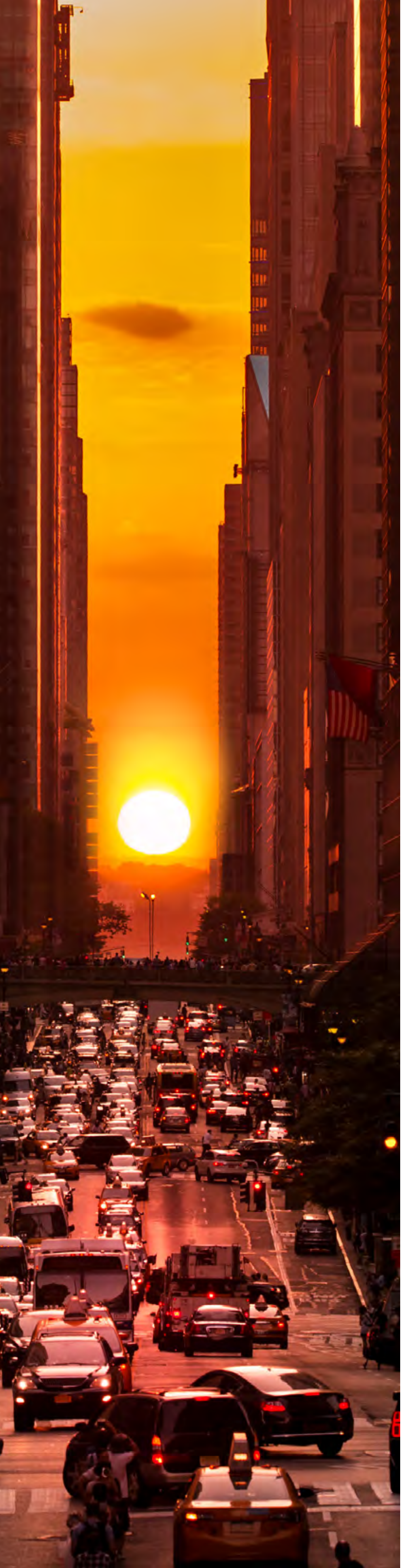

Remaining **Resilient**

Connected and autonomous vehicles (CAVs) reside at the intersection of vehicles and infrastructure, a critical nexus in DOE's SMART Mobility Initiative.

As vehicles progress technologically, their linkages to the surrounding infrastructure will likewise intensify, paving the way for advanced mobility.

One of the more promising aspects of CAVs is that they can use existing infrastructure while still revolutionizing transportation, making their transition less expensive than other popular alternatives, such as subways. But beyond simply "using" infrastructure as a means of movement, CAVs will advance mobility by communicating with the surrounding framework to increase both mobility and energy efficiency.

In order for this transition to occur smoothly, however, America's aging infrastructure must remain secure and resilient.

Experts typically start with four "lifeline" infrastructure sectors when assessing infrastructure resilience: energy, transportation, water/wastewater and communication. CAVs will eventually impact some part of each of these sectors, so ensuring their security and resilience is critical to the effectiveness of CAVs as a transformative technology.

The risks in each sector are being examined and addressed individually, with individual organizations looking after their own immediate needs. For true resilience, however, the lifeline sectors need to be addressed together; what affects one will likely affect the others.

Fortunately, "these infrastructure sectors are all in Argonne's wheelhouse," said Megan Clifford of Argonne's Risk and Infrastructure Science Center.

> Argonne is uncovering previously unidentified infrastructure vulnerabilities for CAVs.

Infrastructure resilience is traditionally the domain of disaster preparedness and national security, and that's where Argonne's expertise comes in. The laboratory has a history of providing federal, state, and local governments and industry with ways to understand potential vulnerabilities and consequences, a capability well-suited to ensuring the safety and effectiveness of both existing and future transportation infrastructures.

For instance, models developed at Argonne allow analysts to examine the vulnerabilities facing infrastructure components such as the electric grid, natural gas distribution and petroleum pipelines.

"A variety of factors can impact a particular infrastructure's operations," said Clifford. "But what impact will the disruptions have on other infrastructures that depend on them? Or on surrounding communities? We are uncovering vulnerabilities that weren't identified before."

While this research is immensely helpful for ensuring today's infrastructure security and resilience, it will be doubly useful in ensuring that future frameworks to accommodate advanced mobility—from smart intersections in which traffic lights communicate with individual vehicles to maximize flow, to the smart electric grid, where cars can locate the closest sources of electrical power for recharging—are as robust as possible.

Whereas today's infrastructure elements, such as medians and yellow lights, are built largely around preventing human error, CAVs and other advanced mobility innovations will remove that need, creating a more efficient transportation ecosystem. However, the introduction of computation and communication into these domains will make cybersecurity a priority, a daunting task that Argonne research teams are already grappling with by examining the cyber vulnerabilities of automobiles.

Funding for the Risk and Infrastructure Science Center primarily comes from the U.S. Department of Energy, the U.S. Department of Homeland Security and the U.S. Department of Defense.

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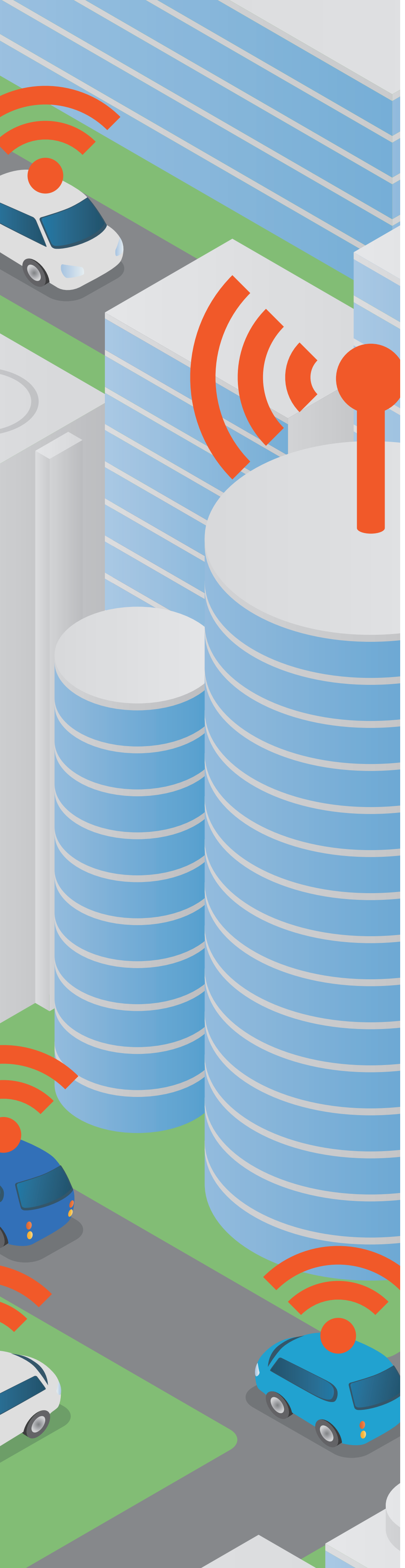
Identifying and mitigating the vulnerabilities to the nation's infrastructure has been identified as a priority by President Obama.



The Search for **Vulnerability**

Automobiles are evolving. Each year new technologies take more responsibility away from the driver and place it instead on the machine, blurring the line between car and computer.

Setting a car to "autopilot" is no longer a pipe dream. In fact, it may be just around the corner. Sit back, relax and enjoy the ride.

Cars today have upwards of 50 electronic control units responsible for performing numerous actions such as steering, braking and cruise control—a number that will only increase in the coming years.

With this enhanced automation, however, comes increased vulnerability. Just as malicious parties hack into our phones, laptops and even secure computers, so too could they infiltrate our car's computer systems and control a vehicle remotely. And it's not just cars—as mobility innovation ramps up, nearly every point in the wider transportation ecosystem will see increased vulnerability.

In recognition of these risks, Argonne is taking the lead in understanding the weaknesses inherent in the networks and protocols of transportation computing systems and designing fixes that will not only make connected and autonomous vehicles (CAVs) a reality, but an inherently safe one. For instance, a cross-disciplinary Argonne team of automotive engineers and cybersecurity experts recently verified that it is indeed possible to infiltrate a car's computer system after establishing a physical connection, exposing critical vulnerabilities in automobile cybersecurity.

By using a commercially available tool to connect to the on-board diagnostics port (the element used by mechanics) of a recent production automobile, the team was able to lock and unlock the car's doors; alter its speedometer values; alter its gas gauge values; and falsely activate a hybrid battery error, among other things, all via a laptop computer.

> Research will help guarantee the safety of advanced mobility systems.

The goal: to understand the potential for automation to be hacked and see how far an inexperienced "outsider" could get. While Argonne's familiarity with various makes and models of popular automobiles is second-to-none due to its world-class automotive testing facilities, it's not laboratory staff they're worried about.

Argonne researchers recently accessed a car's computer system via a physical connection in an attempt to better understand the vulnerabilities introduced by increased automation.

"We want to generalize attacks," said Roland Varriale, an Argonne cybersecurity analyst. "We want to reduce the amount of industry-specific knowledge to see if people outside of these research fields can do it. Additionally, we want to know if these attacks can be applied in a broader sense than to one specific type of car." And sharing knowledge of threats and best practices is critical to that discovery.

Although the team was only replicating previous research, this validation proved vulnerabilities exist in modern automation systems and that future research will be instrumental in guaranteeing the safety of next-generation vehicles, and likely next-generation infrastructure as well.

Ideally, researchers would like to remotely commandeer a moving vehicle, an experiment that presents numerous logistical and safety issues. Dynamometers, such as Argonne's two- and four-wheel-drive models, provide a safe environment for this research and facilitate impeccable analysis by the lab's world-leading advanced vehicle researchers.

"We have a pretty good understanding of these vehicles because we test them all the time," said Eric Rask, a principal research engineer at Argonne's Center for Transportation Research, adding that Argonne is attempting to enhance security within vehicle-to-vehicle communications as well.

Because CAVs communicate with each other and the surrounding infrastructure, there is an additional layer of vulnerability, and securing it will be just as important as securing the communications within a single car. Ultimately, as transportation cybersecurity evolves the Argonne team will guide industry with best practices, including those for threat identification.

A possible solution is in the works as well, in the form of a specific hardware add-on that would fit existing automation systems. "Cars exchange messages at a particular rate," said Varriale. "If we could detect an irregular rhythm in that rate we could check the sensor and correlate it with other sensors to detect potential anomalies."

Funding for this research is provided by Argonne National Laboratory.

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In the **Rearview**

Because science is an iterative process, the road to advanced mobility will take place in stages. The more we learn, the closer we'll be.

In other words, the bigger and more complex questions will require solving the simpler ones first, and by continuously enhancing models and refining research questions Argonne is leading the way in making today's most promising mobility innovations a reality.

Via its expertise in energy, modeling and simulation, standards and testing, and urban design, Argonne will further the state of the art in advanced mobility. Few places have the broad expertise and cutting edge facilities as America's first national laboratory.

But advancing the state of the art is only half of the equation. Many uncertainties surround CAVs, and other mobility technologies, such as dedicated lanes and eco-signals, making crafting policy around their adoption exceedingly difficult.

In order for these technologies to make the greatest impact, policymakers need the best possible information with which to plan for their implementation.

Luckily, Argonne is pursuing that angle alongside the R&D challenges. By quantifying the benefits of these promising technologies, Argonne is helping guide their development and, by extension, the future of American transportation.

With smart mobility, all modes of transportation will be seamlessly integrated to create choice for passengers.

For instance, the laboratory is already working with numerous partners, such as the Idaho National Laboratory, Lawrence Berkeley National Laboratory, National Renewable Energy Laboratory, Oak Ridge National Laboratory and multiple universities, to develop estimates and scenarios for the deployment of CAVs.

This largely means rolling up local and regional case studies to the national level, said Argonne's Principal Transportation Systems Analyst Tom Stephens. Because various studies have come up with different outcomes for energy use, the laboratory is synthesizing these analyses to obtain a more accurate picture of the impact of CAVs on America's energy use.

Argonne is also assisting other projects with specific vehicles and vehicle technologies and the generalization of other specific studies.

These efforts will be critical if the United States is to make the most of the coming transportation revolution. Just as national labs have helped guide the nuclear and space ages, so too will they play a fundamental role in the age of advanced mobility.

And Argonne will be front and center.

Benefits of CAVs and Smart Mobility

- Increased safety
- Smoother traffic flow
- Shorter headways between vehicles
- Better infrastructure utilization
- Decreased number of vehicles on the road
- Efficient driving
- Optimum route selection
- Route-based control
- New vehicle design accommodations
- More efficient use of fueling and charging infrastructure
- Effective infrastructure management
- Advanced manufacturing
- Increased productivity
- More effective land usage
- Greenhouse gas reduction

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WORKING WITH **ARGONNE**

Industrial technology development is an important way for the national laboratories to transfer the benefits of publicly funded research to industry to help strengthen the nation's technology base. The stories highlighted in this issue of **TRANS**FORUM represent some of the ways Argonne works with the transportation industry to improve processes, create products and markets, and lead the way to cost-effective transportation solutions, which in turn lead to a healthier economic future.

By working with Argonne through various types of cost-sharing arrangements, companies can jump-start their efforts to develop the next generation of transportation technologies without shouldering the often prohibitive costs of initial R&D alone. Argonne has participated in dozens of these partnerships and has even been involved in helping to launch start-up companies based on the products and technologies developed here.

If working with world-class scientists and engineers, having access to state-of-the-art user facilities and resources, and leveraging your company's own capabilities sound like good business opportunities to you, please contact our Technology Development and Commercialization division and see how we can put our resources to work for you.

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