The Road to Tomorrow: Energy Innovation in Automotive Technologies

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Before the
Committee on Energy and Natural Resources
United States Senate
January 25, 2018

Thank you, Chairman Murkowski, Ranking Member Cantwell, and Members of the Committee. I am Dr. Mohammad Khaleel, Associate Laboratory Director for Energy and Environmental Sciences at the U.S. Department of Energy's Oak Ridge National Laboratory in Oak Ridge, Tennessee. It is an honor to participate in this hearing with this distinguished panel today.

INTRODUCTION

Oak Ridge National Laboratory (ORNL) is the largest Department of Energy (DOE) science and energy laboratory, conducting basic and applied research to deliver transformative solutions to compelling problems in energy and security. ORNL's diverse capabilities span a broad range of scientific and engineering disciplines, enabling the Laboratory to explore fundamental science challenges and to carry out the research needed to accelerate the delivery of solutions to the marketplace.

DOE's scientific and technical capabilities are rooted in its system of national laboratories—17 world-class institutions that constitute the most comprehensive research and development network of its kind. The laboratories work as a network with academia, industry, and other federal agencies to ensure America's security and prosperity by addressing its energy, environmental, and nuclear challenges through transformative science and technology solutions.

ORNL is actively engaged in helping address these compelling national energy challenges, and we are partnering with other laboratories, industry, and academia to enable the rapid innovation that will be required. ORNL supports DOE's national missions of:

- Scientific discovery—We assemble teams of experts from multiple disciplines, equip them with powerful instruments and research facilities, and address compelling national problems;

- Clean energy—We deliver technology solutions for energy sources such as nuclear fission/fusion, fossil energy, solar photovoltaics, geothermal, hydropower, and biofuels, as well as energy-efficient transportation, buildings, and manufacturing;

- Security—We develop and deploy "first-of-a-kind" science-based security technologies to make the United States, its critical infrastructure, and the world a safer place.

ORNL supports these missions through leadership in four major areas of science and technology:

- Computing—We accelerate scientific discovery and the technology development cycle through modeling and simulation on powerful supercomputers, including Titan, the nation's most powerful system for open scientific computing, advance data-intensive science, and sustain U.S. leadership in high-performance computing;

- Materials—We integrate basic and applied research to develop advanced materials for energy applications. The latest frontier in materials research is at the nanoscale—designing materials atom by atom —and we leverage ORNL assets such as Titan and the Center for Nanophase Materials Science for breakthrough materials research;

- Neutrons—We operate two of the world's leading neutron sources that enable scientists and engineers to gain new insights into materials and biological systems;

- Nuclear—We advance the scientific basis for 21st century nuclear fission and fusion technologies and systems, and we produce isotopes for research, industry, and medicine.

As Associate Laboratory Director at ORNL, I am privileged to lead a talented group of scientists and engineers as we address scientific challenges to advance America's clean energy future. Our researchers work with many of America's best innovators and businesses to pursue scientific breakthroughs in areas such as sustainable, efficient transportation technologies, including intelligent mobility solutions, extreme fast charging and wireless charging, automated vehicle technologies and vehicle cybersecurity, advanced materials, fuels, engines, and emissions research, and big data for decision-making. We also deliver solutions for energy efficiency for manufacturing, homes, and buildings; electric grid resiliency and security; and the advancement of domestic energy sources such as fossil energy and bio-derived fuels and feedstocks.

Our discoveries fuel the growth of science as well as local, regional, and national economies. In partnership with industry, academic institutions, and other DOE national laboratories, ORNL is well positioned to achieve scientific breakthroughs and develop innovative technologies that will meet our nation's clean energy needs for the next generation.

The DOE's Office of Energy Efficiency & Renewable Energy (EERE) is the primary sponsor of vehicle technology research at the national laboratories. EERE's Vehicle Technologies Office leads research on batteries, charging and EVs; energy-efficient mobility systems; advanced combustion systems and fuels; lightweight and propulsion materials, and technology integration. EERE's Fuel Cell Technologies Office supports new fuel cell propulsion system research; its Advanced Manufacturing Office supports research into more efficient production processes,

including additive manufacturing of tooling; and its Bioenergy Technologies Office supports work on new fuels for advanced combustion.

The unique combination of scientific tools and expertise at our national laboratories provide a powerful resource to foster U.S. technical and economic competitiveness, particularly when working alongside American companies to identify and more rapidly develop superior, affordable materials solutions.

The national laboratory system addresses energy efficiency challenges through technology breakthroughs in partnership with the academic and private sectors. DOE ensures that scientific and technical advances can move beyond the national laboratories to increase the economic impact of the intellectual property developed as a result of federally funded research and development. The laboratories are encouraged to work with the private sector to find and implement new approaches for translating early-stage innovations to viable market options. These efforts leverage traditional funding streams and programs focused on early-stage research with private-sector investment and market knowledge that provide a pathway to create new businesses, product lines, and jobs.

THE FUTURE OF TRANSPORTATION SYSTEMS

Efficient, affordable, and secure transportation is essential to the nation's economy and to our standard of living. Some 269 million vehicles traversed America's roadways in 2016, according to the Department of Transportation.[1] The transportation sector consumed 27.9 quadrillion Btus of energy that year.[2] Petroleum has accounted for more than 90% of transportation energy consumption since the mid-1950s.

However, the transportation system of the future is likely to look very different than today. The rapid increase in vehicle electrification and the introduction of autonomous vehicles is revolutionizing the mobility industry not only on-road but also in the areas of air, marine, and off-road. These technologies will forever change personal mobility, the movement of goods, and society in fundamental ways.

Vehicle electrification includes both all-electric and hybrid-electric vehicle architectures. Hybrid-electric systems provide an opportunity to combine the best characteristics of combustion and electric-drive technologies as well as to enable the use of clean, high-efficiency technologies that may not be able to meet vehicle transient power demands on their own. Examples include alternative architecture combustion engines and gas turbines.

[1] U.S. Department of Transportation Bureau of Transportation Statistics, "Number of U.S. Aircraft, Vehicles, Vessels, and Other Conveyances."
[2] U.S. Department of Transportation Bureau of Transportation Statistics, "U.S. Energy Consumption by the Transportation Sector."

Very important to the success of electrification and autonomous vehicles is driving range. We envision a future where vehicle refueling is easy, fast, and convenient—more of a maintenance interval or happening without driver interaction or knowledge. This will be very important for truly autonomous vehicles. DOE's national laboratories have strong research programs for extending vehicle range through better onboard energy storage, wireless charging, extreme fast charging, reduced vehicle weight, and improved fuel efficiency of onboard power generation.

Electric vehicle (EV) adoption is on the rise. Sales of new battery-driven or hybrid plug-in vehicles are likely to have reached nearly 200,000 for 2017 in the United States, up nearly 26% from the year prior, according to DOE estimates.[3]

The International Energy Agency (IEA) in its *Global Electric Vehicle 2017* report found that electric vehicles nearly doubled worldwide in 2016 to more than 2 million vehicles. With research and development leading to cheaper batteries with higher energy density, and with global policies favoring EVs, the IEA predicts that global EV inventories will rise to between 9 million and 20 million by 2020, and between 40 million and 70 million by the year 2025.[4]

China is the largest market for EVs, accounting for more than 40% of the electric cars sold in the world and more than double the number sold in the United States in 2016, IEA notes. Norway has the highest market share, with 29% of its vehicles running at least partly on electricity as of 2016. That is followed by the Netherlands with 6.4%, Sweden with 3.4%, and China, France, and the United Kingdom with electric car market shares close to 1.5%.

Volvo Cars has stated that beginning in 2019, it will no longer sell cars containing just an internal combustion engine. Its vehicles will all contain an electric motor, whether fully electrified or a hybrid. Supporting the future of EVs globally is the news that officials in Great Britain, France, Norway, India, and China have said they will propose a ban on vehicles running solely on fossil fuels in some regions as early as 2040 in an effort to improve environmental quality.

Battery manufacturers are key players in the EV space. Lithium ion battery technology was first commercialized by Sony in Japan in 1991. Other major companies in Japan are Panasonic, the current supplier of Tesla batteries, and Toshiba, typically producing batteries for electric grid applications. Japan fully dominated the battery consumer market for a decade until we began seeing a shift to Korea in the early 2000s, with the rise of Samsung SDI and LG in battery manufacturing.

China entered the battery market with the establishment of Amperex Technology (ATL), mostly as a prismatic cells supplier for phones and tablets, and BYD Company, supplying batteries for EVs and the grid. With these two companies, China has become a hub for battery manufacturing.

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[3] Argonne National Laboratory/DOE, "Light Duty Electric Drive Vehicles Monthly Sales Updates," (accessed January 16, 2018).

[4] International Energy Agency, *Global EV Electric Outlook 2017.*

Companies in Japan and Korea are shifting production to China. The world market is mainly shared between Japan, Korea and China, with a forecasted advantage to China. Europe has limited lithium ion battery manufacturing.

In the United States, the Tesla-Panasonic Gigafactory venture ramping up production now is expected to position our country as a major producer in the battery space. Tesla is targeting annual battery production capacity of 35 gigawatt hours at the facility—nearly as much as the entire world's current battery production combined.

In Japan, the focus has been on hydrogen fuel cell vehicles. Japan's automakers now have two hydrogen powered vehicles on the market, and they are teaming with energy suppliers to expand the hydrogen fueling network. The Japanese government has said it wants 900 hydrogen fueling stations and 800,000 fuel cell cars on the road by the year 2030.

While the outlook for these vehicles is promising, significant research and development challenges and opportunities remain. Solutions are needed in the EV space, for instance, to make the vehicles cheaper and more energy efficient, to increase their range and the number of charging options, and to integrate EVs into our daily lives in a way that makes them a benefit to the nation's power grid rather than a burden.

MOBILITY AND CONNECTIVITY

The goals of next generation transportation systems are to alleviate congestion, reduce energy use and emissions, and improve safety. Core disruptive technologies for such transportation systems include vehicle connectivity, vehicle automation, and the notion of shared personalized infrastructure enabled by mobility on demand systems, which today have their genesis in ride-hailing services. The central challenge is to develop more efficient transportation systems to connect communities and increase access, without also increasing the negative consequences of transportation (e.g., emissions, energy consumption, and congestion).

Scientists at the national laboratories are tackling the challenges for intelligent, ultra-efficient and connected mobility, and the fundamental changes to technology and infrastructure needed to arrive at that future.

National Transportation Research Center

The National Transportation Research Center (NTRC) at ORNL is DOE's only transportation user facility. At the center, we are focused on helping shape a more energy efficient future with foundational research for new materials such as high-temperature aluminum alloys for engines and low-cost carbon fiber for lighter, stronger car bodies and more efficient, low-cost engine components; new battery designs with higher energy density at lower cost; advanced high-efficiency, low-cost power electronics that use wide bandgap semiconductors; cheaper, more efficient catalysts for emission controls; novel materials for fuel cells; new combustion modes for more efficient hybridization solutions; and breakthroughs to enable advanced biofuels.

The NTRC provides an interdisciplinary ecosystem that is critical to driving innovation and scientific breakthroughs to application in these fast-emerging areas. More specifically, this ecosystem has demonstrated success in bridging high performance computing, materials science, and neutron science with the transportation and manufacturing programs to develop and demonstrate new technologies from the fundamentals to the road.

Connected and Autonomous Vehicles

ORNL is leading autonomous vehicle research with an interdisciplinary research strategy that bridges artificial intelligence, machine learning, sensors, electrification, and advanced manufacturing. This includes the use of the fastest open science computer in the United States—Titan—to greatly accelerate the interpretation and use of big data from vehicles and complex mobility systems.

In addition to Titan, ORNL is deploying a new system, called Summit, which may well be the world's most powerful supercomputer, operating at least five times faster than Titan when it comes online later this year. Summit will also be an exceptional resource for artificial intelligence applications, with the potential to address challenging data analytics problems utilizing deep learning in a number of scientific domains.

High Performance Computing (HPC) for the Big Data Era

To help design the transportation system of the future, industry is entering the big data realm. Autonomous vehicles are already generating terabytes of data that can be used to better understand vehicle miles traveled, driving behavior, traffic congestion, and other factors. Expertise and capabilities such as the high-performance computing assets at ORNL allow scientists to develop neural networks to parse that data for the creation of new controls and software to ensure the most efficient use of energy as we move toward a more autonomous and connected transportation system.

DOE's recently announced HPC4Mobility program will support companies, cities, and transportation system operators who seek access to the supercomputing capabilities and data science expertise of the national labs to discover opportunities for energy efficiency increases in mobility systems. First-year projects under HPC4Mobility include: 1) ORNL working with GRIDSMART Technologies on reinforcement of learning-based traffic control approaches to optimize energy usage and traffic efficiency; and 2) Lawrence Berkeley National Laboratory working with the Los Angeles County Metropolitan Transportation Authority on HPC-enabled computation of demand models at scale to predict the energy impacts of emerging mobility solutions. Applications include modeling the impact of autonomous vehicles on transportation energy use and the hour-by-hour impact of ride hailing services on traffic congestion.

Omnidirectional, Autonomous Vehicle Testbed

Our researchers have developed a one-of-a-kind omnidirectional autonomous mobile vehicle, which is used as a testbed for ORNL-developed technologies and complex control systems. It only took two days to rapid prototype the structure of this vehicle at DOE's Manufacturing

Demonstration Facility at ORNL, using large-scale additive manufacturing technology developed at the laboratory and now licensed to Cincinnati Incorporated and Strangpresse.

Control Technologies for Connected and Automated Vehicles
ORNL scientists are helping develop novel control technologies for connected and automated vehicles with the goal of achieving a 20% improvement in vehicle energy efficiency. The work is targeting improvements in optical routing to bypass traffic congestion; accelerating and decelerating based on traffic conditions and the state of surrounding roads; and optimizing onboard powertrain efficiency. Leveraging the connectivity of automated vehicles is a key concept in the project.

Vehicle Cybersecurity
As vehicles get smarter, the technologies that will keep them connected to each other and to central systems also make them vulnerable to cyberintrusion. Our challenge is to produce solutions to better protect vehicle communications and controls while continuing to advance the efficiency and other benefits of intelligent mobility.

At ORNL, our Vehicle Security Center brings together researchers from across the lab with unique transportation, sensors and controls, computational science, and cyber expertise to address this challenge. The center's Vehicle Security Laboratory places cyber experts and advanced software analysis tools in close association with vehicle and manufacturing researchers. The focus is predictive assessment—identifying threats and building in security features to neutralize them. One such tool is Hyperion, developed by an ORNL cybersecurity team to analyze code and identify threats, eliminating them proactively.

ELECTRIFICATION

The national laboratories are creating breakthroughs for electric vehicles as well as ultra-efficient internal combustion engines to support advanced hybrid and full-electric vehicles.

Better Batteries
The national labs are working on new battery technologies that extend battery lifetime, increase energy and power density, reduce battery size and cost, and improve safety for America's drivers. Scientists are concentrating their expertise in electrochemical engineering, materials characterization, material and chemical processing, and materials and systems simulations to identify battery performance limitations and develop revolutionary technologies and manufacturing processes for next-generation batteries. The highest payoff is in the development of advanced cathode materials, since they determine the energy content and lifespan of a battery.

DOE's **Battery500 Consortium** led by Pacific Northwest National Laboratory (PNNL), for instance, brings together the expertise and capabilities of DOE national laboratories, universities, and industry to develop smaller, lighter, and less expensive vehicle batteries. The consortium's goal is to develop lithium-metal batteries with nearly triple energy density than batteries in today's EVs—specifically with 500 watt-hours per kilogram compared with then 170-200 watt-

hours per kilogram found in current batteries. Other members of the consortium include Brookhaven National Laboratory, Idaho National Laboratory (INL), SLAC National Accelerator Laboratory, Binghamton University, Stanford University, University of California-San Diego, University of Texas-Austin, University of Washington, and IBM as an advisory board member.

DOE's **Battery Manufacturing R&D Facility**, housed at ORNL, is the nation's largest and most comprehensive R&D facility for this purpose. Here, our scientists are studying battery materials from the atomic level up to industrially relevant scales, including roll-to-roll manufacturing techniques in which battery components are printed on flexible substrates, resulting in a faster, more efficient process.

ORNL research has resulted in improvements that reduced the cost of lithium ion batteries cost by five-fold, while simultaneously increasing gravimetric energy density by five-fold.

ORNL battery manufacturing has been critical to the nation's recent advancements in the following areas:

- Battery cost reduction by inventing and implementing an industrial high-speed water based process to replace the costly organic and heavy infrastructure electrode fabrication process.
- Energy density improvement by increasing cathode and anode materials loading densities beyond current industry limits while achieving excellent cycle life (700-plus cycles).
- Performance improvement by incubating unique electrode architecture design, formation cycle protocols, and down selecting best matching electrochemical couples.

Quick Coatings for Lithium-Ion Batteries

In one recent project, scientists at ORNL used the precision of an electron beam to instantly adhere cathode coatings for lithium-ion batteries as the components roll down a production line. The process saves energy, reduces production and capital costs, and eliminates the use of toxic solvents. Typical curing processes can require drying machinery the length of a football field and expensive equipment to recover solvents. This new approach presents a faster, energy-efficient manufacturing process for high-performance, low-cost lithium-ion batteries.

ORNL is also advancing scientific breakthroughs for general battery safety under DOE's Advanced Research Projects Agency-Energy (ARPA-E) program. We are exploring innovative technologies to provide robust batteries where the overall system weight and cost can be reduced because the batteries are more durable and require less protection in the event of a collision.

SAFIRE — Safe Impact Electrolyte

ORNL is also improving the safety of EV batteries by developing a shear thickening colloid as the electrolyte in a project called SAFIRE, or Safe Impact Electrolyte, improving the safety of EV batteries by developing a shear thickening colloid as the electrolyte. This electrolyte transforms from liquid to solid upon impact, preventing the formation of short circuits and a potential fire. SAFIRE performs as well as conventional electrolytes under normal conditions

and can significantly reduce electric vehicle weight and increase travel distance by reducing the need for extra materials to shield batteries. A second innovation, Safety Foil current collectors, provides for breakage of large area electrodes into smaller fragments upon impact. This electrically isolates any damaged regions of the electrodes, such that thermal runaway is avoided, and the undamaged areas continue to function.

Convenient, Fast Recharging & Infrastructure

Keeping pace with the growth of EVs, charging infrastructure is on the rise. There are now more than 17,000 EV public charging stations in the U.S., and more than 47,000 individual charging outlets, according to DOE's Alternative Fuels Data Center.[5] The national labs are innovating this infrastructure as well, with development of wireless charging technology, concepts for extreme fast charging solutions, and better planning tools for infrastructure developers.

Recently, a report issued by INL, Argonne National Laboratory, and the National Renewable Energy Laboratory (NREL) identified technical gaps to implementing an extreme fast charging network in the United States.[6] The aim of this DOE/national lab consortium is to develop charging stations with 400 kWh capability—which would recharge a battery-powered EV in less than 10 minutes. The report addressed challenges in three key areas: better batteries with higher energy density, extended lifetimes, and lower cost; vehicle improvements to handle the higher voltage through advanced power electronics, including solving the tradeoff between driving range and recharge time; and infrastructure challenges such as standardization of vehicle systems and recharging stations, careful planning of station siting, and efforts to limit impacts to the larger power grid.

Bi-directional Wireless Charging

ORNL researchers developed and demonstrated a 34-kilowatt wireless vehicle charging system that can charge passenger vehicles five times faster than conventional plug-in systems at the same efficiency as a wired connection, and are targeting 100 kilowatts for next year on the way to an ultimate 350 to 400-kilowatt system. In partnership with Toyota, Cisco Systems, Evatran and Clemson University, our scientists installed the system on several electric production vehicles, including a Toyota RAV4. We are currently working with United Parcel Service to develop a bidirectional wireless charging system with higher ground clearance for the company's delivery trucks. Evatran has since developed a commercial wireless EV charging system based on this breakthrough, "Plugless," which it plans to roll out as automakers introduce vehicles with wireless charging technology.

Recharging Station Planning Tool

ORNL has extensive expertise in developing and applying spatial decision support systems to traffic forecasting and associated infrastructure investment studies. Recently, ORNL scientists in collaboration with Clemson University developed a novel method to anticipate the demand for

[5] U.S. DOE, "Alternative Fuels Data Center Fueling Station Locator" (accessed January 16, 2018).
[6] U.S. DOE, "Enabling Extreme Fast Charging: A Technology Gas Assessment," October 2017.

electric vehicle charging stations and to assist communities with infrastructure planning for inter-city travel. The data-driven method, developed with input from the California Department of Transportation, considers electric vehicle volume and random timing of vehicles arriving at charging stations to determine the optimal number of chargers needed in the near- and long-term.

Integrating EVs into the Power Grid

As we look to an electrified transportation system of the future, questions arise about impacts on the overall power grid and on electricity demand in general. The fastest, commercially available charging stations can deliver about 50kW to electric vehicles. The impact of this growing demand and how the grid may benefit from EVs is the subject of ongoing research at the national laboratories

INTEGRATE — Integrated Network Testbed for Energy Grid Research and Technology Experimentation

In the INTEGRATE project led by NREL as part of DOE's Grid Modernization Initiative, scientists are looking for ways to enable sustainable transportation technologies, renewable power, and energy efficiency to increase the capacity, efficiency, and stability of the grid. A key premise of the research in the program is that vehicle-to-grid technology makes it possible to store surplus electricity generated from intermittent solar sources, for instance, in EV batteries during non-peak periods, and to feed that power back into the grid when needed, thus enhancing grid stability and reducing electricity costs at peak times.

AMIE — Additive Manufacturing + Integrated Energy

With the AMIE project, ORNL demonstrated a future in which an additively manufactured home equipped with its own power generation—in this case a 3.2-kilowatt solar panel system—can produce, store, and consume renewable energy. The house's energy system can wirelessly charge a hybrid electric vehicle, whose chassis was also 3D-printed, and in turn the energy stored in the vehicle's batteries can wirelessly supplement power to the house as needed. A home and vehicle that can store electricity and transfer that power back and forth provide key advantages: occupants maintain electricity during outages; there's less stress on the utility grid if the home can use its own power during peak times; and the EV can function as an energy storage resource. To accomplish this, ORNL developed breakthroughs in several key areas, not the least of which was the ability to wirelessly transfer a large amount of power in both directions.

ALTERNATIVE PROPULSION SYSTEMS

While we look to the future of an electrified transportation system, our researchers are also innovating fuels, engines, and emissions technologies to support conventional and hybrid gasoline vehicles in pursuit of lower petroleum imports, energy efficiency, and a robust economy. ORNL conducts research and development focused on the interrelated areas of advanced combustion engines, lubricants, fuels, and emissions controls.

Co-Optima

ORNL is co-leading with NREL, PNNL, and Sandia National Laboratories and participation by other national labs, universities, and industry on the Co-Optimization of Fuels & Engines (Co-Optima) initiative. This first-of-its-kind effort is focused on combining fuels and combustion R&D, building on decades of advances in both fuels and engines. This effort brings together diverse expertise to simultaneously tackle fuel and engine research and development to maximize light-, medium-, and heavy-duty vehicle fuel economy and performance while mapping lower-cost pathways to reduce emissions, leveraging diverse domestic fuel resources, boosting U.S. economic productivity, and enhancing national energy security.

ACMZ cast aluminum superalloys

ORNL and partners Fiat Chrysler Automobiles and Nemak USA developed a new class of affordable, lightweight aluminum, copper, manganese, zirconium (ACMZ) superalloys capable of withstanding temperatures nearly 100 degrees Celsius greater than current commercial alloys while providing exceptional thermomechanical performance and hot tear resistance. The new alloys are easy to cast and ideal for the next generation of high-efficiency combustion engines.

HPC, Neutrons for Efficiency Improvements

In another project, ORNL researchers are collaborating with General Motors, Convergent Science, Lawrence Livermore National Laboratory, and the Oak Ridge Leadership Computing Facility on virtual engine design and calibration. Researchers are using supercomputers to increase simulation detail and accuracy while accelerating throughput. The team also collaborated with Ford Motor Company and Convergent Science to use supercomputing to identify factors that promote combustion instability in spark-ignition engines, with the aim of improving fuel efficiency and reducing emissions. In another activity, researchers made use of the ORNL High Flux Isotope Reactor and neutron imaging to improve fuel injectors, and ultimately increase engine efficiency.

SuperTruck I and II

DOE's SuperTruck initiatives aim to develop and demonstrate technologies to more than double the freight efficiency of Class 8 trucks, commonly known as 18-wheelers. These trucks haul some 80% of the nation's goods, and use about 28 billion gallons of fuel per year, accounting for 22% of total transportation energy usage. In our work with Cummins, we are designing a more efficient engine and drivetrain and vehicle technologies. We also used novel diagnostics to enable fuel-efficient engine modeling and design, resulting in 86% higher freight efficiency and a 75% increase in fuel efficiency. With Daimler, we are making use of leadership capabilities for engine and vehicle simulation, engine and powertrain-in-the-loop experiments, and advanced combustion strategies to improve efficiency and emissions, and emissions characterization and control. We demonstrated dual-fuel, low-temperature combustion with natural gas and diesel fuel for 115% higher freight efficiency and doubled the truck's miles per gallon. In our work with Volvo, ORNL helped develop emissions control strategy for their advanced engine concepts.

Hydrogen and Fuel Cell Technologies

Fuel cells could be a gamechanger for the electric vehicle industry, promising clean and efficient production of electricity. These cells use the chemical energy of hydrogen or another fuel to produce electricity. If hydrogen is the fuel, electricity, water, and heat are the only products; there are no emissions of carbon dioxide or air pollutants.

H2@Scale

DOE has begun exploring the potential for wide-scale hydrogen production and utilization in the United States to enable resiliency of the power generation and transmission sectors, while also aligning diverse, multibillion-dollar domestic industries. The H2@Scale concept aims to develop transformational technologies that reduce the cost of hydrogen production and distribution, diversify the feedstock available for economic hydrogen production, enhance the flexibility of the power grid, reduce emissions through novel uses of low-cost hydrogen, generate jobs, and provide global technology leadership for export of next-generation energy solutions.

Hydrogen is mostly produced in the United States by reforming natural gas. Switching to clean, low-cost hydrogen would take advantage of increased domestic natural gas supplies and technological advances in carbon capture and sequestration, enabling truly zero emissions for transportation and other applications.

DOE and its national laboratories have hosted three H2@Scale workshops to identify R&D concepts and bring together stakeholders to examine needs of the industry, as well as identifying regulatory, policy, and safety issues. The department has selected 26 collaborative research and development projects in which the national laboratories will work alongside industry with funds from industry going directly to the laboratories for accessing their capabilities. Access to the national laboratories is a key enabler for advancing the technology and the availability of hydrogen and fuel cells throughout the nation.

Nanoscale Materials Characterization and Component Development

ORNL is DOE's leading resource for characterization of hydrogen fuel cell electrode materials through electron microscopy and X-ray photoelectron spectroscopy. ORNL scientists are using atomic-level imaging of catalysts to develop better-performing, lower-cost fuel cell technologies. Fuel cells typically rely on costly platinum to convert chemical energy into electricity. Researchers are using advanced microscopy to aid the design of custom alloys of platinum and cheaper metals such as cobalt, and to take the next step to develop catalysts that are precious metal-free.

LIGHTWEIGHT MATERIALS AND ADVANCED MANUFACTURING

Materials Research

New, lightweight, domestically sourced materials are essential to lowering the cost and increasing the efficiency and driving range of the next generation of vehicles. It takes less energy to accelerate a lighter object than a heavier one; a 10% reduction in vehicle weight, for instance,

can result in a 6-8% increase in fuel economy. By using lightweight structural materials, cars can carry additional advance emissions control systems without increasing the overall weight of the vehicle.

But development of new and improved materials, particularly aluminum alloys and carbon fiber composites, is slow, difficult, and very expensive. Modern materials research tools, staffed by a team of dedicated materials scientists, are extremely costly to purchase and maintain. Consequently, today many firms in the transportation sector possess limited capability to effectively develop superior new materials that will lead future technology. Here is where the national labs can step in with unique capabilities and expertise in atomic-level imaging using advanced microscopy, spectroscopy and neutrons, and with high performance computing to develop a new generation of materials.

Carbon Fiber and Composites

ORNL is leading the nation in developing low-cost carbon fiber to reduce vehicle weight. Estimates show that carbon fiber composites have the potential to reduce vehicle weight by 40% or more.

ORNL is home to DOE's Carbon Fiber Technology Facility (CFTF)—a 42,000 sq. ft. innovative technology facility. The CFTF offers a highly flexible, highly instrumented carbon fiber line for demonstrating advanced technology scalability and producing market-development volumes of prototypical carbon fibers, and serves as the last step before commercial production scale.

Low-Cost Precursor

The CFTF has made available for licensing a new method of producing carbon fibers from multipurpose commercial fiber precursor—such as fibers used in carpeting or clothing. The technology has the potential to reduce carbon fiber production costs by more than 50%. In addition, the method reduces energy consumption by as much as 60% and has applications across the aerospace, transportation, energy, and infrastructure industries. LeMond Composites was the first company to license the acrylic fiber method, with plans to take the technology to market.

Bio-Derived Materials

ORNL is leveraging its expertise in advanced and composite materials and additive manufacturing in partnership with the University of Maine and its Advanced Structures and Composites Center to develop new methods and uses for forest-based biomaterials, including for automotive and other industrial applications—a partnership supported by EERE's Advanced Manufacturing Office.

IACMI — Institute for Advanced Composites Manufacturing Innovation

ORNL is a founding partner of the Institute for Advanced Composites Manufacturing Innovation, one of the Manufacturing USA centers for innovation. IACMI, the Composites Institute, has assembled a consortium of almost 160 members committed to moving carbon and

other advanced fiber composites into mainstream use in strategic application areas for the United States, including vehicles and transportation. IACMI, working with ORNL and other innovation partners are working with leading automakers Ford, Fiat Chrysler Automobiles, and others as they team with partners in their supply chains such as Dow, Faurecia, DuPont, BASF, and PPG to develop and demonstrate new materials and processes on the path to large scale deployment.

IACMI in conjunction with LIFT (Lightweight Innovations for Tomorrow) have opened a manufacturing scale-up facility at Corktown in Detroit, Michigan, where industry and institute members can conduct research and development in lightweight metals and advanced composite materials. ORNL, for instance, is collaborating on a project at Corktown to develop new, lighter materials for EV battery shielding.

Novel Electric Motor

In work supported by the Critical Materials Institute, ORNL researchers designed and demonstrated a novel electric vehicle motor that achieves 75% higher power than commercial electric motors of the same size at a lower cost. The motor makes use of permanent magnets made from common, domestic ferrite material rather than the imported rare earth materials typically used now to manufacture magnets for electric motors. In testing, the motor achieved peak power of 103 kilowatts and exceeded DOE targets for power, efficiency, and cost. That's compared to the 60-kilowatt motor typically found in many hybrid EVs.

Joining Breakthrough

Incorporating new, lightweight materials into vehicle components is very difficult using conventional methods like welding. PNNL has developed a breakthrough method to resolve these issues. PNNL's "Friction Stir Scribe Process for Joining Dissimilar Materials" joins dissimilar materials with drastically different melting points in a continuous, linear, or curved manner without the need for additional adhesives, bolts, and rivets.

Advanced Manufacturing

Advanced manufacturing at the national labs involves working hand-in-hand with industry to enhance the global competitiveness of the American manufacturing sector and to bring manufacturing jobs back to U.S. shores. At DOE's Manufacturing Demonstration Facility (MDF) at ORNL, we are collaborating with automakers to create lightweight, complex components for the transportation industry. Some of our most high-impact research in this space revolves around advances in the tool and die industry—creating custom molds, for instance, for new vehicle designs quickly and at a much lower cost than in conventional manufacturing practice.

Composite Tooling

ORNL is working with Ford and Volkswagen to produce low volume composite tooling out of high temperature thermoplastic materials via additive manufacturing. We are also collaborating with American automotive tooling companies to produce high-volume stamping dies via large-scale metal additive manufacturing.

World's First 3D-Printed Cars
ORNL collaborated with Local Motors to develop materials processes for 3D-printing the chassis of the world's first 3D-printed car—the Strati—using the big-area additive manufacturing (BAAM) machine developed by ORNL and Cincinnati Incorporated. Building on that success, the laboratory 3D-printed the Shelby Cobra electric sports car, used as a living laboratory for integrating advanced vehicle technologies, at the MDF using the BAAM system. Local Motors leveraged the same technology to additively manufacture the chassis for its Olli autonomous shuttle bus. ORNL is working with Local Motors to install its wireless power transfer technology on the Olli.

These remarkable breakthroughs would be difficult if not impossible for industry to solve alone. The national laboratories bring together world-class facilities and experts across a wide spectrum of disciplines to tackle scientific challenges from a vehicle's smallest component to solutions for efficient vast transportation networks, in collaboration with partners from industry, academic, and public institutions who help guide our research for the greatest impact.

CLOSING REMARKS

A robust transportation system utilizing efficient vehicles is essential to lowering consumer fuel costs, supporting our domestic economy, increasing energy security, and minimizing pollution. DOE works through its national laboratories and their industry and academic partners to support research, development, and deployment of efficient, sustainable transportation technologies that will improve energy efficiency, fuel economy, and enable America to use less petroleum and to reduce energy imports. These technologies will increase America's energy security, economic vitality, and quality of life.

The national laboratories are a remarkable asset for the nation. Over the past 75 years, they have consistently provided the science and technology needed to address compelling national problems, and they offer an extraordinary set of resources for sustaining and advancing the national, economic, and energy security of the United States in the 21st century.

Thank you again for the opportunity to testify. I welcome your questions on this important topic.

APPENDIX

ORNL TRANSPORTATION RESEARCH FACILITIES

National Transportation Research Center

The National Transportation Research Center (NTRC) at ORNL is DOE's only transportation user facility. The facility contains several highly sophisticated, experimental research laboratories and leverages unique science expertise and facilities in high performance computing, material sciences, and neutron sciences. NTRC offers industry, academia, and other agencies the opportunity to access state-of-the-art technologies, equipment and instrumentation, and computational resources to advance transportation technologies. In its more than 55,000 square feet of research laboratory space, NTRC contains:

- DOE's largest open access Battery Manufacturing Facility
- Fuels, Engines, and Emissions Research Laboratory
- Power Electronics and Electric Machinery Laboratory
- Vehicle Integration Laboratory
- Transportation Analysis and Visualization Laboratory
- Access to ORNL world-class supercomputing, visualization, and materials science capabilities
- Uninterrupted power backup for entire laboratory
- Transportation data analysis
- 80,000-pound pit reference scale
- Engine and chassis dynamometers
- Analytical chemistry laboratory
- Catalysis function laboratory
- Fuel cell laboratory with evaluation capabilities for cells up to 3 kW
- Unique diagnostic tools for in situ chemical speciation and catalysis surface analysis
- Wide bandgap device evaluation facility
- Co-located with ORNL's Manufacturing Demonstration Facility

Carbon Fiber Technology Facility

Carbon fiber is a strong, stiff, lightweight enabling material for improved performance in many applications, including vehicles. DOE's Carbon Fiber Technology Facility (CFTF) at ORNL is the nation's only open-access, semi-production scale facility for testing new methods of carbon fiber manufacturing. The facility offers two carbon fiber processing lines to test conventional thermal conversion as well as melt-spinning. A third line under development will explore microwave- and plasma-based processing technologies. Backed by ORNL's world-class materials research program, the CFTF aims to reduce carbon fiber production costs and accelerate the adoption of lightweight, strong, and efficient composite materials by US manufacturers.

The 42,000 square-foot facility offers a highly flexible, highly instrumented carbon fiber line for demonstrating advanced technology scalability and producing market-development volumes of prototypical carbon fibers, and serves as the last step before commercial production scale. The facility, with its 390-ft. long processing line, is capable of custom unit operation configuration and has a capacity of up to 25 tons per year, allowing industry to validate conversion of their carbon fiber precursors at semi-production scale.

Manufacturing Demonstration Facility

DOE's Manufacturing Demonstration Facility (MDF), established at ORNL, helps industry adopt new manufacturing technologies to reduce life-cycle energy and greenhouse gas emissions, lower production cost, and create new products and opportunities for high-paying jobs.
At the MDF, we are collaborating with equipment manufacturers and end users to advance state-of-the-art technologies and revolutionize the way products are designed and built using additive manufacturing (AM) technology. Drawing on its close ties with industry and world-leading capabilities in materials development, characterization, and processing, ORNL is creating an unmatched environment for breakthroughs in additive manufacturing.

We are creating metal components and new super alloys by melting metal powder or wire to form the part directly from a computer-generated design file. Metal additive manufacturing can significantly improve energy efficiency by increasing material utilization and minimizing scrap material associated with component fabrication. Elimination of geometrical constraints associated with conventional manufacturing technologies such as casting and machining can result in components that fulfill all of the functional requirements but weigh significantly less than those of conventional design.

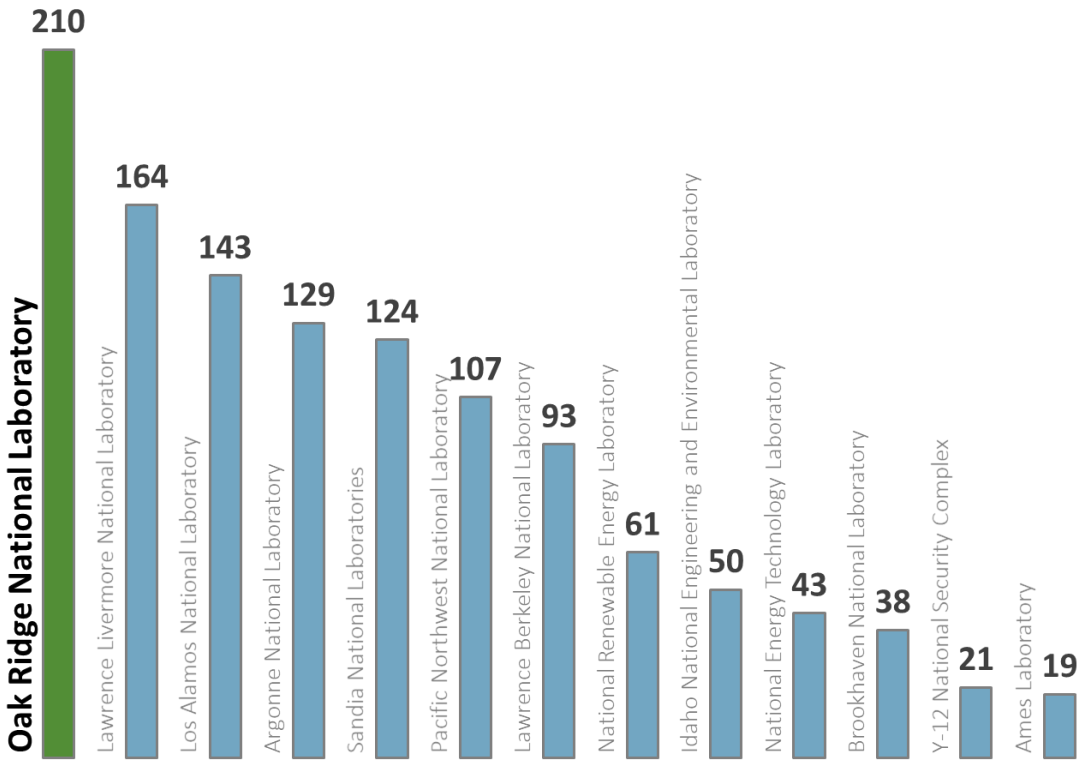
We are also engaged in polymer additive manufacturing, which can enable the rapid manufacture of lightweight, complex components and impact a broad spectrum of manufacturing industries. Examples include the tool and die industry (rapid, low-cost tooling), lightweight components for the transportation industry (automotive and aerospace), and low-cost components for the energy industry. Current objectives are focused on developing composite materials, process monitoring and closed loop feedback control systems to increase the mechanical properties and production quality of fused deposition modeling (FDM) components.

R&D 100 AWARDS

ORNL has earned 210 R&D 100 Awards since their inception in 1963, more than any other single organization. ORNL was recognized with nine total awards in 2017, with six of those coming from DOE EERE, and two specifically supported by EERE's Vehicle Technologies Office:

- *ACMZ Cast Aluminum Alloys* – a new class of affordable, lightweight superalloys capable of withstanding temperatures of almost 100-degree Celsius more than current commercial alloys while providing exceptional thermomechanical performance and hot tear resistance. Supported by DOE's Office of Vehicle Technologies.
- *Filler Materials for Welding and 3D Printing* – innovative filler materials that counterbalance how much the materials expand and shrink and control the residual stress and distortion of high-strength steel structures. The filler materials also do not require the costly, labor-intensive heat treatments normally needed to avoid cracking and material embrittlement, providing significant economic benefits while improving the stability and durability of welded and 3D printed structures. Supported by DOE's Office of Vehicle Technologies and Office of Fuel Cell Technologies.

Total R&D 100 Awards by the National Laboratories



Source: ORNL

PARTNERSHIP SUCCESSES

ORNL actively engages industrial and public-sector partners to guide its research efforts for the most impactful results. Some examples:

Aluminum-Cerium alloy — Eck Industries

As part of DOE's Critical Materials Institute, researchers at ORNL worked with Ames Laboratory, Lawrence Livermore National Laboratory, and Eck Industries to develop a new high-performance aluminum alloy. Aluminum alloys that can operate at high temperatures because of their potential for use in lightweight engine components, which would increase efficiency and fuel economy. To assess the performance of their new alloy under real-world operating conditions, the research team used the resources of MDF and NTRC to cast a cylinder head made of this alloy, using sand molds created by 3D-printing. They retrofitted this component to a gasoline-powered engine designed to operate on the VULCAN instrument at SNS and used neutron diffraction to assess the performance of the running engine. This experiment confirmed that the new alloy outperforms other aluminum alloys under realistic operating conditions. It also demonstrated the benefits of coupling fundamental science with early-stage R&D on new materials and technologies.

GRIDSMART Technologies

ORNL is collaborating with GRIDSMART, a company advancing smart traffic management systems for local communities. Their focus is a camera-based system that controls traffic lights in response to actual roadway conditions, thereby preventing lane closures, improving worker safety, and reducing costs. The system provides data on vehicle volume, turning movements, and other points to remotely control traffic systems. The technology has been installed in more than 3,000 locations worldwide, and plans are to integrate the system into autonomous vehicle technologies in the future.

TennSMART

ORNL is a member of the newly launched TennSMART Consortium, consisting of 20 public and private partners working to accelerate the development and deployment of intelligent mobility innovations in Tennessee. The group establishes a regional ecosystem focused on connected and automated vehicles, heavy-duty trucking and freight efficiency, vehicle cybersecurity, electric vehicles, and multimodal commuting. Other members include: Bridgestone Americas, Cummins Filtration, Inc., DENSO Manufacturing Tennessee, FedEx Corporation, GRIDSMART Technologies, Inc., Local Motors, Lyft, Miovision, Nissan North America, Stantec Consulting Services Inc., the Tennessee Department of Environment and Conservation, Tennessee Department of Labor and Workforce Development, Tennessee Department of Transportation, Tennessee Tech University, Tennessee Valley Authority, Top Five Inc., University of Memphis, The University of Tennessee, and Vanderbilt University.

Grid Modernization
ORNL works with several utilities on grid modernization and security innovations, including the Chattanooga Electric Power Board (EPB), Dominion, Duke Energy, Southern Company, Georgia Power, and Tennessee Valley Authority.

For instance, ORNL and DOE have enjoyed a productive working relationship with the Chattanooga EPB. These efforts support America's technological leadership, national security, and the goal to create a new, more reliable, and affordable electric utility service for the Internet Age. The EPB smart grid and advanced communications network also make a living laboratory to test new technology developed by ORNL and other labs.

Another example demonstrates *Neighborhoods of the Future* with partners like Southern Company and its subsidiaries Alabama Power and Georgia Power. The energy for Smart Neighborhood will be provided by the existing electric grid, as well as a community-scale power system called a "microgrid," which is composed of solar panels, battery storage, and backup generation. The Georgia development will include "EV-ready" townhouses allowing homeowners the ability to add the charging technology later.