NREL

Transforming ENERGY Through SUSTAINABLE MOBILITY

Expanding Low-Carbon Transportation R&D Solutions

AS THE UNITED STATES PRESSES TOWARD a carbon-neutral economy by 2050, the transportation sector will undergo a massive shift in technologies, from the road to the skies. Mitigating the climate crisis is imperative. In the process, we can enhance energy security, increase high-quality domestic jobs, and enable clean energy access for all Americans.

As the nation's premier laboratory for cutting-edge transportation decarbonization research and development (R&D) solutions, the National Renewable Energy Laboratory (NREL) pioneers the creation and deployment of sustainable mobility technologies and strategies, with a focus on slashing transportation sector greenhouse gas emissions and combatting climate change.

Thirty years from now, America's transportation system may look similar on the surface, but it will be dramatically transformed. People and goods will travel primarily using clean energy. As a result, pollution in our air and water will plummet. Getting around will become more affordable, with equitable and ready access to sustainable transportation.

Trucks, planes, cargo ships, and other difficult-to-decarbonize vehicles are part of this essential transition for the transportation sector, which is currently the nation's largest source of the greenhouse gas emissions driving climate change.

NREL provides the scientific building blocks needed to spur innovation through multifaceted analysis, research, and engineering. This work acts as a catalyst to help industry bring affordable, high-performance, energy-efficient, and low-emission modes of transport and related infrastructure to market sooner.

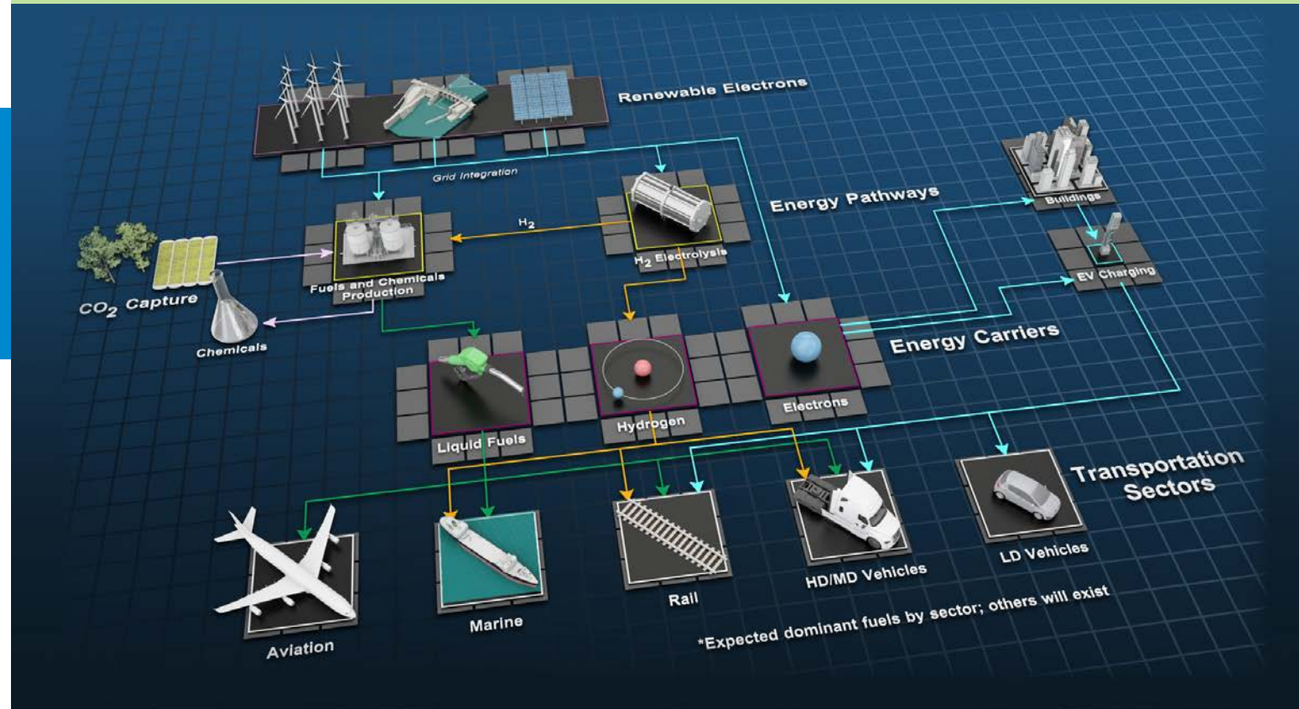
Our researchers collaborate closely with academic, government, and industry partners to design better batteries, drivetrains, and engines. They develop technologies for high-power charging, thermal management, energy storage, and power electronics. They are also reimagining fuels and combustion while creating sustainable lightweight materials. Unbiased expert guidance—backed by credible data and analysis, tools, and scientific rigor—empowers partners to make informed decisions about sustainable transportation.

NREL recognizes that communities with limited mobility options face reduced access to employment opportunities, health care, and education, lowering overall quality of life. Alongside partners, NREL experts are creating transportation solutions that meet community-identified needs and increase mobility equity in historically underserved and overburdened communities.

Rather than providing a one-size-fits-all solution, we take an interdisciplinary approach to mobility equity that considers the needs and challenges of diverse groups, maximizing benefits at the individual, community, and societal levels.

The U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy supports this work via its Vehicle Technologies Office, Hydrogen and Fuel Cell Technologies Office, and Bioenergy Technologies Office.

A WHOLE-SYSTEM APPROACH—NREL's research strategy for deep decarbonization considers transportation sectors as part of a larger energy ecosystem powered by renewable electrons and linked by low-carbon energy carriers.



CROSSCUTTING INITIATIVES

A truly sustainable transportation future will rely on widespread adoption of numerous solutions. These include electric-drive vehicles (EDVs), alternative fuels, more fuel-efficient internal combustion engines, new approaches to fueling and charging, innovative systems of vehicle connectivity, and a grid powered by a variety of clean energy sources. EDVs—which include hybrid, plug-in hybrid, fully battery-electric, and fuel cell electric vehicles—will enable more than sustainable road travel. These technologies can also power off-road and non-road sectors such as aviation, rail, freight marine shipping, and industrial vehicles like forklifts.

Beyond our foundational research spanning a broad spectrum of technologies—bolstered by complex analyses leveraging high-performance computing capabilities—NREL is a national trailblazer in a wide range of crosscutting arenas.

Smart Mobility Systems

Rapid proliferation of automated vehicle technologies and connected, on-demand mobility services, coupled with lightning-speed advances in communications and control technologies, are revolutionizing today's transportation system. NREL approaches transportation as a network of travelers, services, and environments, using connectivity and automation to optimize mobility and overall system efficiency. NREL's Mobility Energy Productivity (MEP) tool is one such approach that quantifies the time, cost, and energy associated with access to services and activities in a given geographical area, making it a valuable way to assess equity. When applied to freight, it can quantify the ease of shipping goods between cities or states via various modes. Its versatility also enables it to measure the ease of accessing an airport from anywhere within a metropolitan area.

Equity and Environmental Justice

Mobility limitations involve more than just having difficulty getting from one location to another—they can present major personal challenges as well. These constraints disproportionately burden low-income and nonwhite populations, as well as older adults and people with disabilities. Working with partners in underserved communities, researchers are exploring how accessible, affordable, and energy-efficient transportation solutions can increase mobility equity. For example, NREL provides technical assistance for the Communities Local Energy Action Program, which is helping more than 20 low-income, energy-burdened communities across the nation develop clean energy action plans that may incorporate sustainable mobility options. Additionally, NREL created an Electric Vehicle Infrastructure for Equity model to evaluate the coverage and concentration of current and future public charging stations to ensure fair access.

Renewable and Sustainable Lightweight Materials

Carbon fiber is an appealing prospect for vehicles because of its strength and lightness. It can cut the weight of a typical passenger car in half, raising fuel efficiency, but it is expensive and energy-intensive to produce. NREL researchers are working on a cheaper, greener version of the material by making carbon fiber composites with epoxies and an anhydride hardener, both bio-based. This innovative material can be dissolved and reused up to three times with no degradation to performance. Being able to recycle carbon fiber would make the material more economical for use in vehicles, which could speed EDV adoption by lowering manufacturing costs. Recycling carbon fiber could also cut the material's greenhouse gas footprint up to 40%.

Supply Chain Analysis

An anticipated surge in EDV adoption will require an abundant, reliable, and affordable supply of raw materials, as well as components such as high-performing batteries, semiconductors, and fuel cells. The complex manufacturing supply chain includes a vast network of mining, processing, manufacturing, materials recovery, infrastructure, and logistics operations. NREL researchers are working to understand the implications of the current clean transportation supply chain, as well as anticipate future needs and challenges. The laboratory's circular economy approach to manufacturing focuses on extending the life span of materials and components while reducing waste, conserving resources, and boosting production efficiency.

Thermal Management Research

Optimized thermal management can increase electric vehicle (EV) battery power by more than 20%, enable electric drivetrains with tenfold higher power density, and decrease climate control systems' energy demands by as much as 68%. NREL research in this domain aims to improve vehicle performance, range, reliability, life span, and affordability.

In addition to investigating the impact of high temperature on power electronics system components, researchers are designing systems that can support thermal management for sustainable aviation applications. This includes designing a 2-MW fully integrated all-electric aircraft powertrain and building a high-power-density motor for aviation propulsion. For such projects, NREL conducts thermal management modeling, analysis, and characterization of the advanced cooling concepts and inverter components. This research also incorporates thermomechanical design and techno-economic analysis for various power electronics, electric motors, and integrated electric-drive components.

Transportation Data Analysis

NREL serves as the nation's most credible and complete transportation energy efficiency clearinghouse for validated, up-to-date statistics, data, and tools. The lab pairs information from government and private-sector partners with its own expertise in forward-thinking analysis and real-world

REGULATING BATTERY AND POWER ELECTRONICS system operating temperatures is key to optimizing EDV performance, life span, safety, and affordability. NREL innovations troubleshoot battery and drivetrain thermal performance issues to keep improving next-generation EDVs.

applications. Drawing on NREL's world-class high-performance computing and simulation capabilities, researchers employ data fusion, multivariate analysis, and leading-edge visualization techniques to investigate complex, multidimensional transportation and mobility issues and solutions. NREL's analytical and data science prowess plays a vital role in accelerating the pace of advancements across the lab's research arenas, informing the transformation to a sustainable mobility future.

Sustainable Transportation Integration

NREL's transportation integration activities increase adoption of advanced technologies and alternative fuels through technology deployment projects and strategies, generating tangible progress toward decarbonizing the transportation sector. Lab experts provide tailored, high-quality technical assistance and resources based on a deep understanding of stakeholder needs through strong, long-term relationships. Energy and environmental justice considerations are woven throughout this work to develop clean transportation solutions via a community-first approach. Alongside partners, NREL creates transportation solutions that meet community-identified needs and increase benefits to historically underserved and overburdened communities.

BUILDING ON NREL'S TECHNOLOGIST-IN-CITIES efforts, researchers have taken their expertise to smaller and underserved communities, partnering with local organizations to gain knowledge of regional travel patterns and priorities, analyze transportation data, and develop affordable, convenient, and energy-efficient public mobility solutions. One such demonstration project in Bastrop, Texas, resulted in an emissions-free, microtransit ride service using low-speed battery-electric vehicles, which sees high demand for local service. Such customizable solutions can be replicated in rural, suburban, and urban communities.

NREL IS LEADING EFFORTS to expand widespread transportation electrification and the nation's charging infrastructure network. NREL plays an integral role in supporting the initiatives and technical assistance efforts of the Joint Office of Energy and Transportation, a partnership between the U.S. Department of Energy and the U.S. Department of Transportation aimed at deploying a nationwide network of EDV chargers, with a focus on highway corridors and underserved communities.

NREL also leads the EVs@Scale Lab Consortium, a first-of-its-kind collaboration to accelerate vehicle-to-grid technologies, associated research, and related codes and standards supporting the establishment of a secure and scalable national charging infrastructure network.

Vehicle-to-Grid Integration

Vehicle-to-grid technology can balance intermittent renewable resources and enhance grid stability, feeding unused energy from batteries back into the electricity system. This potential becomes even stronger with the advent of electric trucks, locomotives, and aircraft—but it also brings infrastructure challenges, since these larger motors may require more than 3 MW of charging capacity.

NREL researchers are developing and evaluating fully integrated systems that connect vehicles, power grids, renewable energy sources, and behind-the-meter storage options. These efforts cover a full range of charging technologies, from home-based Level 1 charging to extreme fast charging. The lab's EVI-X modeling suite of EV charging infrastructure analysis tools equips researchers and stakeholders with integrated tools to inform the development of large-scale charging networks across facilities, regions, and the nation.

In addition to modeling the impacts of charging networks, NREL researchers are investigating ways to address those impacts. This work includes solutions for shared, autonomous EDV fleets, charging station load management, and stationary storage systems to lower costs associated with peak periods of fast charging.

NREL's world-class Electric Vehicle Research Infrastructure (EVRI) evaluation platform enables researchers and industry stakeholders to study and develop a new generation of electrified transportation technologies within the context of the larger energy ecosystem, coordinating EVs with buildings, the power grid, and other energy systems. EVRI makes it possible to conduct research on actual devices under varying conditions to build the next generation of vehicle-to-grid technologies.

Leveraging the EVRI platform, NREL is collaborating with industry experts on a new high-power, multimegawatt charging standard for commercial vehicles, such as heavy-duty trucks. An industry standard for megawatt chargers will inform the development of interoperable connector and inlet designs, providing fleets with stability and certainty in accessing infrastructure globally while facilitating charging capacity up to 3.75 MW.

NREL's Advanced Research on Integrated Energy Systems (ARIES) research platform plays a critical role in enabling high-power charging at utility scale, allowing researchers to measure how varying loads and controls affect the broader electricity system to ensure EV charging and other electricity demands can be met. Developing megawatt-scale charging systems will dramatically improve the speed and convenience of charging medium- and heavy-duty electric vehicles, motivating greater rates of EV consumer adoption.

INNOVATIVE VEHICLE, FUEL, AND INFRASTRUCTURE R&D

NREL researchers are exploring ways to speed the transition to zero-emissions transportation for a carbon-neutral U.S. economy by 2050. The lab's multipronged decarbonization R&D strategy includes powertrain electrification, net-zero/low-carbon fuels such as biodiesel and renewable hydrogen, diverse energy storage solutions, and integrated science and analysis to support the realization of a sustainable transportation future.

Fuel Chemistry and Combustion Science

The share of electric passenger cars on the road is growing, but light-duty vehicles only account for 58% of the greenhouse gas emissions from transportation. The rest of those emissions come mainly from heavy vehicles such as trucks, planes, rail, and cargo ships. While electrification and hydrogen will play a role in decarbonization, the world will also need net-zero-carbon fuels and vehicle powertrain options that maintain efficiency while meeting increasingly stringent global greenhouse gas reduction targets and criteria pollutant regulations. Cargo ship engines, for example, pose a major opportunity to replace current low-quality fuels with bio-distillate, methanol, and ammonia.

NREL is researching the engine technologies and fuel components needed as companions to sustainable fuels. Sophisticated laboratory experiments and high-fidelity combustion simulations allow for more rapid fuel development, analysis of engine performance with various fuels, and evaluation of emissions from all types of engines. Leveraging high-performance computing, researchers can run massive simulations of aviation turbine combustors to characterize and optimize the system performance of drop-in, low-carbon aviation fuel candidates. NREL also wields extensive expertise in working with fuel standards organizations and navigating the fuel certification process to help bring these new fuels to market safely, affordably, and efficiently.

Non-Road Vehicle Electrification

While some modes of transport, such as long-haul commercial flights and cargo ships, will rely on alternative liquid fuels in the near term, other modes—on water, in the air, and across railways—are ripe for electrification, powered by an increasingly renewables-based grid. NREL research is advancing electrification where possible, including efforts to evaluate the technical feasibility of connecting underused small airports with electric and hybrid flights. The lab is also partnering with companies exploring advanced air mobility to analyze the potential of an electric, autonomous air vehicle network.

Through pilot projects from coast to coast, NREL is evaluating battery-powered ferries and the use of small electric aircraft for regional flights. And with NREL's Advanced Locomotive Technology and Rail Infrastructure Optimization System (ALTRIOS) software, the lab is collaborating with industry and research partners on a new modeling framework for analyzing and planning zero-emissions and hybrid freight train networks.

Energy Storage

To meet market demand for long-range, fast-charging, safe, and affordable EDV batteries, energy storage systems must be able to manage rapid charging rates and high heat levels and sustain long operating lives while reducing costs and slashing the use of critical materials. As the country's recognized leader in battery thermal management research, NREL is modeling, simulating, and evaluating systems to assess and optimize energy storage components at the materials, cell, pack, and systems levels.

Meanwhile, NREL's battery materials expertise enables new battery chemistries, such as silicon anodes, low-/no-cobalt cathodes, and solid-state electrolytes. NREL is at the helm of two multi-laboratory partnerships—the Silicon Consortium Project and the Behind-the-Meter Storage Consortium. The former investigates the use of silicon as an anode material to improve energy density and reduce costs. The latter develops critical-material-free energy storage technologies to support the integration of electric vehicle fast chargers, photovoltaic generation, stationary electrochemical and thermal energy storage, building systems, and the electric grid.

To accelerate the fast-charging, affordable, and powerful batteries needed to encourage widespread EDV adoption, NREL researchers are developing high-throughput laser processing and acoustic diagnostics for enhanced battery performance and manufacturing. This work aims to produce better batteries while reducing the time and cost involved in making them.

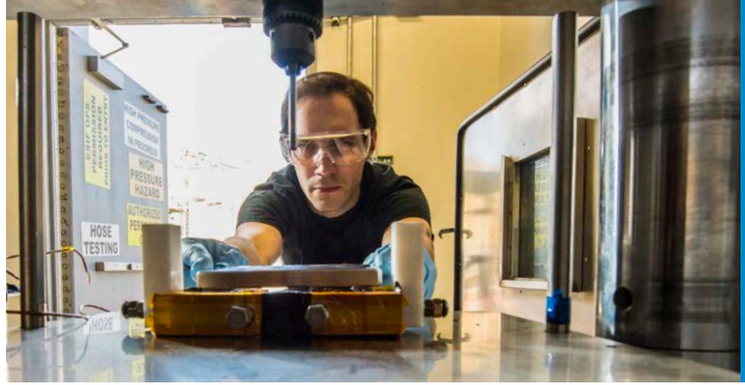
A robust EDV market also requires consumer confidence that they can travel maximum distances under a range of temperature conditions without running the risk of a battery overheating. NREL's "science of safety" research examines lithium-ion batteries under extreme conditions, including exceptionally hot and cold temperatures.

NREL also spearheads ways to repurpose and recycle batteries when they are no longer useful in vehicles. Where possible, batteries that have been retired from vehicles can find secondary use, such as in stationary energy storage. And as part of ReCell, the Vehicle Technologies Office's first advanced battery recycling R&D center, NREL is working to improve direct recycling of lithium-ion batteries, which uses less energy and captures more of the critical materials than current recycling methods.

Power Electronics and Electric Machines

While power electronics help run a wide range of systems in conventional gas-fueled vehicles, EDVs and high-power charging equipment rely even more heavily on these components. So will planes, trains, and trucks in a zero-emissions world. In addition to improving performance, advanced power electronics and electric machine systems can avert overheating during operation, particularly in high-power, high-temperature applications like heavy-duty vehicles.

NREL's advanced power electronics and electric machines research supports the development of innovative lightweight and ultraefficient electric motors, propulsion systems, and thermal management. This research is making widescale EDV acceptance more feasible by developing technologies and components with greater dependability, efficiency, and durability, while dramatically decreasing costs. The lab is also building systems for large and advanced electrified vehicles like commercial aircraft. Steeped in modeling and experimentation, this work has established the lab as a vital national resource for reliability and thermal management of motor controllers, inverters, and traction motors, as well as sensors for mobility, energy efficiency, and renewable energy applications.



TO GUARANTEE EDV SAFETY on par with that of conventional petroleum-fueled vehicles, NREL's Science of Safety Mechanical Characterization Laboratory investigates the reaction mechanisms that lead to failure in lithium-ion batteries. The facility is equipped to examine what occurs within the liquid, solid, and gaseous components of a battery before, during, and after failure.

Fuel Cell and Hydrogen Technologies Research

In addition to their use in light-duty vehicles, hydrogen and fuel cell systems will also be needed to help reduce emissions from difficult-to-electrify sectors like heavy-duty trucking and aviation. NREL's hydrogen and fuel cell research is lowering the cost and increasing the scale of technologies to make, store, move, and use hydrogen across multiple energy sectors. Researchers are evaluating hardware devices for high-flow-rate hydrogen fueling of fuel cell trucks, rail, and marine vessels; characterizing component failures to improve reliability; and creating safety and sensor systems. Ongoing work also centers on evaluating the long-term durability of fuel cell stacks and systems for heavy-duty truck and flight applications, aiming to understand degradation processes during prolonged operation.

NREL has unique experimental and analysis capabilities for integrating hydrogen technologies in future energy systems. These include the ARIES platform, which supports projects to demonstrate direct renewable hydrogen production, energy storage, power production, grid integration, and innovative hydrogen end uses at the megawatt scale, such as heavy-duty transportation.

REPLACING GRAPHITIC CARBON ANODE MATERIAL with silicon in lithium-ion batteries could help deliver smaller, cheaper, and more powerful energy storage. But silicon tends to degrade, leading to short-lived batteries. As part of the Silicon Consortium Project, NREL is working with five other national laboratories to solve this challenge.

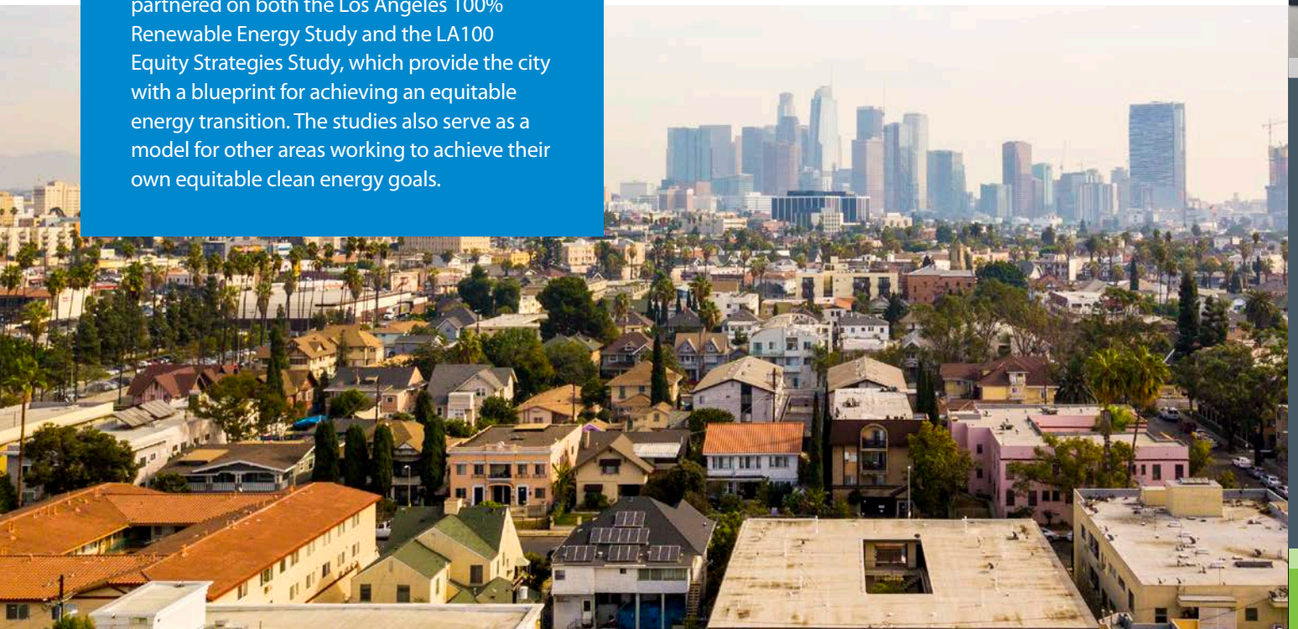
Mobility Behavior Science

Focusing on the interactions among people, mobility, the built environment, and energy systems, NREL's behavioral science research illuminates travel behavior and consumer choice, informing the design of equitable and accessible transportation systems that meet people's mobility needs while saving time, money, and energy. Researchers take a holistic, people-centric approach to improve our collective understanding of how people will respond to technology transitions and dynamic new mobility service offerings across spatial and temporal scales in diverse communities across the nation. NREL's interdisciplinary approach combines behavioral science with analysis, engineering, deployment assistance, and community engagement.

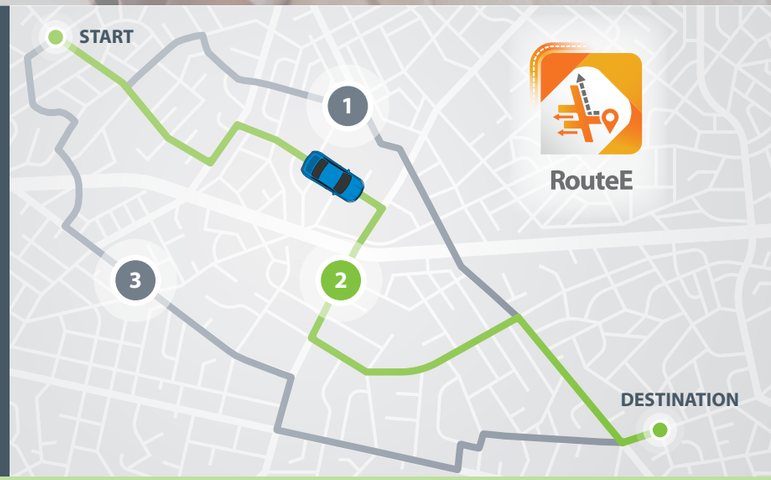
Intelligent Vehicle Energy Analysis

NREL's intelligent vehicle modeling tools are used to conduct scenario analyses to inform future vehicle deployment pathways and reveal how different decisions influence mobility, energy use, and emissions. Researchers employ innovative modeling and analysis capabilities to study vehicle adoption, conduct fuel economy evaluations, assess the life cycle costs of advanced technology commercial vehicles, analyze large-scale green routing opportunities, optimize ride-hailing fleet operations, and explore pathways toward transportation system decarbonization. To ensure the accuracy and applicability of their analyses, researchers tap into NREL's wealth of real-world travel behavior and fleet vehicle operations data.

NREL IS PIONEERING A HOLISTIC APPROACH TO ENERGY ANALYSIS with community-based research. The lab has partnered on both the Los Angeles 100% Renewable Energy Study and the LA100 Equity Strategies Study, which provide the city with a blueprint for achieving an equitable energy transition. The studies also serve as a model for other areas working to achieve their own equitable clean energy goals.



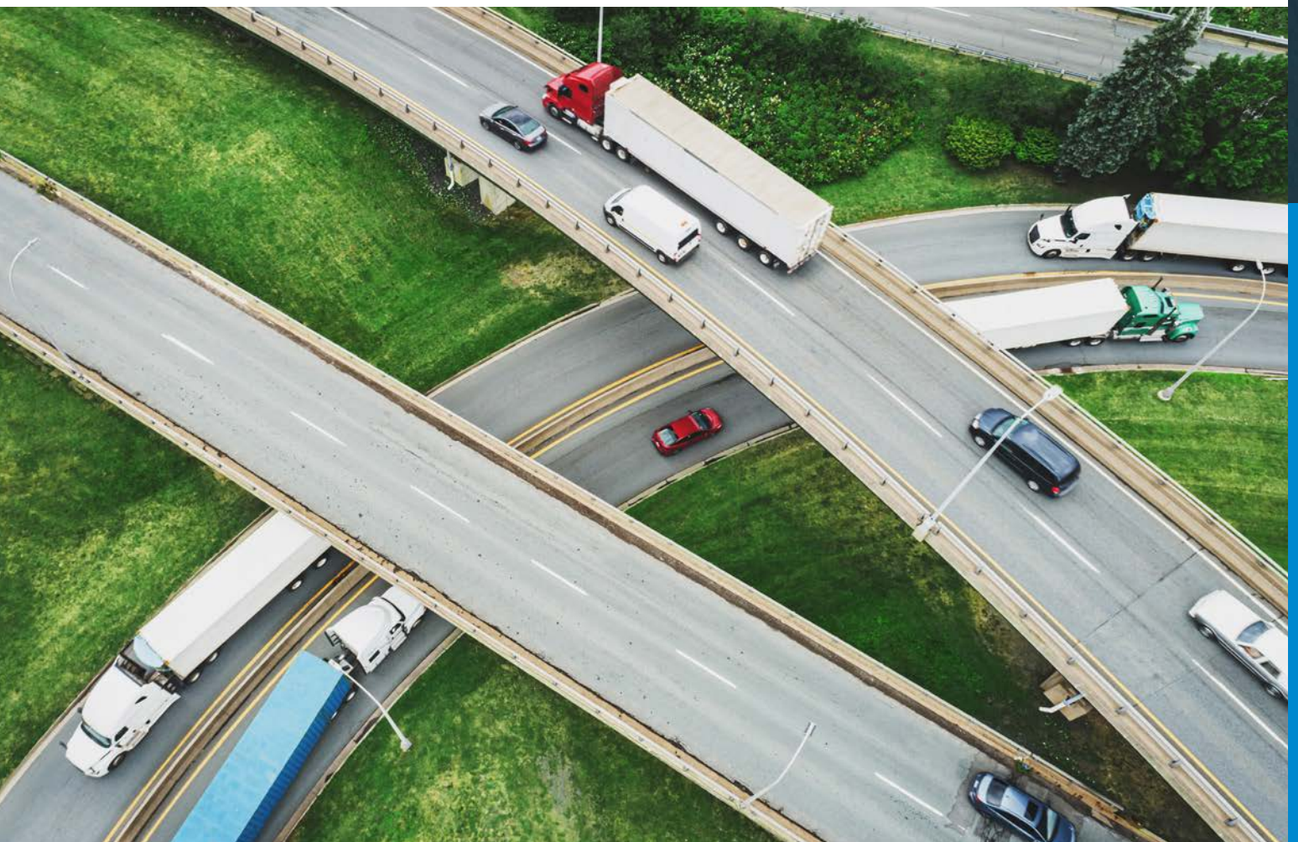
LEVERAGING NREL'S DATA SCIENCE TOOLS AND EXPERTISE, NREL partnered with Google to develop more eco-friendly routing in Google Maps. Now, Google Maps defaults to the route with the lowest carbon footprint when it has approximately the same estimated time of arrival as the fastest route. In cases where the eco-friendlier route could increase travel time, Google Maps displays the relative CO_2 impact between routes, allowing drivers to make informed choices.

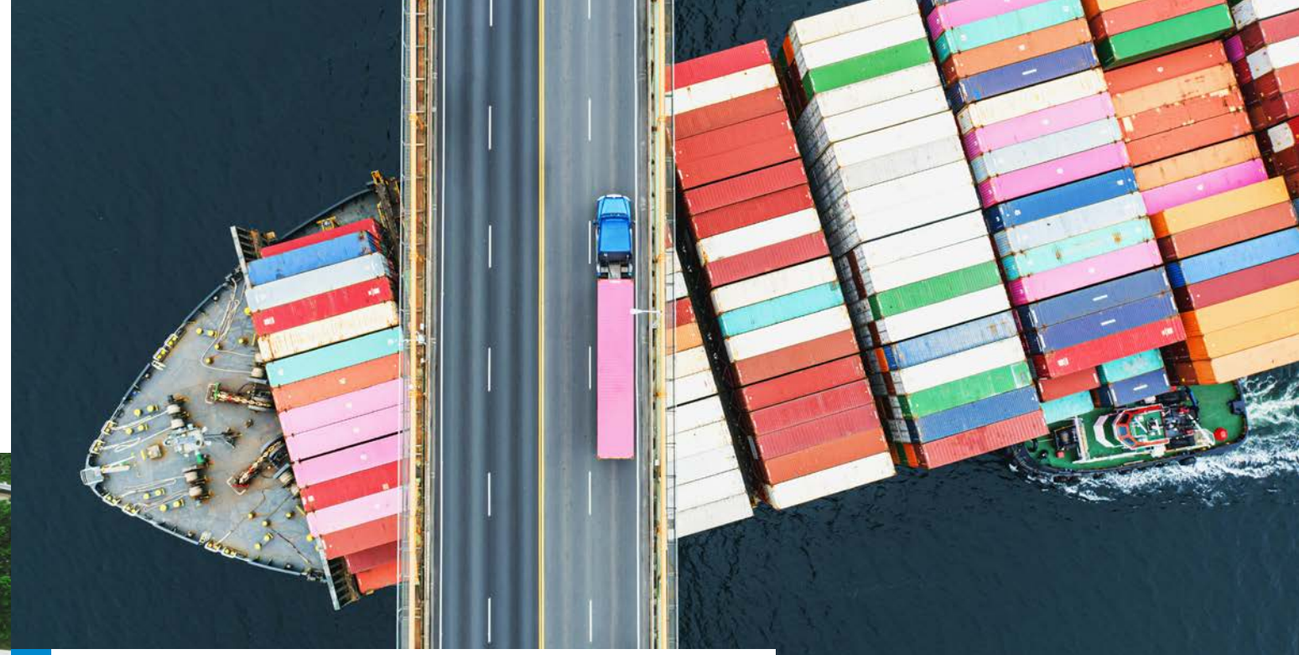


Commercial Vehicle Development, Evaluation, and Decarbonization

Trucks move more than 11 billion tons of freight across the United States each year and account for 23% of transportation-related greenhouse gas emissions. NREL partners with truck manufacturers and fleet operators to deliver equitable solutions that reduce barriers to decarbonization while meeting performance and economic requirements across vehicle vocations—including freight transport, pickup and delivery, port drayage, yard tractors, public transit, and airport shuttles.

Paired with NREL's suite of data-informed modeling, simulation, and analysis tools, researchers' customized evaluations of conventional and advanced vehicles, infrastructure, and operations enable insights critical to the successful development and optimized use of energy-efficient, commercially viable vehicles. NREL's in-depth studies span a full range of commercial vehicle technologies, practices, and considerations, including EDVs, vehicles powered by low-carbon fuels, platooning, drive cycle analysis, total cost of ownership, eco-routing, and more.





Partners in Innovation

Partners from government, industry, and academia tap NREL expertise in advanced ground-based vehicles and fuels, as well as emerging technologies for aviation, rail, and marine applications, for innovative R&D in support of:

- Biofuels, hydrogen, and other sustainable fuels.
- Electric, hybrid, fuel cell, and conventional vehicle technologies.
- Charging and fueling infrastructure.
- Lightweight materials.
- Vehicle connectivity, automation, and mobility systems.

Visit **www.nrel.gov/transportation/working-with-us.html** for information on our sustainable transportation and mobility research partnership and employment opportunities.

Learn More

Visit **www.nrel.gov/transportation** to learn more about NREL's sustainable transportation and mobility R&D, check out our world-class facilities, and subscribe to our quarterly Sustainable Mobility Matters newsletter for updates on recent research results, partnerships, and publications.

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