U.S.-China Clean Energy Research Center (CERC)
Joint Work Plan for Collaborative Research on Clean Vehicles

In November 2009, President Barack Obama and President Hu Jintao announced the establishment of the Clean Energy Research Centers (CERC), the primary purpose of which is to facilitate joint research and development on clean energy technology by teams of scientists and engineers from the United States and China.

U.S. Secretary of Energy Steven Chu, Chinese Minister of Science and Technology Wan Gang, and Chinese National Energy Administrator Zhang Guobao signed the CERC Protocol on November 17, 2009, launching the Center. As the world's top energy consumers, energy producers, and greenhouse gas emitters, the U.S. and China will play leading roles in the world's transition to a clean energy economy in the years ahead. Over the long-term, it is significant to note that much of the energy-consuming infrastructure of the 21st century that will benefit from this work has yet to be built.

Recognizing that energy use in vehicles represents both challenges and opportunities for our two countries, the United States and the People's Republic of China have chosen University of Michigan and Tsinghua University to lead a consortium of experts to collaborate in the field of clean vehicles under the CERC's auspices. The vision for the Clean Vehicles Collaboration (CVC) is to contribute to dramatic improvements in technologies with potential to reduce the dependence of vehicles on oil and improve vehicle fuel efficiency. The CERC-CVC will build a foundation of knowledge, technologies, human capabilities, and relationships in mutually beneficial areas that will position the United States and China for a future with very low environmental impact and highly efficient clean vehicles. The collaboration will advance technologies for clean vehicles through joint research and development.

The CERC-CVC will bring together academia, national laboratories, and industry into a consortium of exceptional intellectual strength and expertise in key engineering, natural science, and social science areas. The U.S.-China teams in each of the major research thrust areas will focus on maximizing collaborative efforts and leveraging the respective strengths of the research partners in order to both accelerate invention and commercial success through close ties with industry partners in both countries. CERC-CVC aims to be the leading US-China effort in the clean vehicle arena by performing both long-range transformational and translational research to bring discoveries and technologies to market. Successful demonstration of the proposed CV technologies will involve strategic partners from industry in the U.S. and China, including leading OEMs in the transportation and energy sectors, suppliers and innovation companies.

The CERC-CVC partnership currently includes the following members: In the US, the University of Michigan leads an academia-national lab team which includes Ohio State University, M.I.T., Sandia National Laboratories, Oak Ridge National Laboratory, Argonne National Laboratory, Environmental Protection Agency, and the Joint Bioenergy Institute. U.S. Charter CERC-CVC partners include Cummins, Fraunhofer, Ford, GM, Toyota, and members include A123, Borg Warner, Chrysler, Delphi, Transportation Research Center, Duke Energy, First Energy, MAGNET, American Electric Power and PJM. In China, Tsinghua University leads an academia-national lab team that includes Shanghai Jiao Tong University, China Academy of Sciences, Beijing Institute of Technology, Wuhan University of Technology, Tongji University, and Tianjin University. China CERC-CVC industry members include Geely Automobile, China Potevio, Wanxiang, CHANA, SAIC.

In order to build a strong and collaborative research program, the University of Michigan and Tsinghua University – led teams plan to:

- Jointly organize and participate in an annual technical workshop. The workshop will bring together both U.S. and Chinese participants working on the collaboration. The workshop will focus on:
    - exchanging information on current research activities and emerging developments;
    - identifying high-priority research needs; and
    - planning mutually beneficial, collaborative work areas for research and projects to be undertaken under the auspices of the CERC.

- Develop a multi-year set of research projects for clean vehicles, the initial version of which will be submitted for review to the CERC secretariat by March 15, 2011, with updates submitted annually by March 15th of each following year of the collaboration.

- Develop a joint annual report on work accomplished under the collaboration, highlighting significant results and research progress in important areas, to be submitted to the CERC Secretariat by March 15, 2012, and updated annually by March 15th of each following year.

The CERC-CVC aims to have an impact on three of society's grand challenges, climate change, energy security and environmental sustainability, while spurring innovations to enhance market growth, economic development and jobs creation in vehicle manufacturing, clean energy industries, and their associated supply chains. A dramatic reduction of petroleum-based fuel consumption and vehicle greenhouse gas emissions for both nations can be accomplished

through the synergy of optimized low-carbon energy carriers, including electricity and biofuels. Highly-efficient electrified propulsion technologies that incorporate novel energy conversion, waste heat recovery, battery storage and connectivity with the grid will be integrated into vehicle platforms based on advanced, low-carbon footprint lightweight materials and components. An integrative life cycle design framework will guide the research and development (R&D) of advanced systems and will enable us to establish greenhouse gas reduction targets, pathways, and policies for translating research results into competitive clean vehicles. Our pioneering research and innovative testbeds will provide unique opportunities to translate laboratory results to full vehicle prototypes.

Transformation of such a complex scientific and technological nature will depend on the availability of a work force with the appropriate skills and abilities to attain clean vehicle mobility. The UC-China CERC-CVC team has a strong representation of faculty and students with diverse backgrounds, spanning the key areas of engineering and science needed to attack this grand challenge. The research accomplishments of the CERC-CV will be leveraged to attract new talent in innovative, global transportation energy research and education. We will capitalize on the multi-disciplinary nature of the CERC-CV to produce a rich set of academic and hands-on experiences for all university students in the program, who will work on CV projects for course and degree credit. The goal is to create a pipeline of new engineers and scientists that are prepared to work on the right problems, to feed the transportation industry and the research enterprise at universities and national laboratories.

To realize this shared vision, the CERC-CVC has developed a highly collaborative research agenda that has been organized in six thrusts, as describe below. Under the CERC's U.S.-China Protocol and its Intellectual Property Annex, no work on any cooperative activity between the two countries can begin without a mutually agreed upon Technology Management Plan. The six thrusts are:

Thrust Area 1: Energy Systems Analysis, Technology Roadmaps and Policies

The combinations of possible technology pathways and fueling strategies to address the fuel economy and GHG challenges are immense. The vehicle and energy infrastructure system integration will address temporal and spatial variation of energy sources, their petroleum demand and CO_2 emissions impacts, diversity in consumer drive cycles and trip patterns, producer and consumer economic factors, global vehicle and fuel market factors, as well as future fuel efficiency and carbon policy regimes.

Thrust 2: Vehicle-Grid Interactions

As adoption of Plug-in Electric Vehicles (PEVs), grows, the power drawn by charging loads may create localized problems for distribution networks, including overloads, voltage profile degradation, and unbalance. At the macro grid level, uncoordinated charging of large populations of PEVs could exacerbate peak loads. Development of advanced control strategies and protocols is needed to coordinate PEV charging and develop interfaces for accelerating the deployment of PEVs.

Thrust Area 3: Vehicle Electrification

To support aggressive vehicle electrification, electrical materials and devices will require higher conversion efficiencies and power/energy densities than are currently possible. The next generation PEVs will benefit from novel electric motors, thermoelectric waste heat recovery, and power electronic devices and electrical topologies that are capable of handling increased loads and multiple combinations of sources and accessories.

Thrust Area 4: Advanced Batteries and Energy Conversion

A major drawback of current Li-ion battery technology for automotive applications is their limited cycle life and charge/discharge capability. Degradation mechanisms in Li-ion batteries remain poorly understood and the basic science required for the formulation of modeling tools to predict battery performance and lifetime is largely absent. For novel battery designs that promise much higher energy densities, such as the Li-air and Li-sulfur batteries, basic R&D is needed to improve key kinetic and catalytic processes. New knowledge of materials properties and processes at the nanoscale can also be used to develop high efficiency thermoelectric materials for waste heat recovery.

Thrust Area 5: Advanced Biofuels and Clean Combustion

Land and other resource constraints currently limit the portion of transportation energy that can be derived from biofuels. Next generation biofuels, such as those made from ligno-cellulosic or algal biomass feedstocks, could in principle provide a significant portion of transportation fuel in the U.S. and China. Advanced biofuels development and deployment can be accelerated by linking biotechnology to combustion process and exhaust aftertreatment design, optimization and control.

Thrust Area 6: Advanced Lightweight Materials and Structures

Reduction of vehicle gross weight is an effective approach to reduce energy consumption during vehicle usage. Challenges exist, however, to integrate components made of aluminum

alloys, magnesium alloys, and carbon-polymer composites into vehicle structures to achieve maximum weight reduction while maintaining structural rigidity and crash safety. Research is needed to realize low-cost, energy efficient, high quality processes for producing, forming, and joining of lightweight materials.

The key scientific and technological innovations that the CERC-CVC aims for include:

- New electrified vehicle architectures with optimized power management and controls
- Control strategies, protocols and communications requirements for vehicle – grid interactions
- Novel materials for energy harvesting, storage and conversion
- Combustion science for novel biofuels and its application to symbiotic design of innovative engine cycles and processes
- Breakthrough structural designs that provide substantial weight savings
- Life cycle design and integrated vehicle-fuel systems analysis methodologies to guide system and policy development that meets renewable resource constraints

Progress of the CERC-CVC towards its objectives will be assessed through the tracking of a number of high-level metrics, which include the following:

- Joint conferences, workshops and symposia organized
- IP disclosures filed; US, China, and international patents issued
- Commercialization of CERC-CVC IP by OEMs, suppliers and start-ups
- Journal and conference papers published
- Students graduated and students hired by CERC-CVC members and affiliates
- Post-doctoral fellows trained
- Number, frequency, duration of personnel exchanged/collocated among organizations
- Awards received (individual, team, technology)
- Prestigious lectureships/keynotes given at national and international conferences

The above Joint Work Plan has been jointly developed and reviewed and is hereby approved by the respective authorities in each country, as indicated by the signatures of the appointed CERC-CVC Directors, below, made this date of January 18, 2011.

For the CERC Clean Vehicles Consortium of the United States:

For the CERC Clean Vehicles Consortium of the Peoples Republic of China:

CERC-CVC Research Thrust Annex

In pursuit of the Clean Vehicle vision, the CERC-CVC has developed a highly collaborative research agenda that has been organized in six thrusts, as follows.

Thrust 1: Energy Systems Analysis, Technology Roadmaps and Policies

The Energy Systems Analysis, Technology Roadmaps and Policy Thrust, co-led by the University of Michigan and Tsinghua University, will evaluate and guide development and deployment of clean vehicle systems in the U.S. and China, synthesizing the technology innovations from all CERC-CVC thrusts. The projects and objectives of Thrust 1 focus on: setting goals for CV and CV Technologies; synthesizing and evaluating CV technologies and innovations using life cycle models; integrated vehicle-energy systems analysis; identification of optimal regional fuel strategies, mixes and constraints for liquid fuels and electricity; and the development vehicle and technology roadmaps to achieve CV goals internally for the CERC and externally for policy recommendations. The analysis framework must address a wide range of dimensions and scales: systems from components to entire vehicle coupled with the fueling infrastructure; spatial including geographic variation in energy and material resources and production; and temporal ranging from renewable intermittency, charging frequency and driving cycles to the longer horizons for carbon stabilization.

The American and Chinese automotive markets are the largest in the world and coordination and collaboration in CV technology, systems design and technology roadmaps and policy are essential for accelerating deployment of more sustainable transportation solutions. The US and China share many critical challenges and opportunities such as energy resources (e.g., large coal deposits), energy security and high oil import dependencies, and large greenhouse gas emissions. On the other hand, consumer markets and driving patterns, regional energy resources and constraints, transportation and electricity infrastructure, and government policies differ significantly. The US-China CERC CVC team will seek to harmonize CV technologies and designs across diverse resource constraints and driving patterns within and between the US and China. Partners from academia, national labs, and industry will collaborate on analytical methods, life cycle models and parameters, scenario analyses and policy analysis. Policy recommendations will be developed for the U.S. and China that are specific to their economies, regulatory systems, and needs. The recommendations will be oriented to improving market diffusion of clean vehicles and identify non-technology areas (vehicle purchase and use patterns) for maximizing the benefits of the CV systems.

Thrust 2: Vehicle-Grid Interactions

The Vehicle-Grid Interactions thrust, co-led by the University of Michigan, Ohio State University and Tsinghua University, will explore opportunities and issues associated with the connection of large numbers of PEVs to the electrical grid. As adoption of PEVs grows, the power drawn by charging loads may create localized problems for distribution networks, including overloads, voltage profile degradation, and unbalance. At the macro grid level, uncoordinated charging of large populations of PEVs could exacerbate peak loads, while simple time-and price-based strategies could actually destabilize grid operations. On the other hand, advanced control strategies could be used to coordinate PEV charging with the variability inherent in renewable generation, allowing greater utilization of carbon-neutral sources of electrical energy.

The US-China research projects in Thrust 2 fall in three areas, vehicle-grid interactions at the local distribution level, impacts of large populations of PEVs at the power system level, and supporting technologies. The US-China CERC-CVC team will pursue 12 complementary projects, including analysis of communications and control architectures for supporting intelligent vehicle-grid interactions, investigation of PEV charging on distribution network conditions and controls solutions for mitigating problems, development of control strategies for PEV charging to track renewable generation output, and prototyping V2G technology.

Thrust 3: Vehicle Electrification

The goal of the Vehicle Electrification thrust, co-led by the University of Michigan and Tsinghua University, is to develop new concepts, models, methodologies, and tools to enable the construction, analysis, design and simulation of key components of electrified vehicles, and to study their controls and integrations. Efficient and reliable components such as electric motors, generators, power electronics and power transfer devices are keys to the success of clean vehicles. In addition, control and system integration are critical in realizing the full potential of hybrid powertrains in fuel economy and emission reduction. The technical challenges include development of high fidelity and computational efficient models, reliable analysis methods, and integrated synthesis tools for electrified vehicles.

The US-China research projects of Thrust 3 can be grouped into three categories: key components, tools/methods, and integration. The US-China CERC-CVC team will pursue a total of 14 complementary projects, including the design of efficient and compact electric motors, development of servo-loop control chips and supervisory power management algorithms, NVH

analysis of key powertrain components, diagnosis and prognosis methods, and fast system integration methods.

Thrust 4: Advanced Batteries and Energy Conversion

The objectives of the Advanced Batteries Thrust, co-led by the University of Michigan, M.I.T., Beijing Institute of Technology and Tsinghua University, are (i) to improve the robustness of current-generation Li-ion batteries, (ii) to explore novel battery chemistries having the potential to achieve dramatically higher energy densities and (iii) to develop a new generation of thermoelectric materials for waste heat recovery having a figure of merit double the current state-of-the-art thermoelectrics. Success on the battery focus will be achieved via detailed characterization of degradation and aging mechanisms in Li-ion batteries, and application of the knowledge so derived to formulate design principles to significantly enhance battery cycle life. In addition, the structural and chemical properties of Solid Electrolyte Interfaces and passivation layers on electrodes will be identified and correlated with battery performance and cycle life. Beyond Li-ion chemistries, we will also pursue metal-air and Li-sulfur batteries as a pathway towards achieving higher capacities and potentially lower costs. Emphasis will be placed on elucidating reaction pathways and catalytic mechanisms in Li-air batteries and application of this insight to design catalyst chemistries and electrode microstructures that enhance rate capabilities and minimize hysteresis. Finally, the design of superior thermoelectric materials for heat recovery will rely on the selection of suitable dopants to promising chemistries such as the $CoSb_3$ skutterudites with the aim of enhancing electronic conductivity and simultaneously lowering thermal conductivity.

The US-China research projects on advanced batteries can be grouped into three major themes. The first focuses on fundamental studies of materials behavior, evolution and degradation during battery usage. The US side will combine advanced modeling tools along with state-of-the-art in-site experimental techniques to determine the relationship between structure at the atomic and electrode architecture and battery performance (including degradation). Insights derived from this effort will inform fundamental research on the China side, which will focus on new materials development of both cathodes and anodes, relying on their expertise in materials synthesis and electrochemical testing. A second theme will focus on the multi-scale characterization of battery degradation mechanisms of Li batteries consisting of current generation electrode chemistries. Both the US side and China side will leverage expertise in materials characterization and multi-scale modeling techniques to provide crucial insights about Li-battery degradation at all length scales ranging from the electrode crystallite level to the

battery pack level. The identification of key degradation mechanisms in this effort will guide the design of accelerated lifetime experiments. The third theme will focus on fundamental studies of electrode chemistries that promise significantly enhanced capacities. The US side will devote an effort on Li-air batteries, while the Chinese side will emphasize Li-sulfur batteries. Both battery chemistries have much in common in terms of rate-limiting kinetic processes that need to be overcome and the US and China efforts will therefore greatly benefit from an integrated, yet complementary research approach.

On the topic of thermoelectrics, the University of Michigan (UM) has a longstanding collaboration relation with Wuhan University of Technology (WUT) on the development of efficient novel thermoelectric materials based on skutterudites. The WUT group is the leader in the formation of stable nanostructures in the skutterudite matrix, the essential prerequisite to fabricating high efficiency nanocomposite thermoelectric materials. The UM-WUT team has published five research papers during the past three years in the leading journals of the field and two WUT students are co-supervised by UM faculty and currently working at UM. Ohio State University also has active collaborations with UM and Zhejiang University. Standardization of Thermoelectric Measurements via the International Energy Agency will be strengthened by a close collaboration with the WUT laboratory that is one of the Chinese selected sites.

Thrust 5: Advanced Biofuels and Clean Combustion

The aim of the Advanced Biofuels and Clean Combustion Thrust, co-led by the University of Michigan (UM) and Shanghai-Jiao Tong University (SJTU), is to establish a systematic process that will characterize and design optimal biofuels and engine processes for clean combustion, efficient power conversion, and improved life-cycle performance. The knowledge gained from these projects will help to identify optimal formulations of fuels based on chemical and physical properties as well as engine control strategies for clean and highly efficient combustion. The technical challenges include developing predictive models for biofuel combustion, measuring chemical and physical properties of the new molecules in lab-scale devices, and characterizing their performance in engines.

The US-China research projects of Thrust 5 can be grouped into three main categories: advanced biofuel formulation, in-cylinder characterization of biofuel performance and emissions under novel combustion modes, and design/calibration of internal combustion engines and auxiliary power units to maximize benefits of advanced biofuels. A total of 8 complementary projects will be pursued, including characterization of physical and chemical properties of advanced biofuels, biofuel atomization and mixing process under both low-temperature and high

load combustion modes, ignition delay and chemical reaction kinetics, in-cylinder combustion of biofuels, including pollution formation and knock suppression, and optimal design and calibration of biofueled engines and auxiliary power units (APU).

Thrust 5 will build on the long-term history of joint research on advanced biofuel combustion between UM and SJTU, which has led to joint supervision of students, joint authorship of scientific papers and complementary research facilities, including fundamental combustion devices and engines. Working together, the US and Chinese researchers will develop an understanding on what motivates biofuel selection in both the US and China; develop biofuels feedstock and conversion technologies that consider regional constraints (agriculture, land, water, weather); and develop joint strategies for deployment of next-generation engines and biofuels. Furthermore, the US-China collaboration will advance our understanding of which of the advanced biofuels perform well in advanced engines, thus providing important feedback to synthetic fuels and engine designers, as well as characterize the combustion tolerance of different engine designs and calibration strategies to a range of fuel properties.

Thrust 6: Advanced Lightweight Materials and Structures

The goal of the advanced lightweight materials and structures thrust, co-led by the University of Michigan, Ohio State University, and Tsinghua University is to develop guidelines, methodologies, and tools to design and manufacture low-cost, energy efficient, high-performance, ultra lightweight vehicle body and other structures utilizing advanced lightweight materials. Reduction of vehicle gross weight is an effective approach to reduce energy consumption during the vehicle usage, regardless their energy sources. However, utilization of lightweight materials such as aluminum alloys, magnesium alloys, and carbon-polymer composites in vehicle structures has been limited due to their limitation in structural performance, affordability, and manufacturability. The technical challenges include realizing low-cost, energy efficient, high quality processes for producing, forming, and joining of lightweight materials and optimally integrating lightweight components into vehicle structures.

The US-China research projects of Thrust 6 are grouped into four categories: materials, components, assembly, and structures. The UC-China CERC-CVC team will pursue a total of 14 collaborative projects, including design, process analysis and manufacturing technology for parts made of lightweight alloys and composites, vehicle body lightweight assembling process, multi-material, ultra-lightweight vehicle structure design. In order to stay at pre-competitive level, we will focus on the development of frameworks, methodologies, tools and approaches, and the generation of sample data, recipes, and cases for demonstration purposes. Our Chinese

partners in Tsinghua University and Shanghai Jiao Tong University have complementary expertise to the US team, which include Al and Mg die-casting and lightweight material forming. They also have facilities critical to the project success not available in the US team: facilities for vehicle crash test and demonstration vehicle manufacturing.