# Natural Gas Vehicle Technology Forum 2021 Meeting Summary

The 2021 Natural Gas Vehicle Technology Forum (NGVTF) was held on May 11 and 12, 2021, in a virtual forum. Following is a summary of the meeting. The National Renewable Energy Laboratory (NREL) hosted the forum in partnership with the U.S. Department of Energy's (DOE) Office of Energy Efficiency and Renewable Energy's (EERE) Vehicle Technologies Office (VTO), the California Energy Commission (CEC), South Coast Air Quality Management District (SCAQMD), and Natural Gas Vehicles for America (NGVA).

## *Day One: May 11, 2021*

### Welcome and Opening Remarks

#### John Gonzales—NREL

John welcomed forum participants and introduced the NREL and DOE team. He provided an overview of the meeting structure and agenda.

### U.S. Department of Energy Update

#### Mark Smith, Dennis Smith, and Mike Laughlin—DOE EERE VTO

Mark welcomed forum participants and thanked everyone for attending virtually. He shared his excitement to hear about projects funded by DOE, SCAQMD, and CEC. The NGVTF annual meetings began in 2002 and they continue to provide a valuable platform to allow participants to hear from the industry. He looked forward to learning more about the issues industry stakeholders are facing, including market hurdles, technical challenges, and issues related to codes and standards. He wanted to know what is working but also what is not working as it relates to natural gas vehicles and infrastructure.

Dennis welcomed everyone and was glad folks could make it to the virtual forum. He wanted to address concerns that DOE may not be focused on natural gas vehicles with the recent interest in electric vehicles. In fact, the portfolio includes all fuels, and DOE's natural gas budget is very healthy. They have a long list of active projects on natural gas and are continuing to introduce new projects.

Mike reviewed VTO-specific funding opportunities. VTO Funding Opportunity Announcements from the last few years resulted in a dozen multiyear projects related to research and development (R&D). Projects here represent about $19 million in funding. VTO is continuing to fund projects in 2021 under the two FOAs that came out this year. Mike provided an overview of the current natural gas FOA topics that are open. He also highlighted the Request for Information issued in early 2021 on medium- and heavy-duty truck research and encouraged attendees to view the recorded webinar summarizing the results. Mike provided information on how to stay informed with VTO activities and provided contact information for key natural gas VTO contacts.

## California Energy Commission Update

### Peter Chen—CEC

Peter updated forum participants on current CEC program activities. He provided background information on CEC research and development, including funding amounts and their approach for identifying research gaps and needs. Peter summarized CEC's transportation research goals, which include energy efficiency improvements, increasing use of renewable natural gas, and improving fueling infrastructure. California's transportation sector is expected to improve drastically over the next decade, partly spurred by an executive order that aims to transition all heavy-duty vehicles to zero emissions by 2045. Peter highlighted some ongoing research related to natural gas vehicles, including an in-use emissions and fuel usage assessment focusing on compressed natural gas, the natural gas vehicle research consortium, and several hydrogen demonstration projects in rail and marine applications. Peter concluded by discussing future research priorities, including hydrogen and ongoing R&D. Forum participants asked Peter for additional details on the fuel use emissions project and assessment.

## Transient Plasma Systems: A Multi-Cylinder Transient Plasma Ignition System for Increased Efficiency and Reduced Emissions in Natural Gas Engines

### Jason Sanders—Transient Plasma Systems

Jason provided an overview of the project, including some high-level information on advanced ignition systems and how they compare to other available engine technologies. Next, he gave some background information on Transient Plasma Systems (TPS), a startup company working to commercialize technology developed at the University of Southern California. The path to market for TPS involves developing relationships with Tier 1 automotive companies that have the product development expertise and manufacturing scale necessary to bring these products to market.

Jason also shared information about a TPS project with NREL. Previously, TPS partnered with Argonne National Laboratory and CEC to evaluate advanced ignition technologies for natural gas on a Cummins engine. This was the first time TPS's nanosecond pulsed transient plasma ignition system ran on a multi-cylinder engine. TPS felt developing a closed loop system would be necessary to display durability. The TPS technology does not use single pulse—it delivers multiple pulses to strike a reactive plasma that enables dilution in the engine. The technology can sense between pulses in the burst and adjust the pulse and other parameters as needed, giving a fine degree of control. The remaining focus of the project involves looking into the best fit for packaging and minimizing footprint of the system, including thermal management and packaging the system as a whole. TPS's plans for the future include investigating new ignition architecture, optimizing igniter design, and engine testing with a closed-loop nanosecond ignition module at Argonne National Laboratory.

## Michigan Technological University: Compression-Ignition Mono-Fueled Natural Gas High-Efficiency, High-Output Engine for Medium- and Heavy-Duty Applications

### Brian Eggart—Michigan Technological University

Brian provided information on the Cummins engine used as the test platform and highlighted some of the key pieces of the single cylinder research engine (SCRE). He showed the SCRE compression ratio and explained different key components. Brian also described the piston design (23:1 compression ratio) and key features of the SCRE, including an increased compression ratio, intake air temperature heating, injection control, injection pressure, and boosted operation. An essential part of the system is the custom Westport compression ignition direct injection injector. In summary, the SCRE consistently achieved compression ignition of natural gas. The engine operates like a diesel compression ignition engine with respect to response to injection and other controls. In addition to modeling work, they also conducted computational fluid dynamics simulations to compare jet penetration and ignition delay with experimental data.

Brian shared an overview and images of the constant volume combustion chamber (CVCC). He discussed the CVCC optical setup and CVCC testing to date. Key findings from CVCC include that stable ignition and combustion are observed at temperatures greater than or equal to 1,050 K. Increase in charge temperature, pressure, and ignition pressure all reduce ignition delay. Brian summarized results from the CVCC and temperature effect on ignition delay, as well as ignition pressure effects.

## Gas Technology Institute: CNG Full Fills with a Complete Smart Fueling System

### Jason Stair—Gas Technology Institute

Jason provided information on a natural gas vehicle (NGV) consortium project that is developing compressed natural gas (CNG) full fills using smart vehicles and dispensers, advanced full fill algorithms, and cost-effective precooling. Two main problems include heat of compression and fueling algorithm uncertainty. The project team is building and testing lab-based versions of these components then designing and building a CNG free-piston expander. The expander is a device that removes energy from a gas as it drops in pressure. Using an expander to remove additional energy from the gas allows it to get even colder so more gas can fit on board the CNG vehicles.

The free-piston expander is proven technology with high efficiencies that can leverage existing compressor seals and valves. This project's innovation is the novel linear motor that enables GTI to maintain a high operating efficiency. Advantages of this include flexible inlet and discharge pressures, high expansion efficiency, ability to be programed to act as flow controller, generation of electricity when expanding gas, and ability to operate as a booster to ensure tanks reach max pressure at end of fill. Preliminary testing is complete; the results demonstrated a 50% to 60% efficiency and filled a test cylinder. Jason also provided an example of steady-state testing with low pressure nitrogen. Over time, the pressure increases to match the downstream tank.

GTI has a fully designed, full-scale expander prototype with completed solid models. GTI sent the drawings to bid and they are in the process of getting fabricated. Next steps will be assembly, commissioning, and testing.

GTI is working on smart vehicles and dispenser components. The first step is vehicle data collection. Systems are collecting Controller Area Network bus data, as well as fuel system data, and the information will be transmitted via Wi-Fi to servers so GTI can analyze the vehicles. The data systems are capable of connecting to a smart dispenser and monitoring fast and slow fills, as well as fuel consumption.

The heart of the smart dispenser is the dispenser receiver, which is used to identify the smart vehicles in the area and supply vehicle data to the fill status using our algorithm to the dispenser. These do not control the dispenser but do allow the dispenser to review the data and decide what to do. Systems will be combined and tested in Des Plaines, and the expander and smart vehicle/dispenser components will be installed at test facility where they will test high-pressure CNG and hydrogen. The expander will be tested first to get a baseline and then will be combined with smart station components. GTI plans to deploy the smart vehicle and station components in the field and is working with dispenser manufacturers to integrate the technology into their products. Demonstrations will not include the expander.

## National Renewable Energy Laboratory: CNG Codes and Standards Considerations for Tank Testing

### Lauren Lynch—National Renewable Energy Laboratory

Lauren reviewed last year's discussion on CNG codes and standards and fuel tank end-of-life testing and provided an update on the CNG codes and standards project. Current federal codes and standards are outdated and limited. They are light-duty focused, and updates should reflect applications in medium- and heavy-duty (MD/HD) because there are more of those vehicles. Lauren's study included CNG, liquified natural gas (LNG), and propane.

NREL presented and received input on this project during past forums. Recommendations were summarized into feedback and findings for DOT to consider to ensure the standards address safety issues, are practical, and do not create future barriers. A published report summarized the recommendations.

Recommendations included updating Federal Motor Vehicle Safety Standards to include MD/HD applications, include propane, add an additional CNG fuel tank integrity test, and incorporate a more repeatable fire test procedure for fuel tank integrity. The report also discussed considerations for minimum safety standards and considerations to reflect industry best practices. Lauren provided a link to the published full report:
https://afdc.energy.gov/files/u/publication/evaluation_of_safety_standards_for_fuel_system_and_fuel_container_integrity_of_alternative_fuel_vehicles.pdf

Lauren also discussed NREL's ongoing CNG end-of-life research. End-of-life requirements can vary from the service life of the vehicle, which makes the vehicle owner replace the tank in compliance with the tank manufacture's end-of-life requirements. This can be costly and can introduce other hazards. Other requirements of visually inspecting the tank bring up concerns about tank resale. It is not uncommon to see vehicles using tanks that have surpassed end-of-life requirements, which proved a need to research the integrity of the tanks after their end-of-life.

Lauren's research investigated the integrity of tanks at the end of their useful life. This information allowed the industry to be informed about identifying and mitigating risks. Testing began in 2016, with a pause for about a year due to budget constraints, beginning again in late 2018 and concluding in 2019. Results were presented in early 2020 at least year's NGVTF.

This project initiated testing on 101 transit application tanks from the Los Angeles County Metropolitan Transportation Authority. The research team evaluated 60 tanks through visual inspection, burst pressure testing, artificial damage, and fatigue modal acoustic emission evaluation. Lauren provided an overview of the testing results and recommendations, which primarily included a potential opportunity of continued tank use.

# *Day Two: May 12, 2021*

## Cummins: High-Efficiency, Ultra-Low Emissions Heavy-Duty Natural Gas Engine Research and Development

### Saradhi Rengarajan—Cummins

Saradhi gave an overview of the NGV Consortia project, which is currently 35% complete with a total project budget around $11 million. The primary objective is to develop a tumble-based combustion system with a pent roof cylinder head using cooled exhaust gas recirculation and increased efficiency and fuel economy. Discussion of the technical approach included combustion system development for a single cylinder engine (SCE), air handling development, multicylinder simulation, and final multicylinder demonstration. Saradhi provided specifics on the combustion system development and air handling development flow charts.

Thus far, the team has analyzed 15 unique intake port designs for the combustion system. They selected four ports with different tumble levels for procurement and testing on the SCE. The SCE then suffered a catastrophic failure and had to be rebuilt. So the team is starting to collect data again with a moderate tumble head. Saradhi provided a summary of the tumble port development with a corresponding graph.

For the air handling work, overall tests demonstrated close to a 3.8% $CO_2$ improvement, as well as a 50 kPa reduction in pumping mean effective pressure achieved. Saradhi described the torque curve targets, including minimum target and stretch target. The discussion of the multicylinder engine design progress focused on how the base engine platform was selected—the 14.5 liter global platform. This is the platform of choice from several standpoints (including that it is global, which is the way the world is moving). The team also completed the multicylinder engine cylinder head and initial overhead layout.

## University at Buffalo: Development of Zeolite-Based Catalysts for Improved Low Temperature $CH_4$ Conversion

### Tala Mon—University at Buffalo

Tala introduced the team working on the project and thanked funding partners. He talked about how methane emissions from NGVs occur because of unburnt methane leaving the tailpipe. Even though methane only makes up 10% of greenhouse gas emissions, it is 23 times more potent than $CO_2$ in terms of climate change impact, which is why there is a goal to decrease methane emissions. However, methane is difficult to activate compared to other hydrocarbons. The conventional catalyst used is palladium supported by alumina but deactivates in the presence of steam. Therefore, the team decided to turn to other material, specifically zeolite, because small pore zeolites are hydrothermally stable. Studies have shown that using ion exchange sodium as the second metal improves performance. The team wants to see what happens when they improve methane oxidation performance using this technique and small pore zeolite. They want to synthesize a high silica to alumina ratio from synthesis to achieve 90% methane conversion below 400°C.

This project has three phases: develop catalysts to low-temperature oxidation, wash coat study of zeolite-based catalysts, and catalyst experimental testing using a cylinder research engine. Tala focused on the first phase in his presentation. This phase involves developing catalysts to low-temperature oxidation. Specifically, he described the successful synthesis of a high silica to alumina ratio with dry gel

conversion. The PD/Na-SSZ-13 improves after aging and meets their target goal of 90% methane conversion below 400°C.
Tala summarized to say that to improve low-temperature $CH_4$ oxidation performance for small-pore zeolite catalysts, they need to load sodium as a second metal and need to synthesize zeolites with less alumina and optimize ratios. Both techniques work by reducing Bronsted acid sites and preventing palladium sintering by blocking palladium migration using ion-exchanged sodium and reducing available sites for migration by increasing silica to alumina ratios.

## Southwest Research Institute: Development of a Pent-Roof Medium-Duty Spark-Ignited Natural Gas Engine in an Optimized Hybrid Vehicle System

### Scott Sjovall—Southwest Research Institute

Scott provided a project schedule and summarized the project goal, which was to improve natural gas engine and vehicle emissions and efficiency. The objective is to reach an efficiency level similar to conventionally fueled vehicles and reduce emissions to near-zero levels. This would be accomplished through improvements to the natural gas engine as part of a hybrid powertrain that is capable of being commercially saleable into a medium- or heavy-duty vehicle. Deliverables include a medium-duty natural gas hybrid demonstration vehicle, a 25% reduction in GHG emissions compared to a diesel baseline, and 0.02 g/bhp-hr $NO_X$.

Scott provided information on the vehicle study task. The objective was to determine which hybrid architecture offered the best balance of fuel consumption savings, air quality improvement, and total cost of ownership. The research followed a three-step process: performance study, fuel economy benefits, and vehicle packaging study. They selected a P2 hybrid architecture with a 100-kW machine and 40-kWh battery pack.

Next, Scott presented on the single cylinder engine development. To determine if the requirements of the project could be met, a single-cylinder research engine based on the Isuzu 4HK diesel platform was configured with a bespoke high-tumble, pent-roof cylinder head, and converted to run on natural gas. The results indicated that the Gen 2 combustion system would meet the vehicle demonstration requirements.

For the multicylinder engine development, the build used an Isuzu 4HK long block assembly. The assembly was completed in October 2020. Scott provided details on the multicylinder engine, specifically the high tumble cylinder head, variable intake timing, and fully automated engine. He also showed photos of the operational engine.

Task 4 of the project involved hybrid system development. Scott discussed drive cycle performance modeling (including hybrid electric vehicle modeling) and the results. The results found plug-in hybrid electric vehicle fuel economy improvements. Scott then discussed hybrid component selection, procurement, and development.

Task 5 of the project was vehicle integration, evaluation, and demonstration. The 4HK-based pent roof engine fits under the existing Isuzu truck. Scott described how they integrated the hybrid mechanization and electric motor onto the vehicle. He also described the hybrid electronics, the location of which are still in flux as the design matures. Scott concluded with a summary of the schedule.

## US Hybrid: Plug-in Hybrid CNG Drayage Truck "PHET"

### Abas Goodarzi—US Hybrid

Abas described their development of plug-in hybrid CNG heavy-duty drayage trucks. They have had generation one vehicles running in the field for about 3 years and are using that feedback on this project. Abas described their performance goals and benefits of using a plug-in hybrid CNG truck, including efficiency improvements, zero emissions range, reducing $NO_X$ emissions, and horsepower.

Next, Abas described the plug-in hybrid electric truck powertrain architecture, which allows decoupling the engine to run in electric vehicle-only mode. The battery is 85 kWh with a 20-kW on-board charger. He said he likes the drivers to plug in, although they have found that current drivers in the field do not plug in. The system operation still performs well whether or not they plug in. They are adapting to the end-user's habits. They optimized the hybrid electric motor characteristics to specifically fit a l9N engine with an electric motor that augments the engine. Drivers wanted more passing power, and the new system provides 650 horsepower, including the passing power.

For the vehicle packaging, there is no compromised cargo load capacity and minimized curb weight. When they integrated the equipment on the vehicle, they found the load was balanced, and they worked to minimize the impact on the existing system. Abas also described the hybrid powertrain components. Next, he listed and described the project partners for the vehicle components. He showed a map of the 9-L engine and a 12-L engine hybrid and reviewed the improved fuel economy enabled by the system. The plug-in hybrid is the commercial aspect of this project. US Hybrid has been doing substantial modeling over the last 20 years. They generated a model for this system and started optimizing around duty cycle, motor size, battery size, etc.

Abas said operational field data indicated the same customer is running diesel and CNG/liquefied natural gas. He said generation one drivers like driving these trucks. Abas then showed the actual field operation data performance and fuel efficiency. He also showed the actual operation of the torque and the power of the electric motor and the hybrid motor. They use this information on the operation for optimization. Abas concluded by describing iZeo technology, which enables repetitive zero-emission operation at targeted areas.

## University of Alabama: High-Efficiency Natural Gas Dual Fuel Combustion Strategies for Heavy-Duty Engines

### Sundar Krishnan—University of Alabama

Sundar provided an overview of the agenda and discussed three approaches for the project, which is looking at system-level simulations. The three approaches are: computational fluid dynamics (CFD) simulations of diesel, natural gas dual fuel low temperate combustion, and single cylinder research engine experiments for characterizing efficiency and emissions benefits of dual fuel. Sundar provided a diagram of conceptual pathways for high efficiency to give an idea of how to achieve high efficiency.

The GT-SUITE tasks provided the baseline input parameters for the CFD model and served as the main platform for performing exploratory variable valve actuation (VVA) studies. GT-SUITE results were crucial in specifying the VVA system parameters for the university's single cylinder research engine. Sundar described accomplishments related to the GT-SUITE by quarter of the project thus far. He also showed a layout of the GT-SUITE model, which uses predictive 1D modeling for simulations. Sundar showed a snapshot of the critical value of the GT-SUITE simulations in the last few quarters. They considered multiple intake profiles, and he showed two of the profiles they are going to use. High-lift profiles were not as beneficial as expected. They decided to use the stock intake of the exhaust as the baseline and one extra set of valve profiles for the intake. Next, they measured the return on investment profiles input for models—critical inputs for the simulations. Finally, he showed the workflow and internal consistency of the GT-SUITE and converge CFD.

Sundar showed the CFD simulations workflow and described accomplishments related to the CFD simulations by quarter of the project thus far. He showed what the geometry looks like on the engine, as well as sample model validations and the effects of methane on the autoignition (it tends to delay ignition). He showed a video comparing the spray penetration of dimethyl ether (DME) and diesel. DME spray under similar conditions is significantly shorter than for diesel fuel.

The biggest experimental result was achieving engine-out $NO_X$ emissions less than 0.1 g/kWh and engine-out smoke emissions less than 0.1 FSN with dual fuel low-temperature combustion (LTC). In summary, the approach utilizes multiple strategies (Spray Targeted Reactivity Stratification (STARS), Variable Valve Actuation, Poly-Oxymehtyl-Dimethyl-Ether, Temperature-Controlled-Exhaust Gas Recirculation) to achieve high-efficiency dual fuel LTC. GT-SUITE simulation results provided critical inputs for the VVA system design and specifications. CFD simulations predicted combustion evaluation, and STARS strategy improved combustion efficiency.