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October 15, 2014

Mr. Todd Sax, Assistant Chief
Mobile Source Control Division
California Air Resources Board
Via Website Upload

RE: Comments on Technology Assessment Workshop (September 2, 2014)

Dear Mr. Sax and CARB Mobile Sources Team,

Capstone Turbine Corporation is pleased to herewith submit comments to the Air Resources Board workshop on Technology Assessment for Trucks and Buses on September 2, 2014. The information provided during that workshop provides an excellent overview of the many technology and fuels issues related to medium and heavy duty trucks and buses, and we applaud the Board's efforts to evaluate future development and deployments that will lead to cleaner air for all of us.

Capstone Turbine Corporation is a California-based company that designs and manufactures microturbines for use in stationary power generation as well as series hybrid vehicle applications. Our technology provides clean combustion, and several of our models are already certified by CARB to meet the stringent 2010 heavy duty diesel engine emissions levels without requiring any exhaust after-treatment. The comments provided below include some general observations as well as specifics related to the vehicle applications Capstone has experience with.

General Comments

The California Air Resources Board has played an extremely effective role in setting increasingly stringent criteria pollutant emissions standards, and all manufacturers have been able to meet these requirements and reduce NOx and PM over a wide range of heavy duty engine models. Exhaust after-treatment in terms of urea injection for NOx and particulate traps for PM are now the primary means to achieve 2010 engine emissions levels. Despite the progress so far, California requires even greater improvements to attain federally mandated local air quality levels and meet the state's objectives for reduced greenhouse gas emissions. There were many future engine and vehicle technology developments defined in the Technology Assessment presentation that hold the promise for additional emissions reductions and efficiency gains. The Air Resources Board should continue to encourage development of traditional engine technologies, however we suggest the following areas for additional analysis and potential standards revisions:

1. Quantify In-use versus certification testing emissions performance – It was pointed out in several slides of the In-Use Emissions section of the Technology Assessment presentation that actual emissions of NOx and PM can be significantly higher than what a given engine achieved during its certification tests. The reasons for this are not completely known, but a multitude of factors may be contributing to the end result. One factor that seems to be important is the impact of drive cycles on the way that a given engine is operated. The CARB engine

dynamometer test procedure proves the engine's emissions using just one such drive cycle. However the engine may be called upon to start and stop much more often in actual use, or operate at different loads where the effectiveness of the exhaust after-treatment is not optimal. Medium and heavy duty trucks and buses rely on engine certifications rather than total vehicle certification. This seems to be appropriate given the wide variety of truck chassis and engine and transmission options available for customers who will use their vehicles in many different applications. We therefore suggest more analysis and demonstration efforts be done to better understand how different real world drive cycles impact engine emissions and the performance of exhaust after-treatment systems before any change to the 2010 emissions levels are set in new regulations. For example, slide 30 in the Heavy-Duty Hybrid Vehicles section of the presentation showed preliminary results comparing emissions of a parallel hybrid delivery truck to a conventional truck using different drive cycles. While fuel economy was better for the parallel hybrid under all drive cycles, NOx emissions were worse. No explanation was given for this emissions result, but it seems that the engine and its associated emissions control systems are operating differently in the parallel configuration. It is also interesting to note that the emissions vary significantly between drive cycles, and there is more variation in drive cycle emissions performance of the conventional trucks than the parallel hybrid trucks.

2. Continue developing more effective On-Board Diagnostics (OBD) requirements – Related to the issue above, a more comprehensive OBD system should be able to annunciate when emissions control equipment becomes ineffective. This would automatically flag operating conditions that are causing a vehicle to emit more than expected, whether due to drive cycle difference or deterioration or failure of the emissions control system itself.
3. Develop charging infrastructure that includes vehicle grid integration benefits – There are clearly local emissions benefits to operating vehicles using some amount of stored grid energy. However there are also benefits of using these same vehicles as energy assets that can benefit the utility grid and local power distribution where the vehicles are connected. Quantifying this additional value will help support adoption of more electric vehicles. Also, building up a significant two-way electric charging infrastructure could benefit from clean distributed generation. It would be beneficial to estimate the amount of new electric infrastructure needed to accommodate target levels of medium and heavy duty plug-in vehicles, as well as including some actual customer demonstration project to better understand the overall costs and benefits when deployed at a large scale.
4. Develop combined CNG and electric quick-charging infrastructure – It is expected that the future will include a mix of CNG, pure battery electric, and hybrid electric vehicles. More public and dedicated private "refueling" stations will be required as these technologies continue to grow. Compressing pipeline natural gas requires onsite electricity. Likewise, quickly charging battery storage on medium and heavy duty vehicles will require high power. For example, Tesla offers supercharge capability at 120kW for 20 minutes (40kWh) to partially recharge an 85kWh battery pack. Such a combined CNG and quick-charge station for multiple vehicles would easily require 1MW of available power. Clean onsite distributed generation may be required to support these stations. Again, a demonstration project to quantify the costs and benefits of this type of station would be useful.

Microturbine Hybrid Vehicles

The Heavy-Duty Hybrid Vehicles section of the workshop presentation covered many hybrid drive system examples of different types, from simple parallel hybrids like the Eaton electric hybrid drive system to what was referred to as a "full hybrid" which could operate in either a series or parallel mode. The description and comments below are focused on the type of hybrid vehicles that the Capstone microturbines have been used in, and which we believe offer benefits that will drive adoption of this technology in selected markets.

Series Hybrid Drivetrain Technology Description

Capstone microturbines operate at high speed with an integral permanent magnet generator on the same shaft as the turbine engine components. Power output is therefore high frequency AC, and no mechanical shaft power is available. Power electronics are used to convert this AC power to DC, where it is connected to the DC bus of an electric vehicle. The vehicle's battery pack is sized to provide sufficient power to a traction motor to accelerate the vehicle and to maintain full speed for some duration without any power input from the microturbine. So another way to characterize such a hybrid drivetrain is to consider it a "range-extended electric drive system". A vehicle controller will command the microturbine to start under preset conditions; such as when the battery state-of-charge (SOC) reaches a predetermined low level or a forward-looking algorithm determines additional power may be needed. Likewise, the vehicle controller will command the microturbine to stop at a higher SOC, or when the estimated range will be just enough to bring the vehicle to the next charging point, or other logic. However when commanded to run, the microturbine power will be set within a band where it is most efficient and has the cleanest emissions profile.

Several Capstone microturbine models have been certified by CARB to meet the 2010 emissions standard, and do so without relying on any exhaust after-treatment. As part of this certification process, an engine duty cycle test procedure was proposed by Capstone, and approved by the Air Resources Board, which represents how the microturbine will be used in range-extended electric drive systems such as described above. For example, this drive cycle for our 30kW model operates between 15 and 30kW. The microturbine is not operated in an idling condition, nor does it directly follow the instantaneous power requirements of the vehicle's traction motor. Therefore emissions are much more predictable than traditional drive systems that must respond to every possible driving transient.

To estimate emissions of this type of vehicle on a g/mile basis, simply calculate the average net energy consumed per mile (for example in kWh or hp-hr per mile) over any given drive cycle and then multiply that by the emissions level of the microturbine (for example the Capstone C30 CNG model is CARB certified at a NOx level of 0.05 g/hp-hr). This is the same way one would estimate the emissions associated with a battery electric vehicle, except that the average utility emissions factor would be used. The US EPA monitors emissions from major utility power plants, and makes this data available in several forms. One convenient website is http://oaspub.epa.gov/powpro/ept_pack.charts , which allows the user to input their zip code and obtain an estimate of what the average NOx and CO_2 emissions are for their utility power, as well as the US average. By example, using the zip code 91311 for the location of the Capstone facility in southern California, the average NOx emissions are reported to be 0.4 lb/MWh. This converts to an average 0.14 g/hp-hr, and does not account for any losses in the battery charging system. Note that the microturbine is actually cleaner than the average California grid power using the EPA reported emissions, and therefore it follows that a Capstone microturbine range-extended electric vehicle is cleaner (on a NOx basis) when the microturbine is charging the batteries than when the utility grid is charging the batteries. This leads to a suggestion for CARB to consider:

5. Confirm predictability of emissions from range-extended hybrid vehicles – Related to comment 1 above, it would be useful to confirm Capstone's perspective on actual emissions for a range-extended hybrid drivetrain and compare that to in-use emissions for traditional and battery electric drive systems. Better understanding of real-world emissions will help CARB set realistic goals and potentially new regulations. A demonstration project that would compare these types of vehicles operating in the same real-world drive cycles is one means to accomplish this.

For medium and heavy duty trucks and buses, CARB uses the engine emissions alone to certify the vehicle. Capstone agrees that this general approach is a good practical method that avoids excessive and costly in-vehicle testing. However, in addition to the more predictable (and in the case of Capstone, extremely low) emissions of a range-extended hybrid drive system, there are two important characteristics that should be considered by CARB in determining policy and regulations. First, in an electric drive system with traction motor and battery capacity sufficient to provide full acceleration and deceleration, the ability to recapture braking energy is maximized. By comparison, all the engine energy (and associated fuel and emissions) used to accelerate a traditional vehicle is thrown out the window whenever the brakes are used to slow or stop it. That energy (and associated fuel and emissions) must be regenerated every time the vehicle is accelerated again. The result is that an electric vehicle can use less overall energy per mile in a stop and go drive cycle. So the effective emissions of the range extender can be less than the CARB certified levels, depending on drive cycle. Second, because the battery pack in a range-extended electric vehicle is relatively large, there is a significant portion of a given day's driving that can be done on stored battery energy that came from a utility grid. Operators of such range-extended electric drive systems are naturally incented to charge their vehicles from the grid to the maximum extent possible for the simple reason that it saves money. As an example, consider that a diesel engine generator set with 35% efficiency and $4.50 per gallon fuel cost would effectively generate power at a fuel cost of $0.35 per kWh. Compare this to utility grid power at a cost of $0.10 or less per kWh during off peak times. When the vehicle is being driven on a utility charge, there are "zero tailpipe emissions", and therefore local emissions should be considered "zero" (as is done for a battery electric vehicle). The impact of both these attributes is to reduce the effective range extender emissions from what it is tested to by itself. One example comparison was done assuming certain vehicle assumptions and starting with a drive cycle derived from the standard CARB engine dynamometer test cycle. For a 100 mile daily drive, and battery capacity sufficient to operate the same drive cycle for 30 of those miles, the result is that vehicle tailpipe emissions are half of what the that vehicle would have produced with the same engine but without regenerative braking and without credit for the "zero tailpipe emissions" driving from utility-supplied energy. Details of this calculation can be shared, however the suggestion is:

6. Establish guidelines for range-extended electric drive systems that quantify emissions benefits – While we are not suggesting a change in general approach to certifying heavy duty engines, a

simple formula could be developed to provide additional incentives to vehicles with given battery capacities (expressed in miles of range) and use type (for example urban delivery van versus electric utility worksite support truck). Results from better understanding of in-use emissions from the suggestions above would provide useful input.

Suitability in Different Applications

A range-extended electric drive system is best suited for stop-and-go drive cycles and where there is opportunity to use battery power and clean range-extender power for auxiliary loads. Since this type of drivetrain is expected to cost more than a traditional drive system, the target market will be those customers with significant operating costs that include fuel, maintenance (both drivetrain and vehicle brakes), and resale value. These trucks and buses will most likely be Class 4 and up, and will include Class 8 that are used in urban and delivery applications. We recently did an analysis of several different customer delivery routes to estimate the fuel savings for a range-extended electric vehicle. One drive route was 33 miles per day, and the second 140 miles per day. Traditional wisdom might have predicted that the low mileage routes would achieve far less savings than the longer route. However the predicted fuel cost savings (using a combination of simulation and recorded fuel consumption) were $6,000 per year for the 33 mile route and $7,300 per year for the 140 mile route. This indicates that a range-extended electric truck can be deployed in a wide variety of applications and still deliver significant value. Some typical applications include:

- Transit Buses
- Package Delivery Vans
- Refrigerated Box Trucks
- Electric Utility Service Trucks
- Trash Trucks
- Short Haul Class 8 Tractors
- Yard Tractors

To support development of these applications, the following suggestion is offered:

7. Continue to support fleet demonstrations to quantify emissions and economic benefits – Capstone currently has several demonstration truck projects covering several of the target applications above. However not all these demonstrations will produce the same types of data, and may therefore not be as useful as they could be to provide broader comparisons that will help CARB determine future policies and regulations. We therefore suggest additional efforts be put into wider scale demonstrations with multiple vehicles in similar applications.

Current State of Technology Development

Capstone is the world leader in microturbines. We started commercial sales of the first models in 1998, and have now sold more than 7,000 units. There are a few other manufacturers currently offering production microturbines, and a few more are developing products. Capstone microturbines have been primarily used in stationary power applications, many of them in harsh environments where reliability is critical. Some Capstone microturbine models have also been deployed in range-extended electric vehicles, mostly transit buses. These hybrid electric microturbine models have also been certified by

CARB to meet the 2010 emissions levels without relying on any exhaust after-treatment. So from the basic technology perspective, microturbines are ready for full commercial production. However, at current production volumes the costs are not on par with traditional engines. The current Capstone microturbine designs are also optimized for stationary applications, and will need some adjustments to better reflect the mobile application requirements. The Air Resources Board, and potentially other California and US Government entities, could assist in further development and deployment of this clean technology in a couple of ways:

8. Fund development of microturbine optimization for range-extender applications – Capstone is already involved in several projects that will deploy our current production microturbines in real world environments. These include a Kenworth refrigerated box truck project partially funded by the South Coast Air Quality Management District and the San Joaquin Valley Air Pollution Control District, the Peterbilt/Walmart Class 8 concept vehicle, a CEC project for a Class 8 Tractor working with Artisan Vehicle Systems and CALSTART, and initial production sales with Wrightspeed for multiple FedEx delivery vans and Class 8 trash trucks. Capstone is participating at different levels in each of these applications, with the intent to learn how our microturbines can be optimized for these types of applications. As we gain this experience, we will be able to quantify the product performance goals and level of development required to achieve a production product that can successfully penetrate the medium and heavy duty vehicle market.
9. Revise certification and incentive procedures for range-extended electric drive vehicles – Capstone has successfully worked with CARB to achieve certification of several of its microturbine models. However the technology is considerably different than traditional engines, and there are often no set regulations and procedures to follow. This requires time to educate certification personnel on how our systems work and how they will be deployed in electric drive systems. CARB could accelerate deployment of this clean technology by providing expedited response for small volume suppliers like Capstone, and by simplifying the OBD requirements for microturbines used in range-extended electric drive systems.

We have learned through active participation in these projects, that there are also development needs in the electric drive system components themselves. Similar to the situation noted above regarding Capstone microturbines, high power motors and their associated inverters have been in production for many years, primarily in stationary manufacturing applications. However there is not a long list of commercial motors and inverters specifically optimized for the needs of this mobile market and readily available at a competitive price. Electric accessory components are also not readily available, including electric power steering, air compression, air conditioning, and battery charging. The batteries themselves remain expensive, and life expectancy under different real-world operating conditions is not well defined. The recent announcement that several medium duty electric drive vehicle manufacturers are scaling back activity is just one example that the market value for these electric drive components does not justify their current costs. The success that Tesla is experiencing with a battery electric system in the luxury car market, and continued sales of the Chevy Volt and other hybrids with significant battery storage capability in the car market may help bring more cost effective technology into the medium and heavy duty vehicle market. However the operating voltage of these systems is lower than the typical

600Vdc class used in heavy duty vehicle drive systems. The workshop presentation noted that plug-in hybrid electric vehicles have co-benefits for battery electric vehicles. This being the case, we suggest:

10. Rationalize incentives for range-extended and battery electric drive systems – The incentive levels for range-extended electric drive vehicles should be the same as for battery electric vehicles, since both are able to operate with "zero tailpipe emissions" for some distance.

Current Per-Vehicle/Equipment Costs

Current costs for both range extender and associated electric drive components are significantly above traditional drive system components, and are difficult to quantify. The Medium & Heavy Duty Battery Electric Vehicle presentation of the workshop estimated current battery costs at between \$500 and \$700 per kWh. Electric traction motor and inverter costs in the 600Vdc class are also relatively expensive, as are the associated electric drive accessories and the microturbine range extender itself. For microturbine-based range-extended electric drive systems, Wrightspeed Inc. publicly stated in a recent article on www.wired.com that their medium duty repowering system will cost less than \$100,000. This system includes a battery pack that can provide a range of about 30 miles, a 30kW microturbine range extender, and dual traction motors and inverters.

Anticipated Costs at Widespread Deployment

Capstone has done some projections for what the incremental cost of a medium-duty range-extended electric drive system would be. In annual volumes of 5,000 to 10,000, the incremental customer price could be \$50,000 to \$60,000 compared with a traditional diesel engine and transmission. At this price point, payback time for the first owner was calculated to be less than 3 years for a 35,000 mile per year usage. Net present value for this incremental investment, with an assumed incremental resale value of \$25,000 after 6 years, would be about \$41,000 with an IRR of 28%. The payback time for the second owner improved to 1.6 years. Even including a \$20,000 battery replacement cost at ten years vehicle life, and ownership of 9 years with no incremental resale value, the net present value for the second owner was calculated to be \$57,000 with an IRR of 54%. These calculations did not assume any incentives. There are a lot of elements that go into this kind of analysis which need to be verified. However the numbers estimated in this example indicate a good value proposition for many potential owners. It will take time to validate the operating cost savings as well as the resale value and battery replacement costs. Typical vehicle development for a major OEM would include a few individual prototypes tested on both track as well as limited customer usage followed by a pilot production of 50 to 100 units that get put into actual customer usage, and finally production roll out. Timing for this could be 3 years for the prototype phase, and at least another 1 to 2 years of validation prior to commercial introduction. This means 2020 for a potential major OEM new truck offering. Repowering applications such as Wrightspeed's can be adopted more quickly, and help pave the way for new OEM offerings. In addition to the suggestions above, we suggest CARB could assist in accelerating deployment using:

11. Incentives for fleet repowering deployment to validate performance – CARB could target a few visible and well-recognized fleet operators to deploy a significant number of trucks, with the

requirement that certain performance information be gathered to validate operating costs and suitability for the intended applications.

Emissions Levels

The demonstrated and certified emissions levels of the Capstone microturbines are currently well below 2010 CARB limits and are achieved without any exhaust after-treatment. Emissions are essentially the same operating on diesel fuel or CNG. For example, our C30 microturbine achieved certification at 0.05 g/hp-hr on CNG and 0.04 g/hp-hr on diesel versus the CARB 2010 standard of 0.20 g/hp-hr. Particulates were also extremely low, with the CNG unit certified at 0.002 g/hp-hr and diesel unit at 0.003 g/hp-hr versus the CARB 2010 standard of 0.010 g/hp-hr. Since these emissions levels do not require diesel emissions fuel to control NOx, or extra diesel fuel for oxidizing captured soot from a particulate trap, they are more likely to continue to operate properly without extra maintenance or operating costs. Plus the microturbines are deployed in a range-extended electric drive system that improves vehicle efficiency with full regenerative braking and has significant battery only range with "zero tailpipe emissions". And compared to EPA reported NOx emissions from the California grid, a Capstone range-extended electric vehicle is actually cleaner than a pure battery electric vehicle. Capstone believes all these factors should put microturbine-based range-extended electric drive vehicles in a preferred position compared with many other alternatives. Therefore we suggest:

12. Establish near term incentives for microturbine-based range-extended electric vehicles – Criteria could be set that would provide extra incentives to recognize the clean emissions from this type of drive train. Criteria could include that emissions of the CARB certified range extender be less than EPA reported NOx emissions for the average California grid, that this emissions level be achieved without relying on exhaust after-treatment components such as diesel emissions fuel or particulate traps, and that the battery capacity have a meaningful range (for example 30 miles under a prescribed operating condition such as average speed of 40 mph).

Conclusions

Capstone appreciates the opportunity to provide written comments to assist CARB in their Technology Assessment efforts. CARB has a significant role to play in reducing criteria pollutants from a wide variety of sources, and helping California eliminate non-attainment conditions across the state. There are many technologies in production and on the horizon that can contribute, and Capstone's clean microturbine technology is one. We will be glad to provide additional information or demonstrate our products if requested by the evaluation team.

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