Conference Summary

SAE WCX 2021

Summary of SAE WCX 2021

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This is a summary of engine and emissions control related content presented at the SAE World Congress 2021, held in a digital format this year.

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Top Technical Papers at WCX

Each year, WCX gathers engineers to discuss the topics and trends at the cutting edge of mobility engineering. These technical papers represent some of the most sought-after resources, offering insights into significant industry advancements and innovations. Explore them today.

Review of Vehicle Engine Efficiency and Emissions (2021-01-0575)
An annual review of global regulatory and technological advances pertaining to emissions from internal combustion engine (ICE) driven vehicles and machinery.

Development of High-Performance FC Stack for the New MIRAI (2021-01-0740)
A review of the fuel cell (FC) stack in the new MIRAI that has increased power performance and reduced size.

Application of Dynamic Skip Fire for NO_x and CO2 Emissions Reduction of Diesel Powertrains (2021-01-0450)
A proposed application of Diesel Dynamic Skip Fire (dDSF™) and its benefits to reducing NOx and CO2 emissions.

Effects of Electrically Preheating Catalysts on Reducing High-Power Cold-Start Emissions (2021-01-0572)
A potential solution for reducing high-power cold-start (HPCS) constituent emissions.

The Influence of eFuel Formulation on Post Oxidation and Cold Start Emissions (2021-01-0632)
A proposed solution of using non-fossil synthetic fuels from renewable energy sources to minimize the vehicle's carbon footprint during the use phase.

Requirements and Strategies for Diesel Cold-Start Catalyst Warmup for Low NO_x Regulations (2021-01-0537)
A systematic, physics-based approach in deriving engine performance requirements for a Diesel cold-start catalyst warmup strategy that would satisfy low NOx regulations.

Powertrain technologies

Cylinder deactivation

Deactivating cylinders is increasingly getting attention to reduce fuel penalty associated with throttling losses and increase exhaust temperatures to assist with emissions control. **Tula Technology** presented (SAE 2021-01-0420) the value proposition for the combination of electrification and dynamic cylinder deactivation, which they term as electrified deceleration cylinder cutoff (eDCCO). The technology combines the ability to deactivate individual cylinders at any given point and propelling the vehicle in electric mode with all cylinders deactivated. The technology was tested on a 2016 VW Jetta with a 1.8L turbo GDI modified to incorporate a mild hybrid system. On the WLTC, 5.5% reduced CO_2 emissions were

obtained compared to the baseline mild hybrid vehicle. In another paper (SAE 2021-01-0459) **AVL and Tula** evaluated the synergistic gains of dynamic cylinder deactivation when paired with Atkinson cycle and cooled EGR. Compared to a 2.0L baseline engine, an upsized 2.5L engine with Atkinson cycle, cooled EGR and dynamic skip fire was predicted to deliver >8% improvement in fuel economy on the WLTC.

Pre-chamber combustion

Active and passive pre-chamber combustion has been extensively studied and shown to enable increase compression ratio and knock mitigation resulting in reduced fuel enrichment and improved fuel economy. **MAHLE** presented a study (SAE 2021-01-0477) in which the compression ratio was held fixed and instead an improvement in performance was obtained. For a 1.5L gasoline engine, an additional 12kW power was enabled under stoichiometric operating conditions. **Aramco** presented their research (SAE 2021-01-0479) on the pre-chamber design – the nozzle diameter, number, volume – on part-load efficiency and emissions of a Miller cycle gasoline engine. Smaller nozzle area and volume and increased number of nozzles was found to deliver increased efficiency. Optimal efficiency was found at lambda ~1.7-1.8, while NOx continued to drop at lambda > 2. **MAHLE and ExxonMobil** (SAE 2021-01-0462) tested the synergistic benefits of pre-chamber technology with a range of high-octane fuels to demonstrate a 1.5L engine with peak brake thermal efficiency of 43.6% and minimum brake specific fuel consumption (BSFC) of < 190 g/kWh. The high RON fuel enabled further increase in compression ratio and an increase in lean limits. On the WLTC, fuel economy of 39.5 mpg was predicted, a 9% improvement over the pre-chamber alone and >20% compared to the reference 1.5L engine.

Low temperature and lean combustion

Hyundai-Kia presented an update (SAE 2021-01-0518) on the DOE funded work on evaluating the benefits of gasoline compression ignition (GCI) engines GCI mode was evaluated on a 2.2L engine in the speed & load ranges of 1200 – 3000 rpm and 5 – 20 bar BMEP, respectively. An optimized injection strategy was recommended, switching from partially premixed (PPCI) at intermediate to mixing controlled (MCCI) at high loads. At low loads spark assisted combustion was recommended. Combustion stability was found to be a challenge at low loads with GCI, while rapid pressure rise was limiting the application at very high loads. Still, peak brake thermal efficiency of 43.4% was obtained, with brake specific NOx at 3.97 g/kWh.

In two papers (SAE 2021-01-0457 and 2021-01-0458), **General Motors** summarized the US DOE funded work on developing a multi-mode combustion system combining lean-stratified combustion at part loads, switching to stoichiometric Miller-cycle operation at higher loads.

On-board separation of ethanol

Honda presented (video only) their progress with developing an octane-on-demand system. A pervaporation membrane module separates ethanol from a E10 fuel, which is stored in a tank and injected when needed during the high load operation. On the LA4 cycle, ethanol was separated at a rate of 0.5 kg/hr, higher than the estimated requirement of 0.2 kg/hr. The permeate had a concentration of 68% ethanol with a RON of 107. Calculations show the potential for improving fuel efficiency by 20% when going from a 1.8L CR 10.5 engine to a 1.5L turbocharged engine at CR 12.5 and using the on-board separation unit.

Gasoline - Gas Emissions Control

Cold-start emissions reduction

- **Umicore** showed (SAE 2021-01-0574) that the use of a hydrocarbon trap (HCT) in the close-coupled position, followed by an under-floor three-way catalyst (TWC) can deliver < 15 mg/mi of combined non-methane hydrocarbon (NMHC) and NOx emissions. The challenge with the configuration is the durability of the HCT when exposed to temperatures > 750 °C, which will likely limit the application to hybrid vehicles with cooler exhaust.

- Under moderate RDE driving conditions, plug-in hybrids are comfortably meeting the RDE regulations, irrespective of the state-of-charge. That was the conclusion reached through a study (SAE 2021-01-0605) conducted at **BOSMAL**. Nevertheless, the authors note that the cold start emissions can be high and the overall low emissions (in mg/km) are in part due to the cold start emissions being divided by the overall driving distance. Plug-in hybrids do have an issue with respect to "high-powered cold start" emissions, however. **Vitesco** (SAE 2021-01-0572) used an electrically heated catalyst along with secondary air to pre-heat the support catalyst to > 300 °C before the engine turned on. The resulting NMOG + NOx emissions during the first engine start in the US06 test cycle were reduced by a factor of two.
- Researchers from **Toyota and Waseda University** evaluated the improvement in TWC conversion when the catalyst was placed in an electric field (SAE 2021-01-0573). Lab experiments demonstrated that in the presence of an electric field, CO, propene and NO oxidation occurred at temperatures as low as 450 K (177 °C). The improved conversion only occurred on Ce-Zr mixed oxides, pointing to the role of ionic conductivities of the catalyst material interacting with the electric field.
- **Corning, SPMC and SAIC-GM** published (SAE 2021-01-0581) the potential of high porosity and low thermal mass FLORA® substrates for PGM reduction and meeting China 6b gas emission limits. FLORA 800/3 substrates were shown to achieve similar emissions performance as a standard porosity 750/2 substrate while using 10 – 25% less PGM. On the RTS-95, NOx emissions of 28 mg/km were achieved on a 1.5L turbocharged MPI vehicle.
- **CETESB** provided an interesting perspective on future regulations for light-duty vehicles in Brazil (SAE 2021-01-0608), which will require European style RDE regulations starting in 2022, while laboratory certification remains on the US FTP-75 test cycle. The paper reconciles these testing methods while also pointing to the unique issue of high cold start ethanol emissions due to the high ethanol content in Brazilian fuel. Another study by **BOSMAL** (SAE 2021-01-0616) also looked at the impact of test cycles on cold start (and overall) emissions from the same vehicle. It was found that the combination of cold start with dynamic driving such as during the US06 test leads to much higher emissions than over other tests.
- **Porsche and University of Stuttgart** provided a glimpse into the possibilities for reducing cold start emissions when using synthetic fuels (SAE 2021-01-0632). Testing done with 3 synthetic fuels showed the possibility to significantly reduce both engine-out and post-TWC gas and particulate emissions. This was attributed partly to the increased fraction of short chain hydrocarbons and hydrogen in the exhaust when using synthetic fuels.

Secondary Emissions: NH_3, N_2O

- Through a study of 9 gasoline vehicles, **Umicore** showed (SAE 2021-01-0580) that NH3 and N2O production depends on the state of the catalyst (fresh, aged), the lambda control and the PGM content. Testing showed that while N_2O emissions were low (< 5mg/km) and unlikely to be a concern, future gasoline vehicles will likely require an ammonia slip catalyst to address the relatively high emissions measured (2 – 48 mg/km).

Diesel

Pre-turbo catalysts are being researched as one option to achieve early catalyst light-off via elimination of the thermal inertia associated with the turbocharger. The issue is the recovering the loss in transient response given that the turbocharger must work with reduced enthalpy. University of Stuttgart presented a simulation study (SAE 2021-01-0579) where a DOC, DPF and SCR was placed upstream of the turbocharger and one SCR downstream. An electrically assisted turbocharger and a P2 hybrid powertrain system was evaluated and found to address the transient response under dynamic RDE driving. Both systems led to significantly reduced NOx (85%) and HC (38%) emissions due to the warmer exhaust, however CO emissions were increased due to a need for richer combustion. Passive regeneration of soot was also improved due to higher temperatures.

Fuel quality can have a significant impact on the long-term performance of emission control systems. **FCA and Umicore** studied (SAE 2021-01-0614) a field returned diesel vehicle with unacceptably high emissions and verified that the loss in

DOC conversion and a related increase in DPF backpressure was associated with high levels of alkali metal (Na and K) accumulation, possibly derived from poor quality biodiesel.

Particulate control & measurements

Fundamentals of soot formation in engines is of continued interest. Researchers from Chalmers University presented work on understanding the sources of soot formation in GDI engines (SAE 2021-01-0622), attributing it to mostly cold piston surfaces.

Particulate formation is also intricately linked with the fuel composition and **GM & SGS** presented a review of global fuel quality in the last 5 years and the impact on sooting tendency (SAE 2021-01-0623). The authors show the need to include the heat of vaporization of ethanol to improve correlation of PM vs particle evaluation index. Also, they note that aromatics content in most regions has decreased but in the US the trend has been the reverse. Another joint paper from Sinopec, GM, Dongfeng and others (SAE 2021-01-0540) also stressed the importance of including the heat of vaporization of oxygenates when trying to predict particulate formation. The paper also looked at the impact of MTBE, an octane booster used in China, on emissions.

Soot formation models are advancing. A modeling framework combining detailed reaction mechanism coupled with CFD was shown by **ANSYS** (SAE 2021-01-0618) to be able to predict soot formation and particle size distribution for a wide range of conditions for both gasoline and diesel engines.

GPFs are now ubiquitous in Europe and China and studies are looking at in-use performance. **Umicore and Corning** showed (SAE 2021-02-0582) the performance of a catalyzed GPF in the 2nd close-coupled (CC-2) position on a mild hybrid US Tier 3 compliant SUV. Emissions were measured as a function of mileage starting with a new vehicle and running to 4000 miles. Both engine out and tailpipe particulate emissions were found to decrease with mileage such that at around 1800 mi both PM and PN were below the Tier 3 and China 6b limits with a safety margin. In another study, SAE 2021-01-0587, **Umicore** compared the use of coated and uncoated GPF in the CC-2 position and showed that the presence of coating is helpful for meeting China 6b gas emission limits and also for enhanced soot oxidation due to the exotherm associated with CO oxidation. The increased backpressure due to coating did not lead to a noticeable increase in fuel economy.

China 6b particle limits are effectively not as stringent as Euro 6d. Testing of 4 vehicles and comparing the emission results using the European and Chinese regulatory framework, **Corning** showed (SAE 2021-01-0588) that the vehicles would meet China 6b but fail the Euro 6d standard. In the current form, China 6b excludes cold start emissions, maintains a higher conformity factor (2.1 vs 1.5) and retains the package 2 RDE analysis, which makes it less stringent.

Robust particle measurement protocols will be necessary for implementing future Euro VII standards, with likely reduced limits and inclusion of sub-23 nm particles. **KTH Royal Institute of Technology** compared two dilution systems and sampling at various locations in the after-treatment system (SAE 2021-01-0619). The study showed that the choice of dilution method depends on the sampling point, with the one using the evaporation tube better for tailpipe measurements after SCR as it can pick up increase in nucleation mode particles due to unreacted urea.

Southwest Research Institute, SWRI (SAE 2021-01-0624) investigated the impact of DEF dosing on PN measurements conducted in accordance with the EU PMP protocol. Testing was done using a 2015 6.7L diesel engine with a DOC, DPF and SCR. Measurement system used an evaporation tube to address the volatile particles. Still, a clear signature of higher particle count was observed when the engine was operated with DEF dosing. PN emissions were found to increase up to 180% due to urea-induced particles.

Heavy-Duty

Fuel Economy

Studies explored the improved fuel economy with hybridization. **Argonne National Lab and Aramco** (SAE 2021-01-0717) used simulations using Autonomie to compute the change in fuel consumption for Class 4 through 8 trucks operating on wide range of driving routes and applications with increasing electrification: mild hybrid, parallel hybrid and series plug-in hybrid. Compared to the conventional non-hybrid engine, the study concluded that strong hybridization can save 25 – 40% fuel depending on the vocation and drive cycle. The benefit does not extend to long haul trucks operating mostly on highway, which showed a limited 3 – 6% improvement with full hybridization.

FEV (SAE 2021-01-0720) evaluated the improvements due to 48V mild and 350V hybrid powertrain configuration for a Class 6-7 urban vocational truck. A P3 configuration was found to deliver 22% and 27% reduced fuel consumption for the two voltage levels, respectively, and a payback period of 2 years. In an accompanying second paper (SAE 2021-01-0723), mild hybridization was compared with other range extender electric vehicle (REEV) powertrains. The mild hybridization was found to be most suitable for the urban vocational application with 17% reduced fuel consumption along with a 6% reduced cost of ownership and payback period of less than a year. CNG-REEV was shown to reduce the fuel consumption by a factor of two with a payback period of 3 years. The BEV and fuel-cell REEV were found to increase freight ton efficiency by 4X and 2.5X, respectively, but the improvement is offset by a reduced payload capacity. A similar cost of ownership as conventional diesel powertrain was found assuming advanced batteries with $200/kWh and 125 Wh/kg pack energy density. The studies show that mild hybridization may be an effective tool to reduce CO_2 / fuel consumption from urban applications as we transition to full electrification.

Hybridization is also being explored for off-road machinery. **Caterpillar** presented (SAE 2021-01-0449) early results of a multi-year DOE funded study, aimed at exploring the benefits of hybridization. Simulations were done for a 13L engine downsized 30% from 18L and paired with other hybrid technologies such as mechanically driven turbocharger (SuperTurbo), high speed flywheel and motor-generator unit.

HD Low NOx

A joint study by **UC Riverside and the South Coast Air Quality Management District (SCAQMD)** has conducted one of the largest real-world NOx emissions test programs including 50 vehicles covering a large range of engine technology & fuel type and vocations. This was an oral presentation, but a recent publication covers the work (https://doi.org/10.1016/j.scitotenv.2021.147224). As has been reported earlier by other researchers, this study found that heavy-duty vehicles generally greatly exceeded the FTP certification limits, with the highest average exceedance of 80% for the diesel vehicles certified to the 0.2 g/bhp-h limit. CNG vehicles were relatively cleaner, although they also were found to cross the limit for some applications. SCR temperatures were strong drivers of tailpipe emissions, however one surprising finding of the study was that NOx emissions remained elevated even at T > 250 °C for some of the high emitters.

The key challenge for meeting California's 2027 HD Low NOx standard is getting the after-treatment and specifically the SCR above the operating temperature within a short time, especially at low loads. **National Research Council Canada & Transport Canada** published their work (SAE 2021-01-0535) on cold start and idling emissions on a single cylinder engine. The work shows that a strategy of 30% EGR and post injection could provide some reduction in engine-out NOx and increased exhaust temperatures.

SWRI provided an update on the Low NOx Stage 3 program (SAE 2021-01-0589). A combination of modified engine calibration with new hardware such as cylinder deactivation and an updated after-treatment system with close-coupled catalyst has enabled almost reaching the goal of 90% reduction without increasing CO_2. The final tailpipe levels were at 0.023 g/bhp-h on the FTP cycle, slightly higher than the target of 0.02 g/bhp-h, mainly due to after-treatment deterioration. What remains is further improvement under fully aged conditions representative of 435,000 miles. Note that there is ongoing work with a separate DOC + DPF after-treatment which is delivering even better results. **Eaton and SWRI** have further extended this work, evaluating the use of an electrical heater to further reduce NOx emissions (SAE 2021-01-0211).

NOx sensors are going to be critical in ensuring in-use compliance. The on-board measurement accuracy depends on various factors including tolerance, exhaust flow rate estimation and cross sensitivity to ammonia. Starting model year 2022, NOx emissions will have to be measured on-board as part of the Real Emissions Assessment Logging (REAL) regulation in California. **General Motors** showed (SAE 2021-01-0593) that the cumulative effect of these factors can result in errors exceeding 20% on a per cycle or instantaneous basis.

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