

Q1 (CARB – 02.10.2017)

Under what conditions are nanoparticles formed during braking and what are the controlling factors? Does it depend on brake temperature, brake pressure?

- ✓ A1 (Theo Grigoratos - JRC) Several factors affect brake emissions and specifically nanoparticles formation. Environmental conditions, driving and braking patterns, dimensions and type of the brake system are some of them. Most of these parameters are linked to the brake temperature which has been proved to be the most crucial parameter linked to nanoparticles formation. In other words it can be said that all other parameters result in a specific temperature which is responsible for the nanoparticles emission. It has been shown in several studies that the critical temperature above which there is an "explosion" in the nanoparticles emissions is 180°C (Please refer to Mattia Alemani, Sebastian Gramstat, Dmytro Lugovyy, David Hesse and others for such studies). The question is how often the brake system reaches this temperature under real world conditions? Preliminary results from the WLTP cycle being developed in TF1 show that not many braking events go near this temperature. However, they exist. We will have future discussions on this as soon as the cycle is completed and become available to the PMP group.
- ✓ A1 (Dmytro Lugovyy - HORIBA) Controlling factors for particles under 23 nm are disc speed, disc temperature and less brake pressure. Please refer to slides 43-45 of Horiba's presentation at the 43^d PMP Meeting. Appearance of 10 nm particle depends not only on testing conditions, but also on brake material properties. For example, for NAO pads these particle are present even at mild section of AK Master (characteristic value, section 4.1-4.3). So it has nothing to do with matrix oxidation or destroying. On other side in ECE brake pads content of organic compounds is quite low and will not affect total brake emission. Nevertheless, nanoparticles appear at the point when dissipation energy increases. I believe it is more mechanical, then chemical effect.
- ✓ A1 (Carlos Agudelo - LINK) There is probably a strong correlation with mechanical work (KE dissipated) and transfer layer temperature.
- ✓ A1 (Ilja Plenne and Andreas Paulus - TMD) During initial tests we also observed temperature respectively power dependent occurrence of small nanoparticles

Q2 (CARB – 02.10.2017)

Under what conditions are nanoparticles formed during braking and what are the controlling factors? Can these conditions be easily replicated?

- ✓ A2 (Theo Grigoratos - JRC) H2020 LOWBRASYS Project shows that these conditions are highly repeatable in the brake dyno as long as some requirements are kept. Tests were performed over a realistic short LACT driving cycle. Horiba also confirmed this (please see comment below). I guess there are also other partners who have already performed tests and can confirm. We will need to define these conditions in TF2 and then at a later stage carry out a round robin to confirm.
- ✓ A2 (Dmytro Lugovyy - HORIBA) Yes, it was actually done by using different sampling concepts at two different brake dynamometers. Please refer to slides 46-47 of Horiba's presentation at the 43^d PMP Meeting.
- ✓ A2 (Carlos Agudelo - LINK) Yes, that is the idea behind the development of a standard peer-reviewed test cycle with validated test setups.
- ✓ A2 (Ilja Plenne and Andreas Paulus - TMD) The formation of small nanoparticles due to high temperature seems to be repeatable.

Q3 (CARB – 02.10.2017) How representative are these nanoparticles of a real-world situation? The sampling method could be encouraging particle formation due to lower dilution relative to a real-world situation. Could this be tested by increasing and decreasing flow rates specifically for conditions where nanoparticles are observed?

- ✓ A3 (Theo Grigoratos - JRC) A dilution tunnel like set-up is used by most researchers in TF2 in order to replicate real world dilution. Of course we know that this is not enough in terms of accuracy but it is a compromise we need to live with like in case of exhaust emissions. Otherwise we will never achieve a reproducible measurement procedure. Increasing and decreasing flowrates will be tested/used but in my point of view it will be only for the purpose of successfully replicating the real world behavior of the temperature of the brake system (i.e. 1. Run the cycle on road under real world conditions, 2. Record the temperature of the brake system over the cycle, 3. Run the cycle in the dyno, 4. Adjust the flowrate based on the real-world temperatures).
- ✓ A3 (Mattia Alemani - BREMBO) Due to phenomena particles are subjected to (coagulation, settling, different forces influencing motion) the sample properties could differ depending on the sampling point. If we measure near or far away from the source outcomes could differ. Therefore we need to decide which the best set-up is for our purpose. If the aim is to characterize the brake system itself (and thus get the most information about the “raw” generated particles) then going near the source is meaningful. Otherwise, if we think of real world conditions, an interesting approach would be to think that people do not breathe particles near the source but probably at a height of 1.5-1.7 m, thus particles will need to have time to settle and coagulate and therefore different sampling approach should be followed.
- ✓ A3 (Carlos Agudelo - LINK answering also to Mattia’s and Theo’s comments above) in theory it is doable and within the range of efficient debris collection. Depends upon the duct layout, airflows, and sampling method. Not sure the dilution tunnel is meant to replicate real world dilution. In my understanding the dilution tunnels serves mainly for: (a) providing aerosol homogenization prior to sampling, (b) transport the airflow that replicates the brake thermal regime (within reason) from real world, and (c) ensure stable air speed for sampling and to minimize resuspension inside the duct. Also, please reference the EPA Method 1A attached on 31OCT2017. An interesting approach would be to think that people do not breathe particles near the source but probably at a height of 1.5-1.7 m which nicely match to the isokinetics to sample > 8D after the last duct disturbance if we use a 150 mm duct as an example.
- ✓ A3 (Dmytro Lugovyy - HORIBA) Yes, we observed such effect. Particle number per test with and without housing are presented on pages 35 and 32 respectively. As can be depicted from these data, reduction of air flow leads to reduction of PN per test regardless the presence of the housing (air flow is shown by vertical labels). Observed variation in PN due to reduction of air flow is estimated at approximately 30% for every step and certainly cannot be attributed to reproducibility issues. One possible explanation of the effect is coagulation of particles. As depicted on page 44 (left graph), increasing air flow from 2700 to 3300 m³/h results in nanoparticles appearance in particle size distribution at much lower concentrations (respectively at brake events with lower brake pressure), whereas transition temperature for their formation becomes stable. Number of peaks for nanoparticles also increases with increasing air flow-right graph with zoomed data.
- ✓ A3 (Ilja Plenne and Andreas Paulus - TMD) As it is not practicable to replicate real world air flow with reasonable effort on the dyno for different brake systems, the focus should be on achieving a good reproducibility.

Q4 (CARB – 02.10.2017) How representative are these nanoparticles of a real-world situation? The sampling method could be encouraging particle formation due to lower dilution relative to a real-world situation. The sampling method could also be underestimating total numbers for reasons we don’t understand.

- ✓ A4 (Carlos Agudelo - LINK) If we follow industry practices for nozzle sizing, location, and isokinetics, the estimates can be useful and comparable.

- ✓ A4 (Theodoros Grigoratos - JRC) When it comes to this discussion we will also have the very useful opinion from the PMP Exhaust experts. They have been dealing with these issues for more than a decade, therefore their experience could prove useful.
- ✓ A4 (Michal Vojtisek - TUO) Close to the brake assembly the particle distribution is not yet fully uniform and the flow is not laminar, therefore sampling cannot be isokinetic - this is less of a problem with nanoparticles, but the magnitude of the problem introduced increases with particle size. Within the tunnel, there are diffusion losses (primarily of very small particles), settling losses (larger particles), and possibly nucleation (formation of particles), coagulation and agglomeration of particles. Finally, chemical processes vaguely described as "particle aging" cannot be excluded.

Q5 (CARB – 02.10.2017) How representative are these nanoparticles of a real-world situation? The sampling method could be encouraging particle formation due to lower dilution relative to a real-world situation. Could coagulation/accretion be calculated for these particles as an additional source of loss in the brake dyno test setup?

- ✓ A5 (Carlos Agudelo - LINK) Yes, and from talking to instrument experts at SAE Brake Colloquium in Orlando, it should be added to the correction/losses estimates. Travel times of the particles will be the main factor (besides the actual particle size distribution, median diameter and geometric standard deviation) to determine coagulation coefficients (Hinds, Chapter 12 and Kulkarni et al, section 3.5). Travel times will be a function of duct size and airflow (to determine air speed), duct length prior to sampling nozzle (following guidelines from EPA and ISO for # of diameters of stable and straight duct in front of the sampling plane), and sampling train length between the sampling nozzle and the particular instrument.
- ✓ A5 (Dmytro Lugovyy - HORIBA) Yes, please refer to slides 25-29 of Horiba's presentation at the 43^d PMP Meeting. We compared different sampling concept presented on slides 25-26. For concept compromising enclosure with mini-dilution tunnel, PN concentration per test was found to be at least two times smaller in comparison to Horiba-Audi concept over AK Master and WLTP. As depicted on slide 27, for concept with mini-dilution tunnel peaks in particle size distribution are shifted to bigger particles, thus implying coagulation. Number of peaks also reduced in comparison to Horiba-Audi concept. We were assuming coagulation effect and for that reason polydisperse coagulation for particle sizes determined at peak position (presented in slide 27) was calculated. The formula applied as well as the results are presented in slide 28. The strong coagulation for concept compromising enclosure with mini-dilution tunnel (results are marked as Chamber) is expected due to high measured concentration. In SAE Paper 2012-01-0443, authors performed similar calculation for polydisperse coagulation using only one coagulation coefficient for total concentration. In both cases, Horiba and SAE paper, same formula were used and results agree as well. Based on both research, we can conclude that measured particle concentration (not mean, but every time point) should be $\leq 5 \times 10^6 - 1 \times 10^7$ particles/cm³ (we have to take in account residence time) and the fact will bring us once more to question how dilution and air flow will affect results of measurements (please see my Answer A3)

Q6 (BREMBO – 03.10.2017) Particles residence time is considered one of the most important parameters. About the discussion on the sampling point what should our sample represent? General discussion regarding the type of instruments and diameters used.

- ✓ A6 (Dmytro Lugovyy - HORIBA) I agree that we have to consider such effect as settling and coagulation. We just have to keep in mind that once particles are emitted (at real world conditions), they will be immediately diluted with indefinite amount of the air. So we have to find a correct way to translate distance 1.5 -1.7 meter away from the vehicle to meaningful brake dynamometer conditions (dilution ratio, air temperature, etc.). Regarding the diameters, I think we should not spend much time on discussion what kind of equipment (based on electrical

mobility or on aerodynamic diameter) will be used for measurements. I would wait until we will get more information regarding physical and chemical properties of brake dust particles and address the discussion to calibration issues.

- ✓ A6 (Mikko Moisio - DEKATI) I believe this is one of the fundamental questions which can be tracked back to the mission of the task force and PMP. Almost all the PM_{2.5} health related studies are made using the aerodynamical diameter, the standards for ambient and indoor air quality are defined by aerodynamical particle sizes. Also the human lungs themselves are definitely collecting particles either by inertial impaction (aerodynamical particle size) or diffusion (more related to particle surface area or length). As my own opinion I believe we should at least try to simulate the real world conditions AND be interested in creating comparable and harmonized measurement systems for R&D and scientific purposes as much as it is practical. Regarding the question of which parameters we should look, I believe we should include both PM and PN.
- ✓ A6 (Ilja Plenne - TMD) Each measurement method has its advantages and there surely are reasons to investigate all different kinds of parameters. Considering this, my suggestion would be to create a setup or methodology which enables a correct and reproducible measurement of all kinds of values (PM, PN, size distribution). The idea would be to let the end users decide which values to measure in accordance with the aim of their work and research focus. Maybe we even will need varying sampling methodologies to investigate different parameters like e.g. PN which is dominated by small particles and PM which is dominated by larger ones. Furthermore, I also appreciate the approach of keeping the measurements as close as possible to real world conditions as long as this is practical.
- ✓ A6 (Michal Vojtisek - TUO) in nearly all instruments, the particle diameter is assessed indirectly based on some property (i.e., electric mobility in SMPS and FMPS, aerodynamic diameter in impactors), as a diameter of a hypothetical particle having the same property. The problem is that there are differences among these equivalent diameters, i.e., between electric mobility diameter and aerodynamic diameter, and in my opinion, there is no consensus on any universally applicable "conversion factor" for brake wear particles given the variety of materials and conditions.
- ✓ A6 (Theo Grigoratos - JRC) based on the feedback of TF2 members having a methodology capable of providing meaningful and reproducible measurement of all kinds of values (PM, PN, size distribution) is very challenging. The aim is to try to better represent real world behaviour of brake wear particles, while creating comparable and harmonized measurement systems for R&D and scientific purposes will not be compromised. Overall, as other colleagues mentioned we should try to do both as much as it is practical.

Q7 (Theo Grigoratos – 15.10.2017) Based on Matt’s general comment “it is probably worth considering to monitor the rotor temperature rather than pad temperature for dynamometer testing in general as it is a much more stable value.” could we have a further insight/explanation about this issue? How the particle production is affected by the two temperatures?

- ✓ A7 (Michal Vojtisek - TUO) In engines, the local temperatures in the combustion chamber, responsible for the formation of various pollutants, are far different from any temperature measured by a thermocouple. It appears that the formation of, for example, metallic nanoparticles in the braking process requires local temperatures far in excess of what is being measured as the pad or rotor temperature. Considering that there is a temperature gradient between the point where the particles are formed and the point at which the temperature is measured, I would like to ask if additional parameter, such as the rate of change of temperature, should be considered when discussing the relationship between particles and temperature.
- ✓ A7 (Dmytro Lugovyy - HORIBA) TF2 will have to consider the rotor temperature because it is more representative of the actual temperature of the brake system (of course with many assumptions). So far Horiba has found

correlation only between rotor temperature and wear amount but no correlation to pads temperature. Comment regarding local temperatures is correct. Of course temperature on surface in braking zone differs much from measured on rotor/pad. Still, rotor temperature will be measured using at least 2 thermocouples and measured temperature is averaged over the half disk surface. Using IR methods can provide theoretically much more precise information about spot temperature, but emitted particles will introduce some errors to temperature results. So far, I don't see need to introduce additional correlation factor to exiting temperature measurements- otherwise we will make our experiment set-up even more complicated. Perhaps we can use rotor temperature as it is (we still have to define number and position of thermocouples), without any additional correlation factor.

- ✓ A7 (Ilja Plenne and Andreas Paulus - TMD) Regarding temperature measurement we have to distinguish between the purpose of the measurement - temperature measurement for controlling the test cycle and temperature measurement to gain insights into particle formation processes. For both purposes thermocouples are not necessarily the best way to go.

Temperature measurement for controlling the test cycle: As the effective friction radius changes even within one brake application due to so-called hot bands, from our point of view thermocouples are not the best choice here. From experience it can be said that measuring temperature with an IR sensor on the side of the disc is the most stable and reproducible one because it is much more uniform and representative of the mean temperature of the disc.

Temperature measurement to gain insights into particle formation processes: To understand the connections between temperature and particle emission we have to go as closely to the friction surface as possible with the measurement. Probably the best way to do this are open ended thermocouples which opposed to conventional thermocouples continually measure temperature in the friction surface and provide a very short response time. For further information please see:

http://www.fzd.tu-darmstadt.de/media/fachgebiet_fzd/publikationen_3/2007/2007_degenstein_sensor.pdf.

Q8 (Theo Grigoratos – 15.10.2017) which are the most important parameters affecting brake temperature when a time based cycle is considered and which need to be defined/discussed within the TF2?

- ✓ A8 (Carlos Agudelo - LINK) Brake temperature for driving cycles (WLTP-based, LACT, or similar) will be mainly a function of:
 1. Total airflow and enclosure shape and size
 2. Duct shape, size, and distance to the brake
 3. Clock position of the caliper relative to the incoming air
 4. Environmental conditions (mainly cooling air temperature); air humidity would affect coefficient of friction of some materials under certain test conditions
 5. Brake size (rotor size, design, and thermal mass)
 6. Test inertia (vehicle weight, brake work split during regular driving, and tire size)

TF2 should focus its efforts to commonize/specify (options or allowable configurations) at least items 1 through 4.

- ✓ A8 (Ilja Plenne and Andreas Paulus - TMD) The list should probably be extended by the following two points:
 7. The brake temperature measurement method
 8. Friction couple: rotor material and coating, pad material