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Innovative Catalyst System to Achieve EU7 Legislation for Electrified Powertrains

Innovatives Katalysatorsystem zur Erfüllung der EU7 Gesetzgebung für elektrifizierte Antriebe

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Abstract

The new passenger car emission legislation for Europe (EU7), California (Advanced Clean Car 2) and China (China 7) most likely will be introduced in the time frame between 2025 and 2027. Unfortunately, as of today (February 2022) no “official drafts” are published. It seems that for example the EU7 commission proposal might be published in July 2022. In addition to this very late announcement the politically wanted and funded introduction of electrified and battery electrical vehicles makes it difficult to predict which powertrain concepts will be needed in the future. This situation is aggravated by the fact that today the absolute market numbers for combustion engines are unforeseeable, or at least not plannable in the different regions of the world.
Based on the up to now published information and studies of a possible EU7 legislation it can be assumed that because of a shortened trip length for real driving emission testing and also lower ambient testing temperatures like -7°C, compared to today, the cold start will become even more challenging and that catalyst light-off will be needed within a few seconds. Also, for electrified powertrains, which can start a trip by pure electrical driving, so called rapid accelerations might become the most challenging operation mode. Based on today`s exhaust system layouts for such driving conditions the catalyst system is still cold while the engine is rapidly speeding up to high engine speed and torque, which might require preheating of the catalyst system.
Also, CO_2 continues to be the decisive factor for the choice of the future powertrain type. As of today, CO_2 from transportation is still defined as pure tailpipe emissions (tank-to-wheel). A life cycle analysis is not required. That means that neither e-fuels with their potential nor CO_2 from electrical power production or CO_2 emissions from manufacturing processes are considered. In case the assumption of tailpipe CO_2 emission stays also in the future, the combustion engine will be forced out of the market also for electrified powertrains.
Seeing electrified powertrains as a chance, at least for an interim period, until the CO_2 emissions from electrical power production has been dropped significantly, will offer additional chances.
Up to today, beside in serial hybrids, the combustion engine of plug-in hybrids is not optimized or even designed for the use in a hybrid vehicle. For example, in a hybrid vehicle most of the drivers dynamic driving demands can be fulfilled with the motor, while the combustion engine is mainly used for the “constant” power need with much lower engine dynamic. Taking this into account specially designed engines will be able to run with increased efficiencies and thus lower fuel consumption and CO_2 emissions [1, 2].
Still the need of having “Zero Impact” emissions from the combustion engine remains a challenge.

Kurzfassung

Die neue Pkw-Emissionsgesetzgebung für Europa (EU7), Kalifornien (Advanced Clean Car 2) und China (China 7) wird höchstwahrscheinlich im Zeitrahmen zwischen 2025 und 2027 eingeführt werden. Leider wurden bis heute (Februar 2022) keine "offiziellen Entwürfe" veröffentlicht. Nach aktueller Information soll der EU7-Kommissionsvorschlag im Juli 2022 veröffentlicht werden. Zusätzlich zu dieser sehr späten Ankündigung macht es die politisch gewollte und geförderte Einführung von elektrifizierten und batterieelektrischen Fahrzeugen schwierig vorherzusagen, welche Antriebskonzepte in Zukunft benötigt werden. Verschärft wird diese Situation dadurch, dass die absoluten Marktzahlen für Verbrennungsmotoren heute in den verschiedenen Regionen der Welt unvorhersehbar oder zumindest nicht planbar sind.

Basierend auf den bisher veröffentlichten Informationen und Studien zu einer möglichen EU7-Gesetzgebung kann davon ausgegangen werden, dass aufgrund einer verkürzten Fahrlänge für reale Fahremissionsprüfungen (RDE) und auch aufgrund niedrigerer Umgebungsprüftemperaturen wie -7°C, im Vergleich zu heute, der Kaltstart noch anspruchsvoller und dass innerhalb weniger Sekunden Katalysator Light-Off benötigt wird.

Auch für elektrifizierte Antriebsstränge, die rein elektrisch eine Fahrt beginnen, könnten sogenannte schnelle Beschleunigungen zum anspruchsvollsten Betriebsmodus werden. Basierend auf den heutigen Abgassystemlayouts ist das Katalysatorsystem bei solchen Betriebsbedingungen immer noch kalt. Solch rasche Beschleunigungen, bedeuten einen hochdynamischen Motorhochlauf auf hohe Drehzahlen und Drehmomente. Um die Abgasemissionen in diesem Fall umsetzen zu können ist eine Vorwärmung des Katalysatorsystems erforderlich.

Auch CO_2 ist nach wie vor der entscheidende Faktor für die Wahl des zukünftigen Antriebsstrangtyp. Bis heute wird CO_2 aus dem Verkehr noch als reine Auspuffemissionen (Tank-to-Wheel) definiert. Eine Lebenszyklusanalyse ist nicht erforderlich. Das bedeutet, dass weder E-Fuels mit ihrem Potenzial noch CO_2 aus der Stromerzeugung oder CO_2-Emissionen aus Herstellungsprozessen berücksichtigt werden. Sollte die Annahme des reinen Fahrzeug- CO_2-Ausstoßes auch in Zukunft bestehen bleiben, wird der Verbrennungsmotor, auch als Teil der elektrifizierten Antriebe, aus dem Markt gedrängt. Es ist sicherlich sinnvoller elektrifizierten Antriebe, zumindest für eine Übergangszeit, als Chance zu sehen, bis die CO_2-Emissionen aus der Stromerzeugung deutlich gesunken sind.

Bis heute ist der Verbrennungsmotor von Plug-in Hybriden, außer bei seriellen Hybriden, nicht für den Einsatz in einem Hybridfahrzeug optimiert oder gar entwickelt.

So können beispielsweise in einem Hybridfahrzeug die meisten fahrdynamischen Anforderungen des Fahrers mit dem E-Motor erfüllt werden, während der Verbrennungsmotor hauptsächlich für den "konstanten" Leistungsbedarf mit deutlich geringerer Motordynamik genutzt wird. Unter Berücksichtigung dessen werden speziell konstruierte Motoren in der Lage sein, mit erhöhten Wirkungsgraden den Kraftstoffverbrauch und damit die CO_2-Emissionen zu verringern. [1,2]

Die Notwendigkeit, "Zero Impact" -Emissionen aus dem Verbrennungsmotor, bleibt eine Herausforderung.

1. Cold Start Emissions - Challenge and Opportunities

As already mentioned, the cold start emissions will be "The" challenge for electrified powertrains.
To develop targeted technical solutions, it is needed to differentiate between the different types of hybrids:

Mild Hybrid (definition used for this study):

- Electrical motor: 20KW
- Batterie Size: 1 kWh
- Voltage: 48V

  - Operation modes: Slow, short term electrical driving possible. Combustion engine is used with full dynamic like a "normal" ICE powertrain. Combustion engine has to be prepared to start immediately with start of the trip.

  - Catalyst Heating: 3-5 seconds preheating and heating after engine cranking possible. Maximum heating energy 6kW.

Plug-in Hybrid (definition used for this study):

- Electrical motor: 65KW
- Batterie Size: 10 kWh
- Voltage: 400V

  - Operation modes: Electrical driving possible for a driving distance of at least 60km. Electrical driving up to 130km/h. Combustion engine is used with reduced dynamic.

  - Catalyst Heating: a) 1-3 minutes preheating and heating after engine cranking possible. OEM decision to block engine cranking for the preheating time.

    b) If engine cranking is allowed with start of the trip: 3-5 seconds preheating and heating after engine cranking. Maximum heating energy 6kW.

Serial Hybrid (definition used for this study):

- Electrical motor: 140KW
- Batterie Size: 2 kWh
- Voltage: 400V

- Operation modes: 100% electrical driving. Combustion engine is used in steady state load points. In addition, catalyst cold start operation possible.

- Catalyst Heating: 1-3 minutes preheating and heating after engine cranking possible. Maximum heating energy 6kW.

Based on the above definitions it becomes apparent that depending on the possible start of the combustion engine after beginning of the trip, the plug-in hybrid either can use a catalyst preheating strategy like a serial hybrid or like a mild hybrid.

Figure 1 shows the principle heating strategies and engine dynamic for different type of hybrids and drivers.

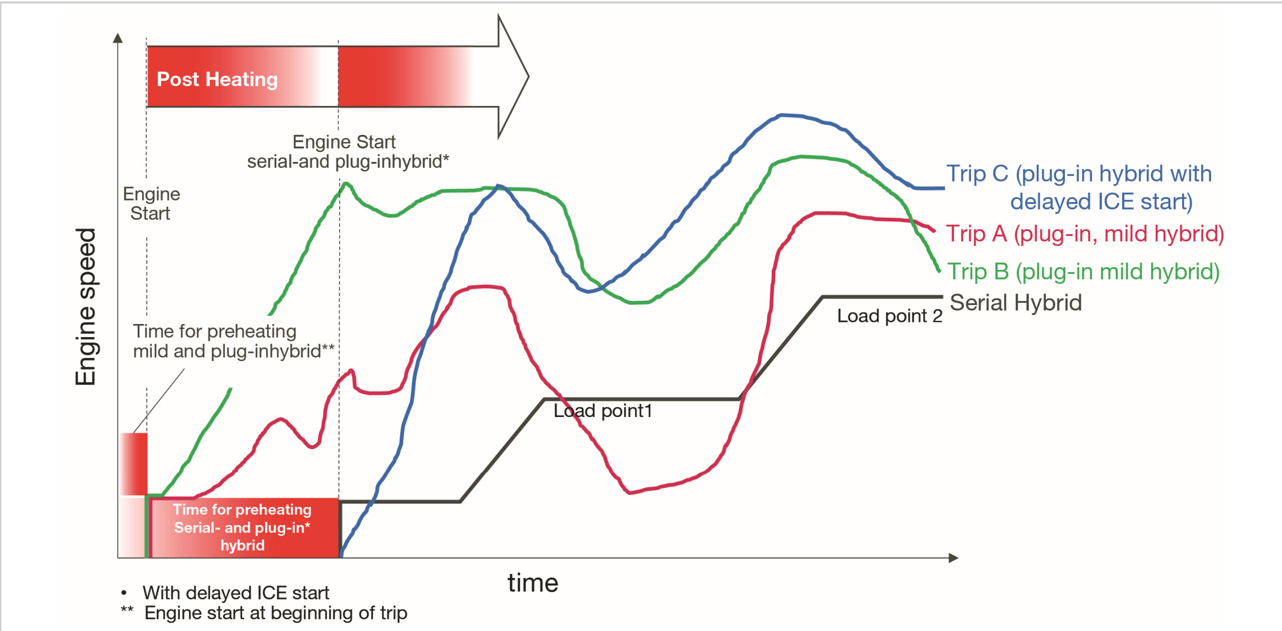

Figure 1: Principle heating strategies depending on type of hybrid, ICE start strategy and driving behavior

The black line represents the engine speed of a serial hybrid using 2 different load points for charging the battery. For this kind of hybrid, a long preheating time is possible was well as a defined engine cold start strategy because the engine is 100% decoupled during this period from the driver's behavior. In addition, the ramp-up to a “charging” load point can be smooth.
The green and red line represents the speed of 2 real driving events for a mild hybrid and a plug-in hybrid in case the engine is “allowed” to start with beginning of the trip. In this case just a short preheating time of 3-5 seconds is possible beside the post heating after engine cranking. The blue line represents a plug-in hybrid with delayed engine start. In this case, similar to the serial hybrid a long preheating time is possible after the beginning of the trip. In opposite to the serial hybrid the dynamic of the combustion engine is depending on the driver`s behavior.

In order to transfer this principle driving behaviors, for this study, a specific dynamic cycle consisting out of 2 times the CARB rapid acceleration cycle 6 (ACC6) [3] followed by an RDE aggressive was defined with a total trip length of 16km. For the serial hybrid 2 constant load point were defined with an engine speed of 2000 rpm / 175 Nm and 4000 rpm / 220 Nm. In addition, the WLTP was used as reference. Figure 2 shows the velocity of the used test.

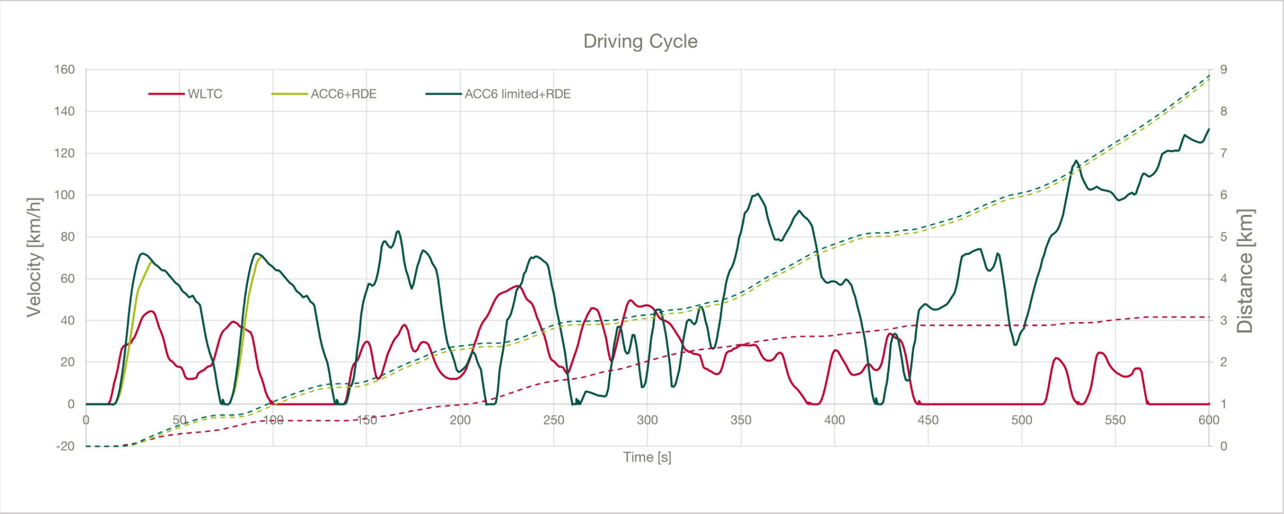

Figure 2a: First 600 seconds of the 2xACC6+RDE aggressive cycle with and without torque limitation and WLTP as reference (velocity)

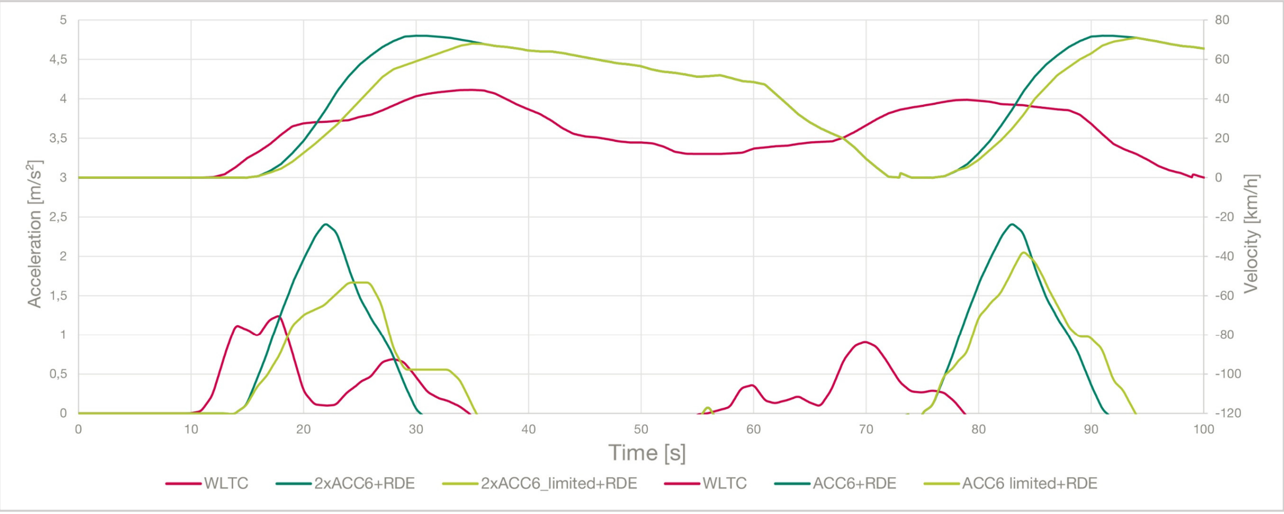

Figure 2b: First 100 seconds of the 2xACC6+RDE aggressive cycle with and without torque limitation and WLTP as reference (velocity)

To see the influence of combustion engine torque reduction for the hybrid powertrains an additional cycle with a torque limitation of 100Nm in the 1st ACC6 acceleration period and 150Nm in the 2nd ACC6 acceleration period was created, called ACC6 limited

To examine the influence of the single parameters like:

- preheating time
- engine catalyst heating measures
- torque limitation
- low ambient temperature

different catalyst systems and catalyst heating modes were defined.

2. Influence of Operation Strategy on Driving Cycle Emissions

For the first part of the examination the CARB ACC6 was used in order to see the influence of engine catalyst heating measures, electrically heated catalyst [EmiCat] [4,5,6], preheating and idle time. The tests were done on a roller test bench with a 2l Mild hybrid Gasoline Demonstrator vehicle. The heating power of the electrically heated catalyst was 4kW. The emissions were measured 60s after engine cranking in order to see the direct impact on cold start tailpipe emissions. The test was done at 20°C. The results are shown in figure 3.

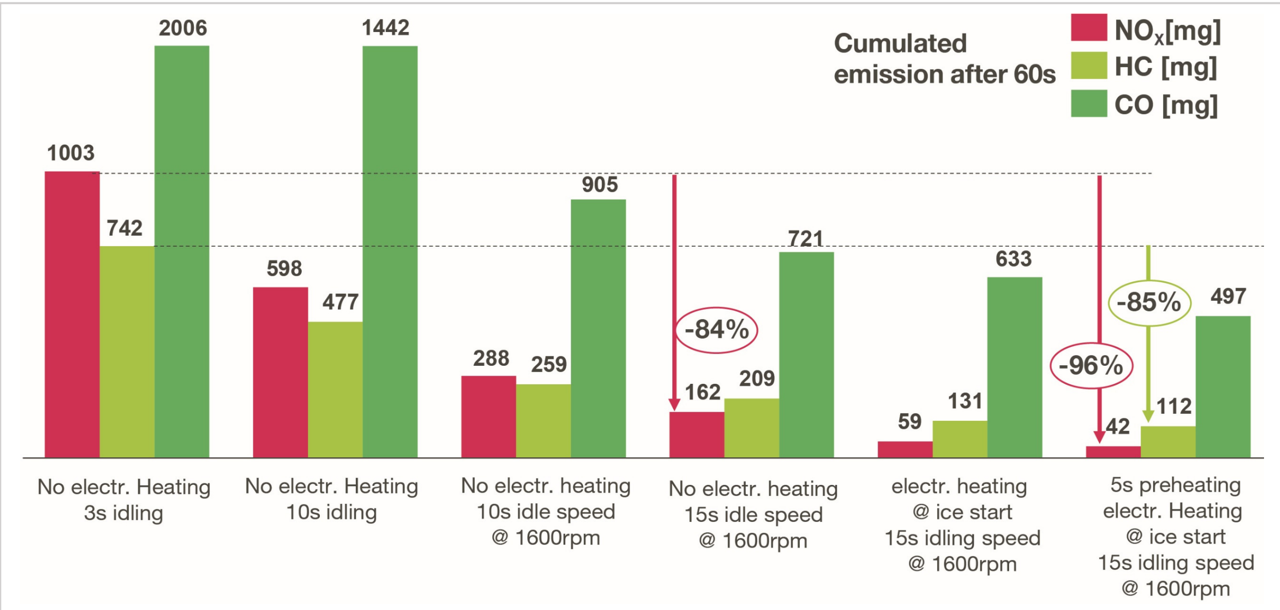

Figure 3: Influence of idling time, speed and heating on emissions after 60s in the ACC6 cycle

By extending the idle time from 3 to 10sec without heating NO_X-Emissions could be reduced by 40%. Increasing the idle speed (strong engine catalyst heating measures) a gain in NO_X reduction of 71% and with longer idle time of 15 seconds of 84% could be found.
Applying an electrical heated catalyst which operates pre and post ICE start, a total reduction of 96% in NO_X-tailpipe emissions could be found. The heating itself gave a NO_X-reduction of 74% compared to the non-electrically heated test. Also, the HC-tailpipe emissions were reduced by 85%.

Using the significant number of tests done, an approximation about the catalyst volume needed to be above light off temperature was done. Figure 4 shows the tailpipe emissions until catalyst light-off versus the percentage of catalyst volume above light-off temperature. Based on this study at least 30-40% of the catalyst volume should be preheated.

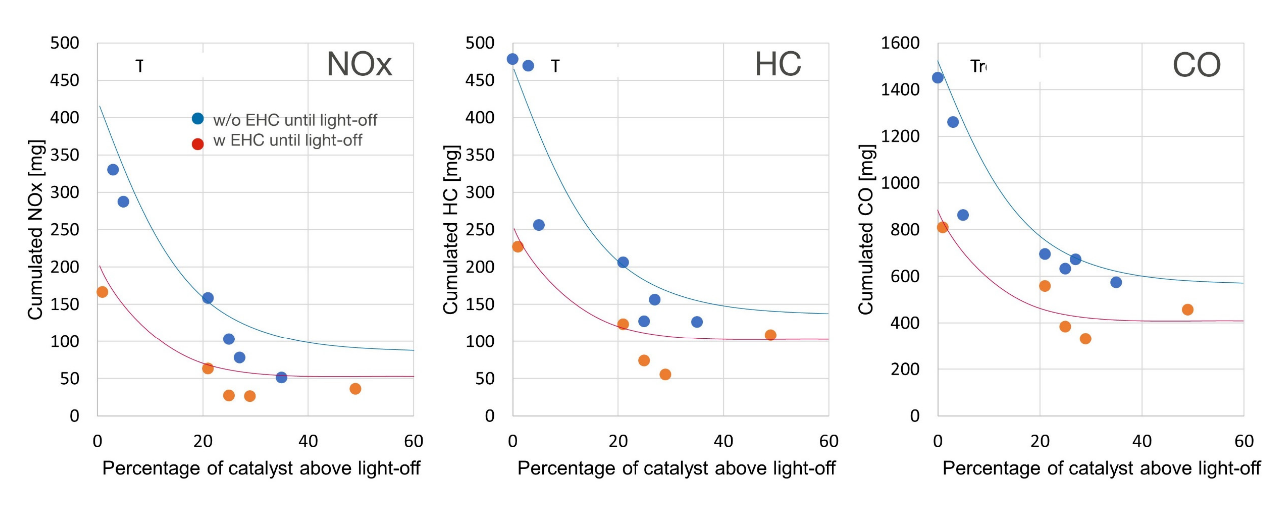

Figure 4: Required catalyst volume above light off for optimized tail pipe emissions on ACC6 cycle

3. Influence of Ambient Temperature on Driving Cycle Emissions

The second part of emission measurements were done on a high dynamic engine test bench. There it was also possible to run the cycle with torque limitation and -7°C tests.
The test cycles WLTP, 2x time ACC6 followed by the RDE aggressive test with and without torque limitation, as shown in figure 2, was used. Test temperatures of 20°C and -7°C were chosen.
For comparison of the different driving cycles tail pipe emissions after 60s of driving were investigated whereas the amount of accumulated emissions of the WLTC @20°C at 60s were taken as reference. Driving started at WLTC after 11sec, at 2xACC6 at 15sec of idling.

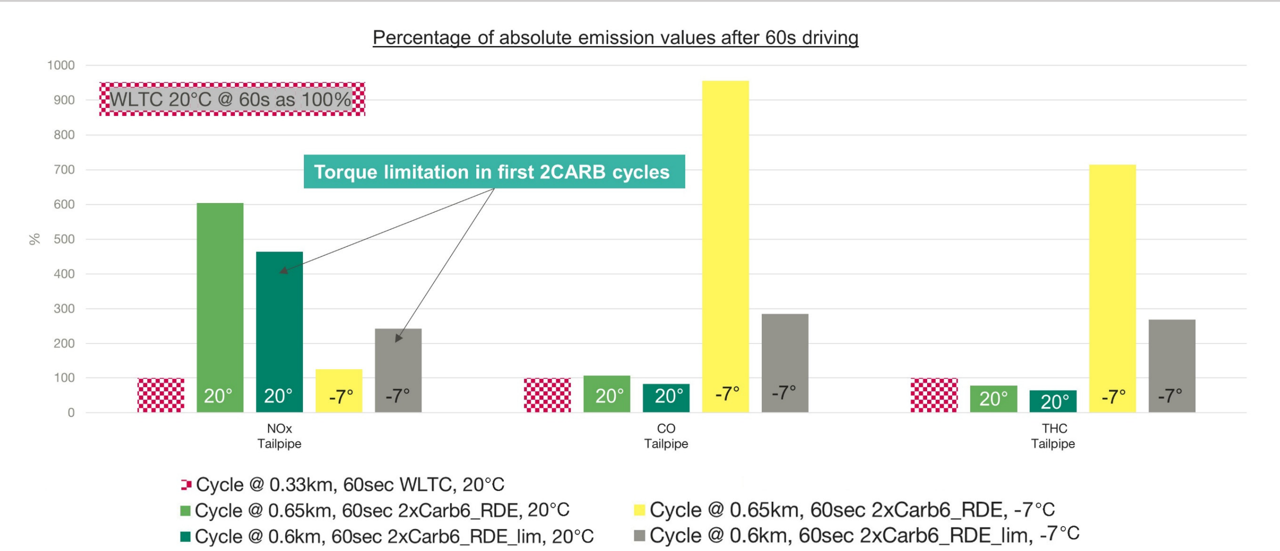

Figure 5: Tailpipe emissions after 60s as function of torque limitation and ambient temperature; reference WLTC after 60s at 20°C

In the examined time period of 60sec the torque limitation just influenced the first acceleration in the ACC6. As a result a reduction in all 3 emission components NO_X /CO/HC of 23/20/18% at 20°C was achieved by the torque limitation. Looking at the -7°C values the reduction in CO and THC is even larger 70/62%.

4. Catalyst System Layout for „Hybrid Powertrain Catalyst“ Testing

4.1 Secondary air for preheating and flow distribution

Based on the above results it becomes obvious that the focus has to be on the first seconds after engine cranking. In order to get close to “near zero emissions”, a preheating of the exhaust system will be necessary. To transfer the heat from the heater through the complete catalyst system a secondary air flow is needed and has to be implemented. Having a close coupled catalyst, the space to distribute the secondary air is limited and needs special efforts to guarantee a uniform flow distribution.
For electrical heaters a uniform flow distribution is a must, because the differences in flow speed along the cross section have a direct impact on the heater temperature and of cause also on the temperature distribution in the catalyst system behind the heater.
Usually the so called Uniformity Index (UI) is used to describe the quality of the flow distribution in exhaust systems, but in case of heated systems this index does not help, because it doesn´t give an information about the range of the flow speed. For example, even a good flow distribution with a uniformity index of 0,945 still can have flow speed differences of a factor 3. For active heating that means also a factor 3 difference in temperature increase along the cross section (Figure 6).
By that for electrical heating devices the flow speed distribution is the relevant factor!

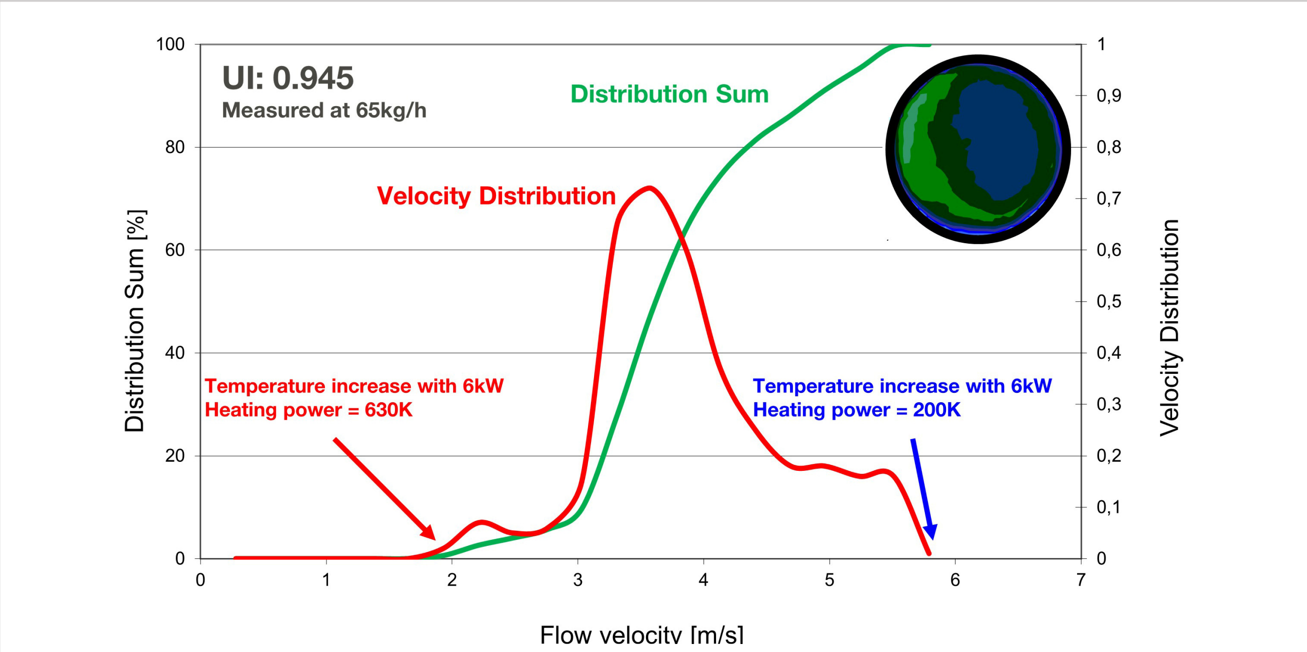

Figure 6: Uniformity Index UI versus flow speed distribution

For preheating with secondary air the design of the air injection and air nozzle is important for the flow distribution. Several designs were tested in order to get the best result. Figure 7 shows the design and the flow distribution of a secondary air mass flow of 30kg/h for the close coupled catalyst system used in this test program.

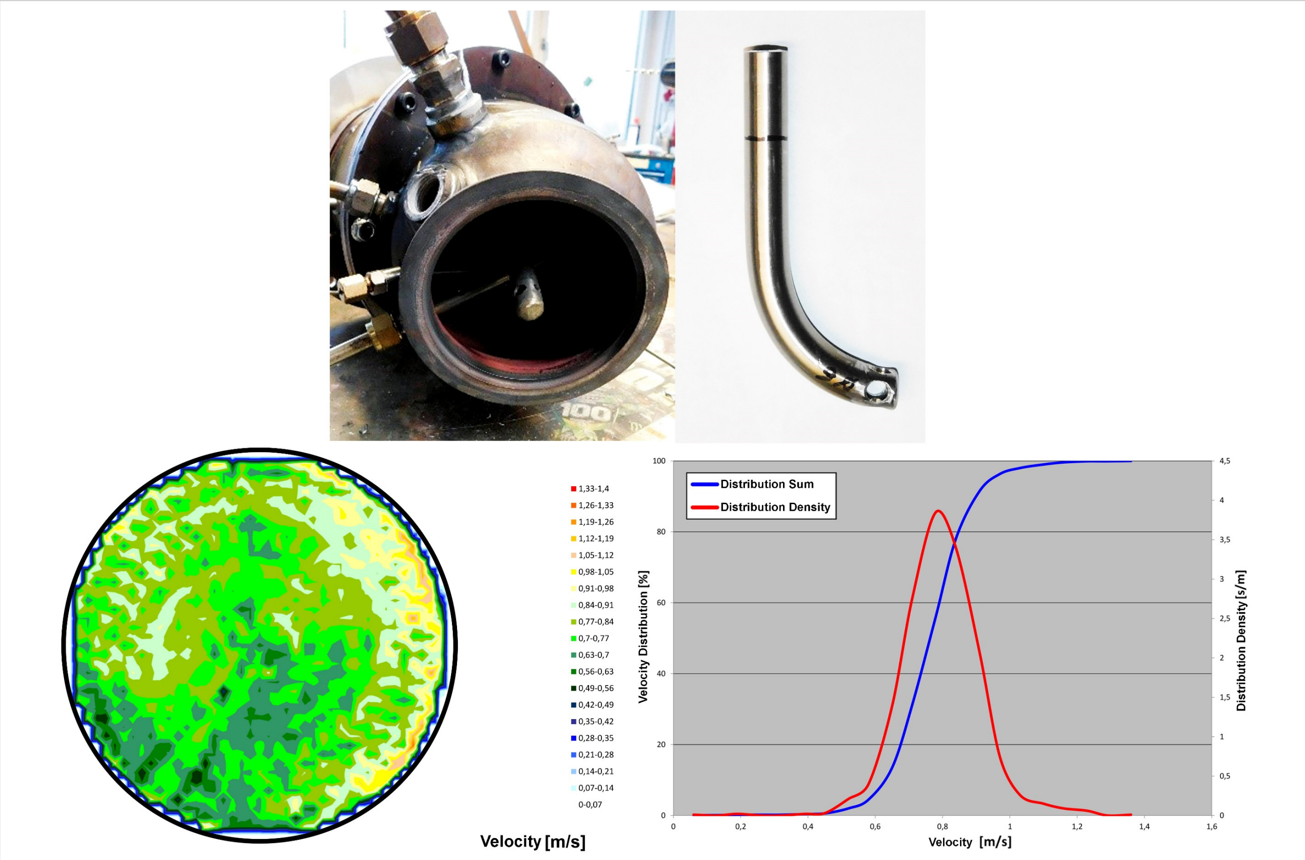

Figure 7: Secondary air injection and resulting flow distribution with 30kg/h, measured after the EHC

The result still shows some areas for improvement to gain uniform heat distribution and to avoid areas with low flow which may affect the durability or catalyst light-off. For the following tests this design of air injection was used. Another possibility is to introduce the secondary air in front of the turbocharger which was not examined in this test program, but shows in other tests a good potential. Emission tests on the engine bench were done with a secondary air mass-flow of 78kg/h.

4.2 Test set-up

The catalyst system consists out of a close coupled electrically heated catalyst as 1st Three-Way-Catalyst (TWC) and a second TWC with high PGM loading. As an option, it is also possible, to install a HC-Trap in front of the Electrically Heated Catalyst. Specially for the serial hybrid that is a possible solution, because the maximum exhaust gas temperature of such applications is within the durability temperature range for modern HC-Trap coatings.
An additional TWC was installed in the underfloor position for simulation of the catalytic activity of a coated gasoline particulate filter.
Tests were carried out on an engine bench with a 1,5l, 3-cylinder Turbo engine with EU6c calibration which was not modified. Figure 8 shows a sketch of the exhaust systems.

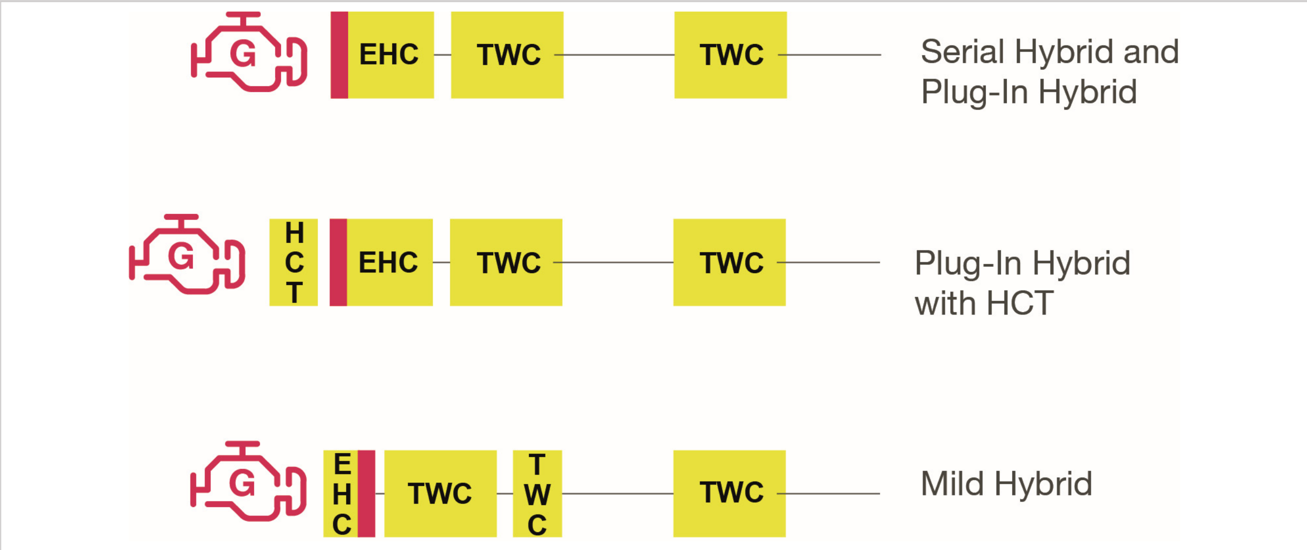

Figure 8: Tested catalyst system

Different preheating strategies were defined to match the different demands of the different powertrains, described in the beginning in figure 1. For the mild hybrid the electrically heated catalyst was turned around to have the heating disk on the outlet side of the first TWC.

Table 1: Heating strategies

	No heating	G EHC TWC	G EHC TWC
Mild Hybrid = Plug in hybrid with very short preheating	15s idle 2x Carb6+RDE agg		Preheating: 5s, EHC6kW, 0kg/h AAI Postheating: tbd
Plug in hybrid with long preheating Serial Hybrid	15s idle 2x Carb6+RDE agg	Preheating: 150s, EHC 6kW, 78kg/h AAI Postheating t~20s*	
	15s idle LP1 (t=15s): 2000rpm, 175 Nm LP2 (t=300s): 4000rpm, 220 Nm	Preheating: 150s, EHC 6kW, 78kg/h AAI Postheating t~20s*	

For a catalyst system with air injection and possible longer preheating times (serial hybrid) it is beneficial to have the EHC as first brick. For a system without secondary air and only short possible preheating times (mild hybrid) it is useful to place the EHC as second brick (or EHC heated disc on gas outlet side of first catalyst). In this case short after engine cranking 2 light-off areas occur. One at the gas inlet side due to engine catalyst heating measures and a second at and behind the coated heating disk in the middle of the catalyst. By that the catalyst volume above light of temperature gets larger during cold start and the total efficiency is increased.
In the next chapter a comparison is shown between non heated catalyst systems of the 3 powertrains as well as the benefit of pre- and post-heating.
To compare the serial hybrid emissions with the plug-in hybrid a comparison of the break power was done. For the serial hybrid an additional efficiency factor of 0.9 was added [7] for possible losses during energy generation and energy storage. Means the accumulated

break power at the constant load points was multiplied with a factor of 1.1 and was compared to the emissions of the defined test cycles at 8km
The 2 times ACC 6 followed by the RDE aggressive has a break work of 1,75 kWh after 8km and 3,41 kWh after 16km.

4.3 Test Results

4.3.1 Preheating

As already mentioned, to get a “hot” catalyst system, at least 30-40% of the catalyst volume has to be above light-off temperature to convert the emissions in the very first seconds. For the first testing it was decided to heat-up the whole catalyst system to an average temperature of 500°C to see the utmost potential. The catalyst system used with a volume of 3,1l has a thermal mass of appr. 1600J/k. The test system is equipped with flanges between the catalyst bricks which will increase the temperature loss. For that reason, 150 seconds of preheating time was used for the first tests. For plug-in hybrids in which the ICE start is “per definition” delayed and for serial hybrids for which each trip starts with electric driving it is possible to use longer preheating times. To avoid any temperature-drop after engine cranking a short post heating period was also installed.
Below figure shows the gas temperatures after the different catalysts in the test system during pre and post heating in the 2xACC6+RDE cycle. The volume of each brick represents approx. 1l.

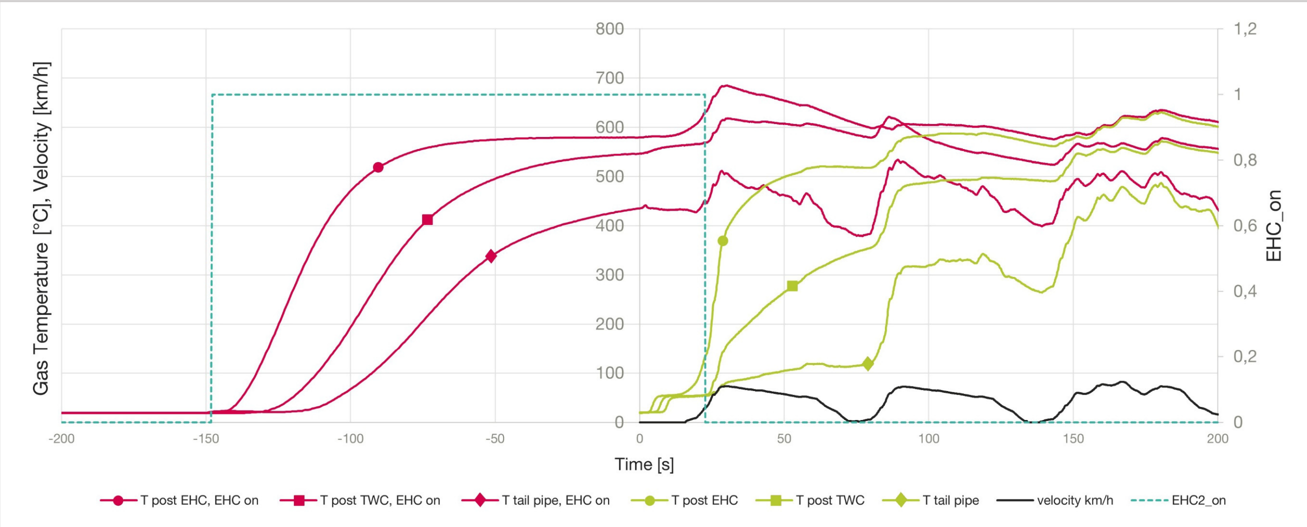

Figure 9: Gas temperature of the catalyst system w/wo preheating on 2xACC6+RDE

After 150s of preheating the gas thermocouple after the whole catalyst system T3 records a temperature of 430°C. That suggests that the total catalyst system is above light-off temperature which is, generally speaking, arround 350°C for aged catalyst. It also can be recognized that the temperature behind the 2nd brick (total catalyst volume ~ 2l) is reaching 350°C after 60s of preheating. Looking at the temperatures of the system without preheating, 350°C is reached behind the total catalyst system at 146s.
The preheated catalyst system enables the conversion already in the very first seconds after engine cranking, independent on the driving cycle.

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Using the same preheating strategy on the serial hybrid operation mode similar temperatures can be achieved as shown in figure 10. The difference occurs after engine start, as the serial hybrid operation mode allows for a special engine cold start strategy and a smooth acceleration to the first constant load point.

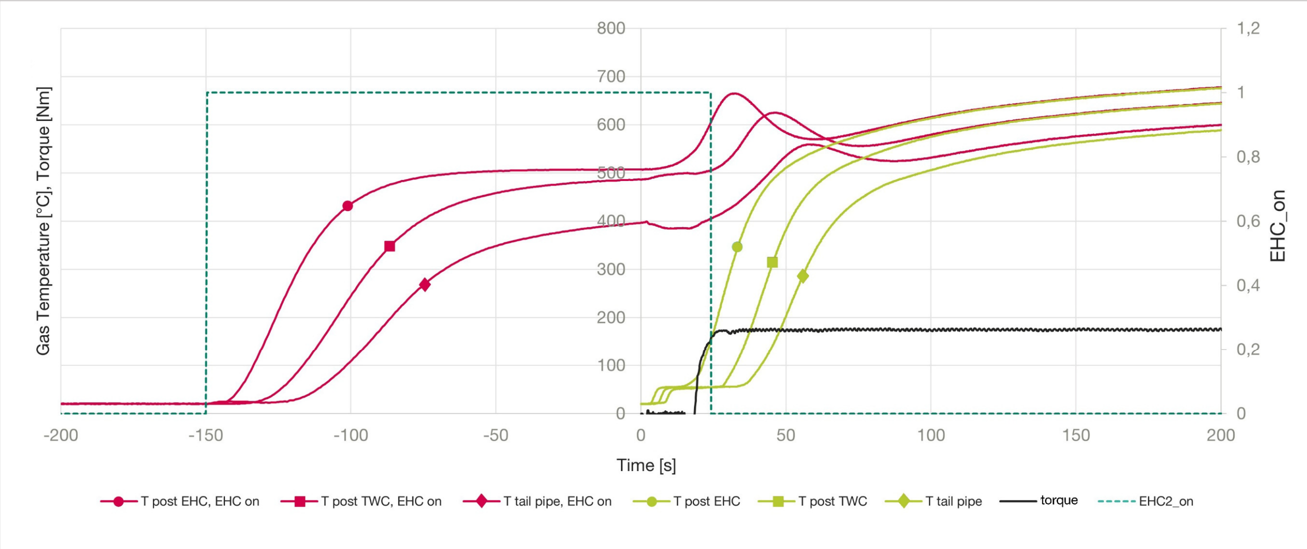

Figure 10: Gas temperature of the catalyst system w/wo preheating on serial hybrid ramp-up

4.3.2 Emission Results

Emission tests were done in the 2x ACC6 + RDE aggressive cycle to simulate a mild hybrid and plug-in hybrid .For the serial hybrid after a cold idling phase a 2 load point strategy was tested.
All tests were done on a dynamic engine test bench which is located in a climate chamber:

- For serial hybrid: 150s preheating with SAI and 20s postheating at 20°C
- For plug-in Hybrid: 150s preheating with SAI and 20s postheating at 20°C
- For mild hybrid: Preheating time of 5 seconds and a post heating time of 30s at 20°C

All emission examinations were done after a trip length of 8km. In addition to compare the emissions from the plug-in hybrid and the serial hybrid the emission values were calculated in g/kWh using the power generation efficiency of 0,9 for the serial hybrid. In the first approach a comparison was done for the plug-in hybrid with delayed ICE start. Figure 11 shows the relative emissions after 8km of the test cycle with and without preheating.

As mentioned before, without preheating, more than 90% of the HC-emissions and about 80% of the NO_X-emissions are emitted during cold start within the first 30 seconds of the test.
Preheating the catalyst system shows a potential to reduce the HC-emissions by more than 90% and the NOx-emissions by 65%. Analysing the accumulated emissions of the preheated tests it can be recognized that the first acceleration after idling still creates 50% of the HC tailpipe emissions. Taking a look into details of the test data it could be recognized that lambda control might be the reason. Of cause it is very difficult to have a tight lambda

control with a cold engine and a harsh acceleration so that additional measures like HC-trap functions might be needed. The same fits for the NO_X-emissions for the idle phase.

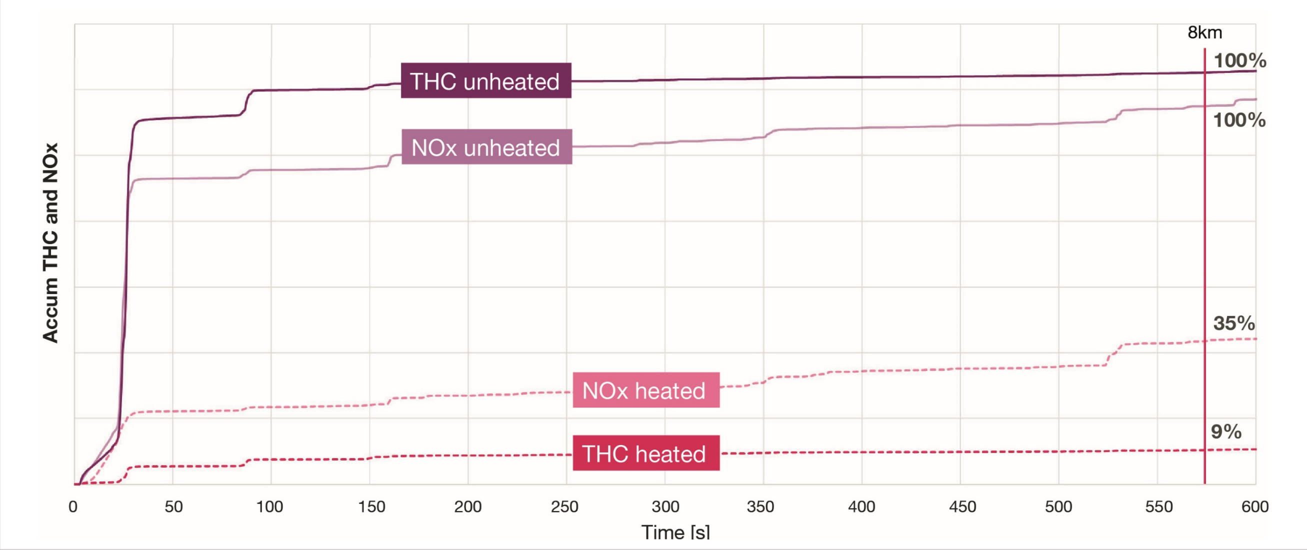

Figure 11: Accumulated HC- and NO_X-tailpipe emissions for 8km (577s) during 2xACC6 + RDE test with and without preheating

For plug-in hybrids an idle time of 15s as used for the ACC6 rapid acceleration is in reality not practicable. For that reason, an additional test was done with 10s and 3s idling time. Figure 12 shows the HC-, CO- and NO_X-tailpipe emissions corresponding 8km for the plug-in powertrain with delayed engine cranking and this preheating.

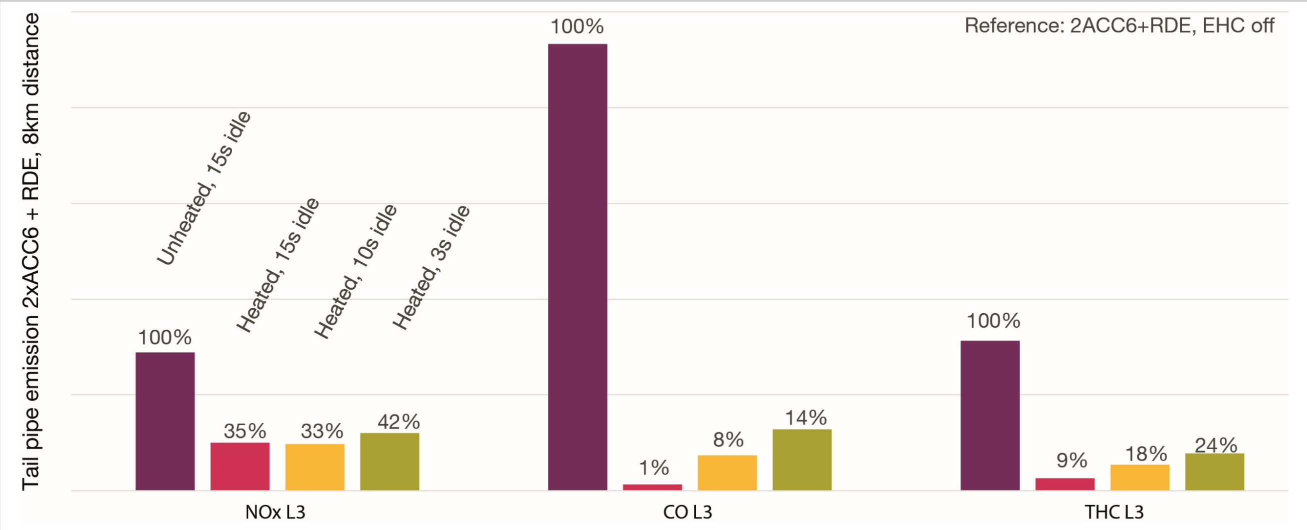

Figure 12: HC-, CO- and NO_X-tailpipe emissions for *8km (577s) during 2xACC6 + RDE test; with and without preheating*

The unheated test with 15s of idling was used as reference. For NO_X the impact of idle time is only minor, achieving instead of 65% improvement 58%. For CO and HC the influence is larger; CO drops from 99% down to 86% and for HC 9% down to 24% of the reference emission level. Still the results show that also with very short idling times a preheated catalyst system can give a significant advantage compared to the todays Euro 6d levels.

By that preheating is a good solution for real life emissions of plug-in hybrids even with a “aggressive” driving style.
In the next step the serial powertrain was tested. It has to be mentioned that all powertrains were simulated on the dynamic engine test bench by using the same test engine without any change in calibration. The mechanical load of the generator in the serial hybrid powertrain was simulated with the engine break of the engine test bench as done for the other test cycles.
To get a first impression the serial hybrid powertrain was also tested with a non-preheated and a preheated catalyst system. The total engine on-time to produce the energy for the 8km 2xACC6 + RDE trip was 213 seconds taking again a generator efficiency of 0,9 into account. Figure 13 shows the engine out emissions during the different test cycles.

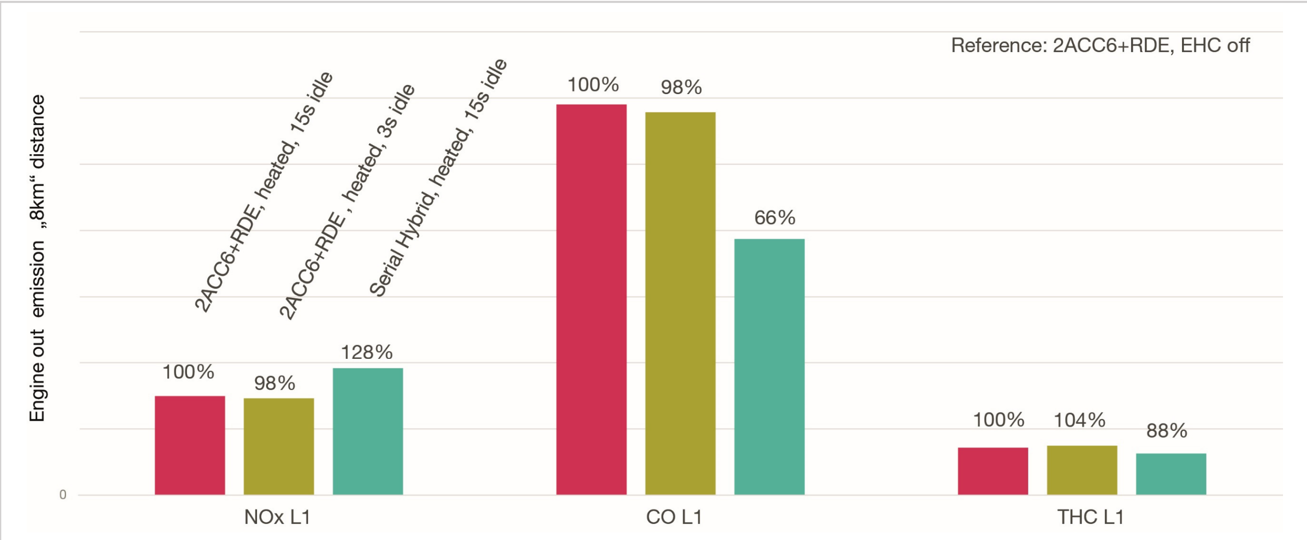

Figure 13: Engine out of the 2xACC6+RDE with 3 and 15 seconds idle for 577s (8km) and for the serial hybrid for 213s (8km)

As can be expected the idle time difference has only a minor influence on engine out emissions. Before analysing the serial hybrid results, the following has to be taken into account.
As said before for all tests the same engine was used and the engine is not designed for the need of serial hybrids. By that the 2 load points were chosen based on high fuel efficiency load point of the given engine map.
As a result the engine warm-up happens faster for the serial hybrid application which ends in higher NO_X engine out, but smaller CO and HC engine out emissions.
Next emission tests were done for the serial hybrid powertrain using the same catalyst system as for the plug-in hybrid tests with and without preheating. Figure 14 shows the emission results after an engine on time of 213s which is equivalent to a driving distance of 8km. After engine cranking the engine was running 15s at idling and accelerated within 5s to the first load point. The tests were done with a preheating of 150s and without preheating.
As explained above the comparison of the emission is based on equal break work. The following figure represents the tailpipe emissions of NO_X/CO/THC at 8km driving at 20°C w/wo EHC on. As reference the emission results of the plug-in hybrid tests with 15s of preheating were taken.
Without preheating the tailpipe emissions of the serial hybrid test were on a similar level compared to the plug-in hybrid without heating. For the preheated version the NO_X- and HC-emissions could be reduced to even lower levels compared to the plug-in hybrid solution.

The lower CO reduction is most likely based on the lambda control because, as mentioned before, that engine calibration was not adapted at all for these tests.
In addition, the fuel consumptions were compared. For the plug-in hybrid version, the fuel consumption was 0,72l for 8km driving. It is important to say that 100% of the work needed to run the cycle was delivered from the combustion engine. Comparing that to the serial hybrid, for which also the work was delivered 100% from the combustion engine, incl. a loss of 10% for electrical power generation a fuel consumption of 0,66l was measured. This comparison shows the benefit of about 8% based on running the combustion engine in load points with high thermal efficiency.
A comparison of emission values in g/km is of cause quite difficult for analysing catalyst systems for different powertrains on an engine test bench. For that reason, similar to heavy duty applications an examination of the tailpipe emissions in g/kWh was done.
As a result, figure 15 shows the comparison of the tailpipe emissions of the plug-in and serial hybrid with and without preheating in g/kWh.

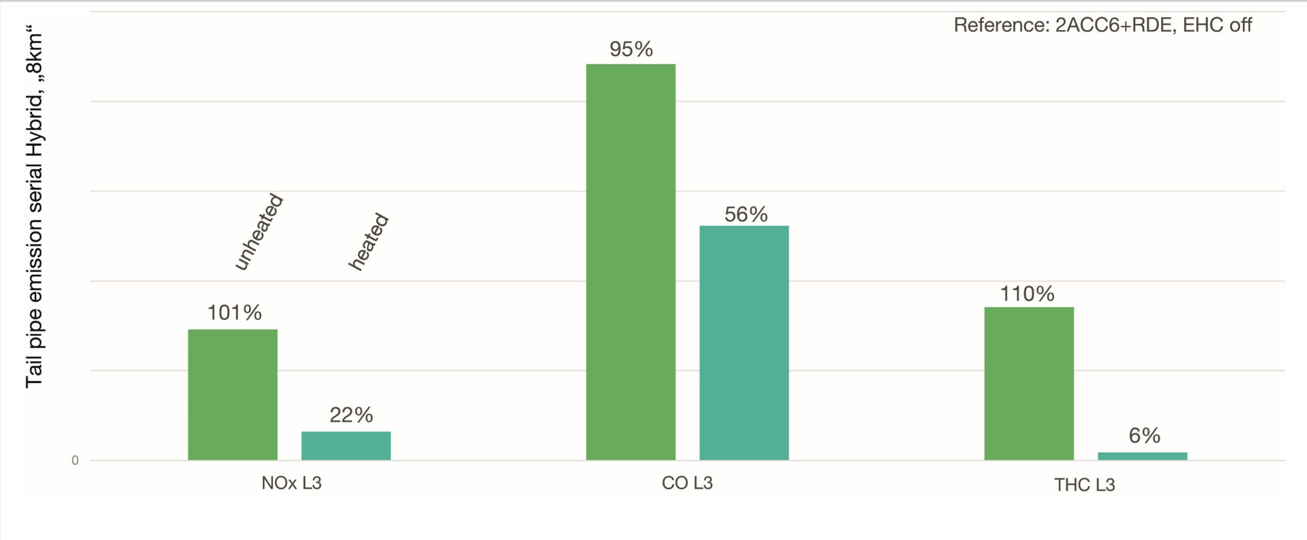

Figure 14: *HC-, CO- and NO_X-tailpipe emissions for 8km (213s) for the serial hybrid test cycle; with and without preheating*

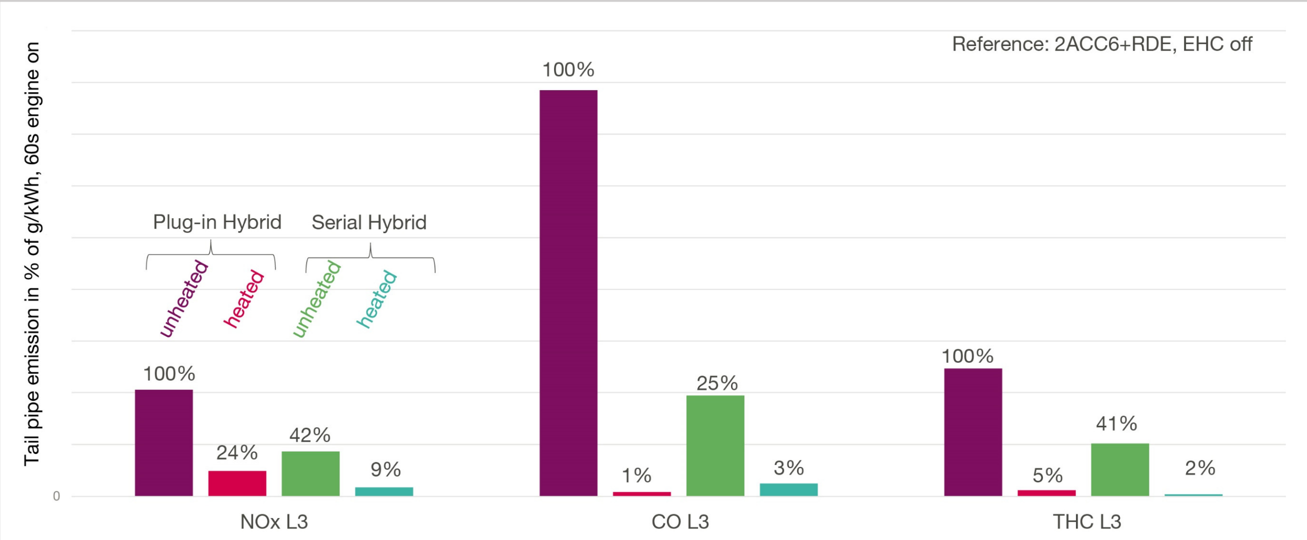

Figure 15: *HC-, CO- and NO_X-tailpipe emissions in g/kWh for plug-in and serial hybrid with and without preheating at 60s engine on*

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Taking the plug-in hybrid unheated as reference, it can be recognized that the tailpipe emission levels, both unheated and heated in g/kWh are significantly lower for the serial hybrid-

5. Summary and Outlook

At the time of writing the paper not all tests were finished but will be published during the presentation of the Vienna Motorensymposium.
To summarize, it is fair to say that a preheated catalyst system is able to reduce the tailpipe emissions of plug-in and serial powertrains to very low levels. The used preheating time is of cause very long but was chosen to see in the first step the potential.
Out of the temperature measurements during preheating at different positions within the catalyst system it can be assumed that preheating times of 60s would be sufficient. In combination with very low thermal mass substrates and improved insulation a further reduction of preheating time will be possible. Emission tests with these configurations will be done and presented.
Further work will also examine emissions at -7°C for all powertrains.
Based on the results of the preheated catalyst systems it can be recognized that the use of passive HC- and for the serial hybrid also NOx-adsorbers would be helpful to get a more robust solution, minimizing the impact of lambda control for the first seconds after engine cranking.
Tests with adsorbers done in the past showed, that the adsorber will have a quite small volume of less than 0,4l being installed in front of the heated catalyst.
The results in this paper proofs that the combustion engine with a heated catalyst installed and the ability of preheating has the ability to achieve “near zero impact” emission levels.

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