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Analysis of the EU7 Emission Limits; Exhaust System Solutions to Meet the Requirements

Analyse der EU7 Emissionsgrenzwerte; Abgassystem-Lösungen zur Erfüllung der Anforderungen

Abstract

Parallel to the discussion regarding the future of internal combustion engines in Europe, the EU Commission proposal on EU7/VII passenger car and truck emissions legislation was announced on 10th of November 2022.
In addition to the limit values, the definition of "normal" and "extended" driving conditions will be of significant importance for the future catalytic converter system design. This includes, apart from the minimum driving distance for real driving profiles, the length of the idling phase before the first drive off, the driving dynamics and thus the allowed average engine power during cold start. In addition, in hybrid vehicles, purely electric driving up to the motorway entrance with subsequent rapid start-up of the combustion engine on the acceleration lane is conceivable. Accordingly, even an acceleration phase immediately after engine cranking without prior idle phase must be considered.
Superimposed with extended ambient conditions, such as a 0°C ambient temperature under "normal" driving conditions, this results in a completely new requirement profile for the powertrains and exhaust gas aftertreatment.
CARB and EPA are also considering so called "rapid acceleration cycles" and proposing to reduce the idle time in the American FTP test from 20 seconds down to 5 seconds.
On the basis of and compared to the published EU7 proposal, extensive tests were carried out. This includes both the predefined "normal" and "extended" driving conditions, driving without idle time (different average engine power during cold start), acceleration based on the rapid acceleration tests, with and without torque limitation as well as trailer operation on an air-conditioned engine test bench. The results are shown and discussed in relation to the legislative proposal and targeted catalyst systems are presented.

Kurzfassung

Parallel zur Diskussion um die Zukunft des Verbrennungsmotors in Europa wurde am 10. November 2022 der Vorschlag der EU-Kommission zur EU7/VII Gesetzgebung für Pkw- und Lkw-Emissionen bekannt gegeben.
Neben den Grenzwerten wird die Definition von "normalen" und "erweiterten" Fahrbedingungen für die zukünftige Auslegung von Katalysatorsystemen von großer Bedeutung sein. Dazu gehören neben der Mindestfahrstrecke für reale Fahrprofile die Länge der Leerlaufphase vor dem ersten Anfahren, die Fahrdynamik und damit die zulässige durchschnittliche Motorleistung beim Kaltstart. Zudem ist bei Hybridfahrzeugen ein rein elektrisches Fahren bis zur Autobahnauffahrt mit anschließendem Motorstart und schnellem Hochlauf des Verbrennungsmotors auf der Beschleunigungsspur denkbar, damit sogar eine Beschleunigungsphase unmittelbar nach dem Motorstart ohne vorherige Leerlaufphase.
Überlagert mit erweiterten Umgebungsbedingungen, wie z.B. einer Umgebungstemperatur von 0°C unter "normalen" Fahrbedingungen, ergibt sich ein völlig neues Anforderungsprofil an den Antriebsstrang und die Abgasnachbehandlung.
Auch CARRB und EPA erwägen sogenannte "schnelle Beschleunigungszyklen" und diskutieren, die Leerlaufzeit im amerikanischen FTP-Test von 20 Sekunden auf 8 oder sogar 5 Sekunden zu reduzieren.
Auf Basis und verglichen mit dem veröffentlichten EU7-Vorschlag wurden umfangreiche Tests durchgeführt. Dazu gehören sowohl die vordefinierten "normalen" als auch die "erweiterten" Fahrbedingungen, das Fahren ohne Leerlaufzeit (unterschiedliche durchschnittliche Motorleistung beim Kaltstart), die Beschleunigung auf Basis der „Schnellbeschleunigungstests“, mit und ohne Drehmomentbegrenzung sowie der

Anhängerbetrieb getestet auf dem klimatisierten Motorenprüfstand. Die Ergebnisse werden in Bezug auf den Legislativvorschlag gezeigt und diskutiert und verschiedene Katalysatorsysteme vorgestellt.

1. Introduction

After several postponements, the planned EU7-Limits (light and heavy-duty vehicles) and initial information on the planned boundary conditions were published in November 2022. The original assumption that the EU7 emission limits will follow the "medium zero pollution ambition" scenario developed in the EU7 Impact Assessment, was not confirmed. The present limit values correspond to the "Light Option" scenario [1] and are thus comparable to the EU 6e limit values for gasoline engines except for carbon monoxide emissions (CO). The particulate number limit now also includes the particulate size 10-22nm which was excluded in the past.

	EU6e Gasoline	Light Option[1]	Medium Option[1]	Stricter Option[1]	EU COM proposal EU7 COM(2022) 586	China6a 2020	China6b 2023
NOx	60 mg/km	60 mg/km	30 mg/km	20 mg/km	60 mg/km	60 mg/km	35 mg/km
PM	4.5 mg/km	4.5 mg/km	2 mg/km	2 mg/km	4.5 mg/km	4.5 mg/km	3 mg/km
PN	$6*10^{11}$ >23nm	$6*10^{11}$ >23nm	$1*10^{11}$ >10nm	$1*10^{11}$ >10nm	$6*10^{11}$ >10nm	$6*10^{11}$ >23nm	$6*10^{11}$ >23nm
CO	1000 mg/km	500 mg/km	400 mg/km	400 mg/km	500 mg/km	700 mg/km	500 mg/km
THC	100 mg/km	100 mg/km			100 mg/km	100 mg/km	50 mg/km
NMHC	68 mg/km	68 mg/km			68 mg/km	68 mg/km	35 mg/km
NMOG			45 mg/km	25 mg/km			
NH3	-	-	10 mg/km	10 mg/km	20 mg/km	-	-
N_2O+CH4	-	-	45 mg/km	20 mg/km			
N_2O	-	-				20 mg/km	20 mg/km
HCHO			5 mg/km	5 mg/km			
RDE CF	NOx 1.1/ PN 1.34	4	2	3	1.0		2.1
Cold start	(16km) **				10km **		
Durability	160kkm	160kkm 8y	200kkm 10y	240kkm 15y	160kkm 8y 200kkm 10y *	160kkm	200kkm

[1]EC Proposal 27.09.2022
* Durability multiplier of 1.2 applicable between 160kkm and 200kkm
** EU7 Cold start budget [mg] =Distance x emission limit; EU6 minimum trip distance of urban phase RDE

Figure 1: EU7-Limit value proposal compared to Euro 6e and China limit values for gasoline engines

Compared to EU6e limit values for passenger cars, ammonia (NH_3) has been added, as well as particulates from brake and tire abrasion as well as durability requirements for batteries. New are also the "Boundary Conditions" under which an exhaust gas measurement can be carried out (Figure 2). In particular, the "Cold Start Budget" in which the absolute emissions during the first 10km were set. Also, the definition of a maximum wheel power relative to the engine power for the first two kilometers, has to be mentioned.

The "Boundary Conditions" distinguish between “normal” and “extended” driving conditions. For the "extended" driving conditions, 1.6 times the proposed limit values are allowed for the test [2]. Surprisingly, the launch date was set to 1. 7. 2025 for all vehicles.

	Normal	Extended
Ambient temperature	0° C to 35° C	-10 to 0 °C or 35 to 45 °C
Maximum altitude	700 m	700 m to 1800 m
Maximum speed	<145 km/h	145 km/h to 160 km/h
Towing or aerodynamic modifications	Not allowed	Allowed according to manufacturer specifications and up to the regulated speed
Auxiliaries	Possible as per normal use	-
Max. avg. wheel power during first 2 km after cold-start	<20% of max	>20% of max
Trip composition	Any	-
Min. mileage	10000 km	3000 to 10000 km

Figure 2: EU 7 conditions for testing compliance with exhaust limits

The exact test conditions and which tests will be judged as valid will be discussed in 2023 in the AGVES (Advisory Group on Vehicle Emission Standards) meetings. The first meeting took already place on 30.11. – 1.12.2022.

Considering the introduction of previous European emissions legislation and the normal procedure, it is unlikely that the final EU7 legislation will be adopted before the end of 2023. Assuming this, vehicle manufacturers and suppliers must start from assumptions for the final limits and test conditions in order to have any chance of completing the development of vehicles and powertrains for the launch date of 1. 7. 2025.

For example, today (January 2023) there is the statement that only one of the "Extended Driving Conditions" (Figure 2) is permissible - otherwise the test will not be evaluated [3]. This statement needs to be discussed, since driving e.g. at an altitude of over 700m at temperatures below 0°C would not be counted. However, these are quite normal conditions over longer periods of time in many European countries. Also, the combination of trailer operation and an average engine power over 20% in the first 2km would not be counted. This is very surprising, since trailer operation leads to a higher engine load, but the combination would currently be excluded.

The goal of EU7 was discussed in the past to equate the internal combustion engine with a zero-impact powertrain similar as the “stricter option” (Figure 1). By that EU7 limits would have been adopted in many areas of the world and would have guaranteed the export of European developments and technologies. With the “light option” limit values and “medium” boundary conditions [2] being discussed now, there is a high probability that the combustion engine will remain in the environmental political discussion and that other countries such as China will issue stricter limit values and take the lead in development. This at the end would lead to the scenario that also production of combustion engines for the future will not be done in Europe.

The political decision to ban the internal combustion engine from Europe via the 2035 CO_2 limits, based on the European Fit for 55 Package, may have been an ulterior motive in setting the EU 7 limits as proposed. However, the political idea that European suppliers will supply technology for combustion engines to other non-European countries through EU7 in the future is at least strongly doubtful.

What's next in Europe?

By 2025, a method for life cycle analysis in the automotive sector is to be developed. Presumably, corresponding analyses will be worked out in 2026. Whether the life cycle analysis will influence the revision of the CO_2 limits in 2026 is still unclear. But important is that such an analysis would end the political tank-to-wheel consideration of CO_2 emissions and thus also CO_2 emissions in battery production and electricity production to charge batteries in electric vehicles would be shown.
If, by that, "surprisingly" the result is that a battery-electric vehicle is not CO_2-free in the entire life cycle chain and also indirect via power generation (as politically defined today), it remains to be seen whether there will be a change of opinion regarding the use of synthetic fuels and the combustion engine as such for a longer transitional period.

Based on the present (January 2023) EU7 proposals and status of discussion, emission measurements were carried out with a gasoline engine on a dynamic engine test bench to determine how the boundary conditions influence the tailpipe emissions and which technologies and/or engine strategies are likely to be implemented.

2. Influencing factors and their significance

In the past, passenger car emission measurements were only carried out on chassis dynamometers running defined test cycles such as the NEDC or WLTC. In recent years, there has been a growing recognition that vehicles must comply with emission limits, regardless of driving style or environmental conditions. In so called RDE (Real Driving Emission) measurements, vehicles have also been measured outside the certification tests for several years. One of the ideas behind EU 7 was that there should be no restrictions any more for emission measurements, except for extreme boundary conditions (statistically not relevant) and misuse. For this reason, the term "any" was also used in the line “trip composition” (Figure 2). Of course, it is necessary to exclude misuse. A test with pure digital driving behavior (full throttle, idle, full throttle, idle, ...) is not normal driving and should be excluded. From the point of view of common sense, logical, but the difficulty is to exclude such driving behavior by boundary conditions and at the same time not to restrict normal use.
This raises the question, what is “normal use” that statistically occurs to a certain percentage and thus has an influence on emissions and the environment.
In 2018, Emitec presented at the 39th INTERNATIONAL VIENNA MOTOR SYMPOSIUM under the title " Procedure and design of exhaust systems to fulfill all emission limits during real driving conditions; „In Use Conformity " [3] an analyses of driving behavior. At that time, recordings from test vehicles were used in daily operation to detect and analyze critical driving conditions for exhaust aftertreatment. Figure 3 shows examples of records of daily journeys and Figure 4 the relevant driving conditions derived from them.

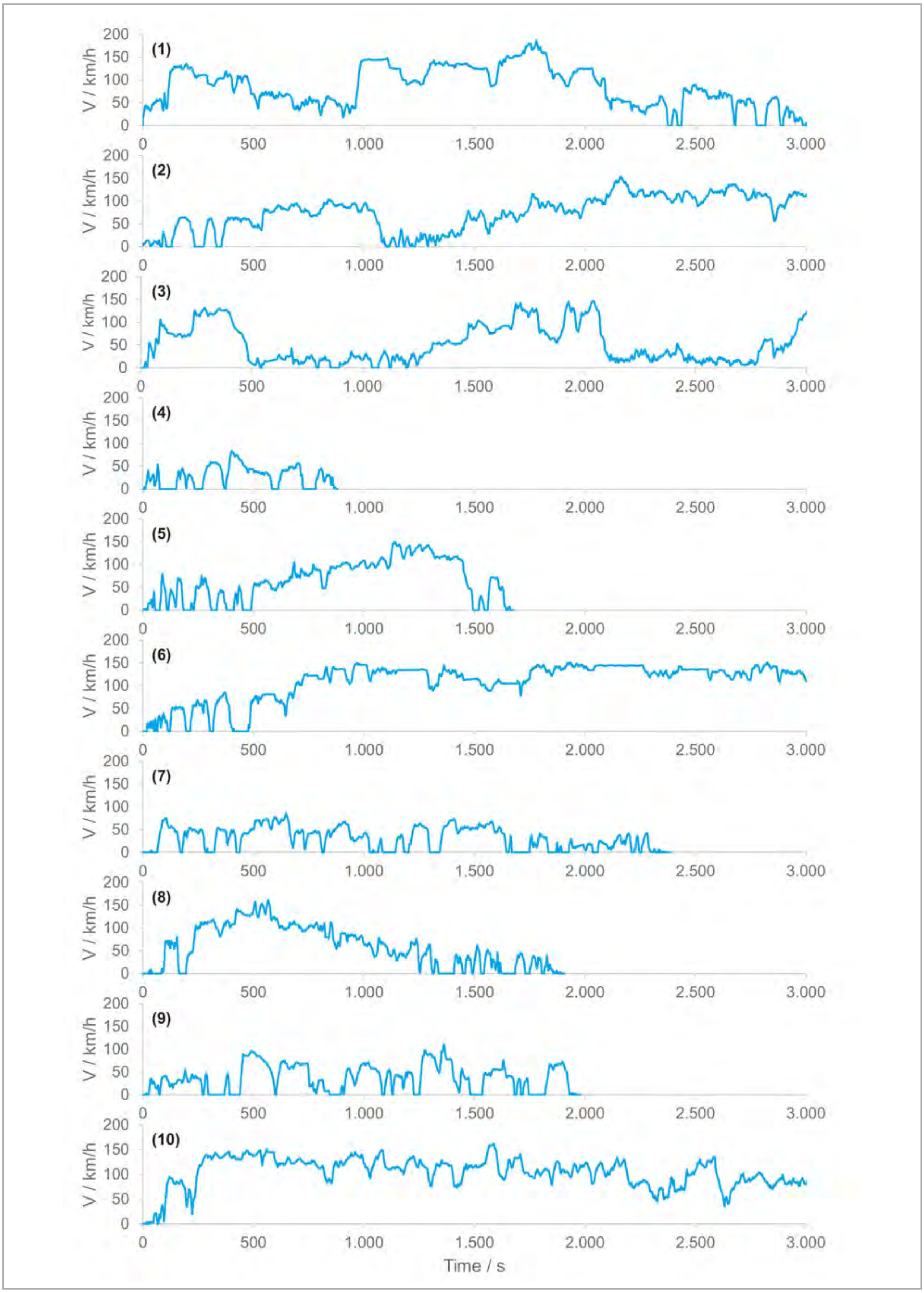


Figure 3: Speed profiles of daily journeys

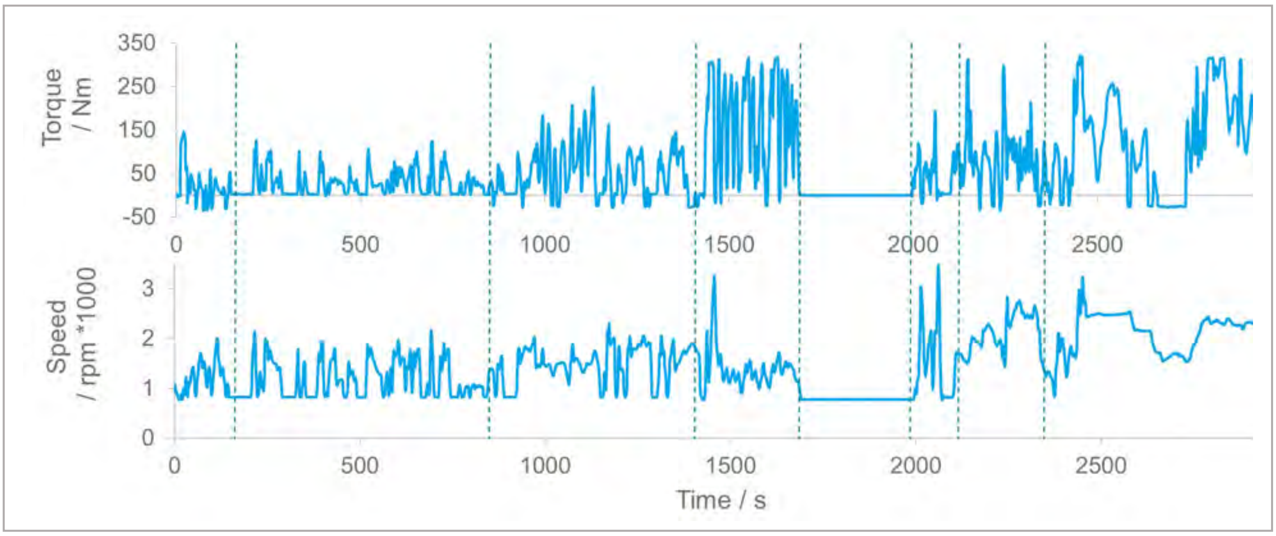
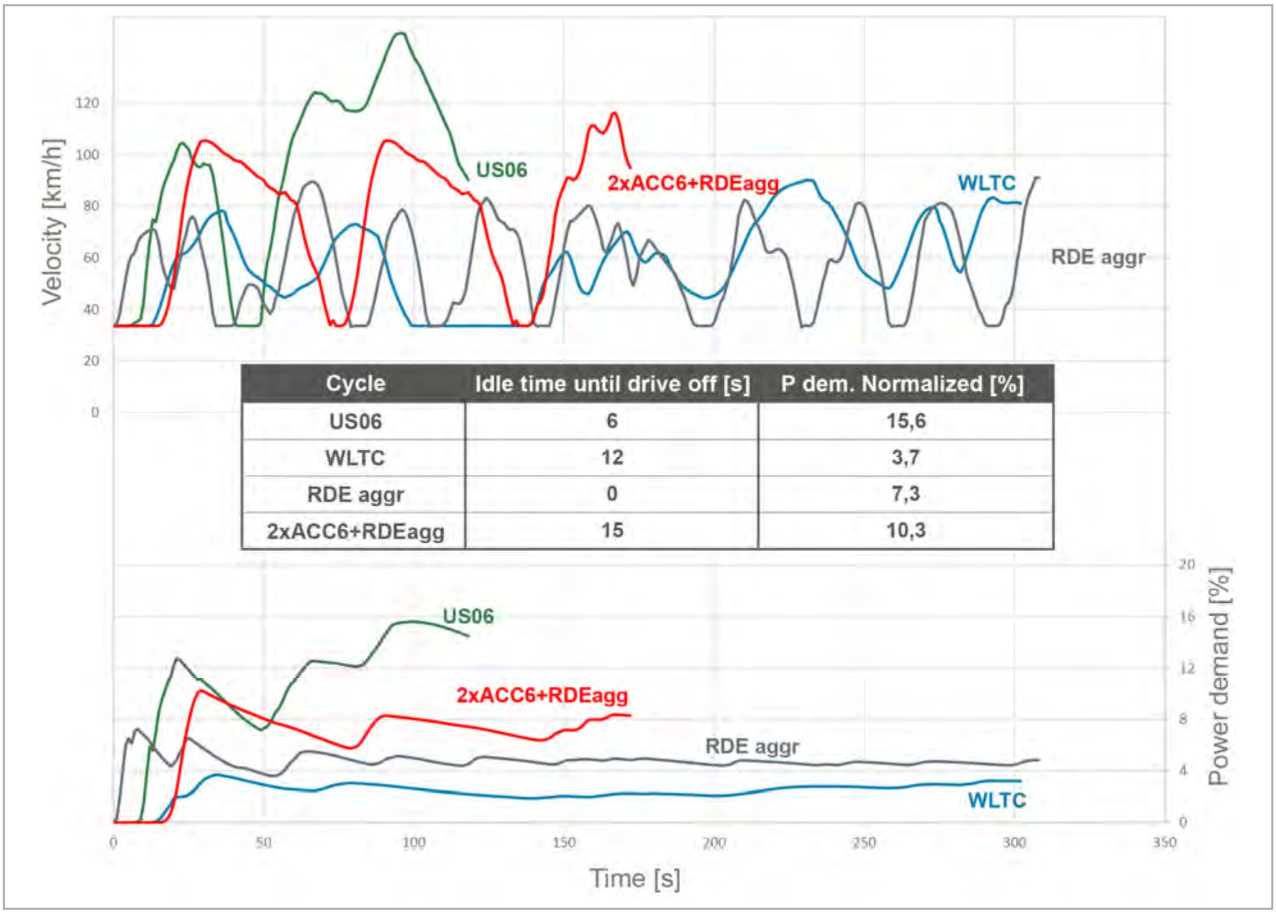


Figure 4: Relevant driving conditions

In addition, individual driving profiles were examined, and a catalytic converter system was presented with which emissions could be effectively reduced. The electrically heated catalytic converter played a decisive role, especially for the cold-start situations in gasoline engines and low-load operation in diesel engines.
It is of course impossible to check all driving conditions, just as it is impossible to incorporate all boundary conditions into the legislation. For this reason, a general definition of boundary conditions (Figure 2) makes sense.
In the following, factors such as idle time, ambient temperature, engine load were examined individually and in combination based on the boundary conditions. However, such an investigation can only be evaluated if a driving cycle is defined. First of all, this contradicts the idea of "any trip composition" but is necessary for the developer to be able to evaluate the influencing factors both on the raw emissions side and on the tailpipe emission side.
In 2022, Emitec published studies on various driving cycles at the 43rd INTERNATIONAL VIENNA MOTOR SYMPOSIUM under the title "Innovative catalytic converter system to comply with EU7 legislation for electrified drives". A useful test, with the claim what is relevant for the USA should also be relevant for Europe, was the combination of the so-called CARB (California Air Research Board) Rapid Acceleration Cycle 6 (ACC 6) with the RDE aggressive test used in Europe. The Rapid Acceleration Cycle describes the sudden start of the combustion engine in a hybrid vehicle when entering the highway. This Californian cycle is also relevant for Europe and certainly does not represent a misuse.

2.1 Engine Power

In the EU7 boundary conditions, the engine power plays an important role, especially during the first 2km. The legislator has tried to exclude misuse by using a moving average of the engine power relative to the engine rated power. This means, for example, that a direct start with high engine load like racing starts should be excluded. For "normal" driving, a limit value of 20% was proposed. Figure 5a shows an analysis of the percentage load over the first 2 km as a function of different test cycles and Figure 5b shows the respective influence of setting idle time to zero seconds. It has to be mentioned that even with idle time of zero seconds an engine start time of 3 seconds was used but not taken into consideration.



Cycle	Idle time until drive off [s]	P dem. Normalized [%]
US06	6	15,6
WLTC	12	3,7
RDE aggr	0	7,3
2xACC6+RDEagg	15	10,3

Figure 5a: Moving average of the engine load in the first 2 km of different test cycles in a mid-range vehicle

From figure 5a it can be examined that the test presented in 2022 (2x ACC6 + RDE aggressive) at an idle time of 15 seconds, has a maximum moving average of 10,3% and with 0 seconds idle (Figure 5b) of about 20%. Thus, the test describes exactly the border between normal and extended driving with regard to engine power. The following emission measurements were carried out on a dynamic engine test bench in a climatic chamber with a 3-Cylinder engine. In principle, the exhaust system corresponded to a Euro 6d exhaust system located close to the engine but, was designed as a test system with flanges between the bricks in order to investigate, for example, an electrically heated catalytic converter. All the tests, even the unheated ones, were done with an EHC in first position. For cold start this layout has a negative cold-start factor [4] and thus higher emissions compared to an optimized passive catalyst system.
The engine management or calibration corresponded to an EU6d temp application and was not adapted for these investigations.
All following tests were done with the test cycle 2 times ACC6 followed by RTS95 (after 300 seconds).

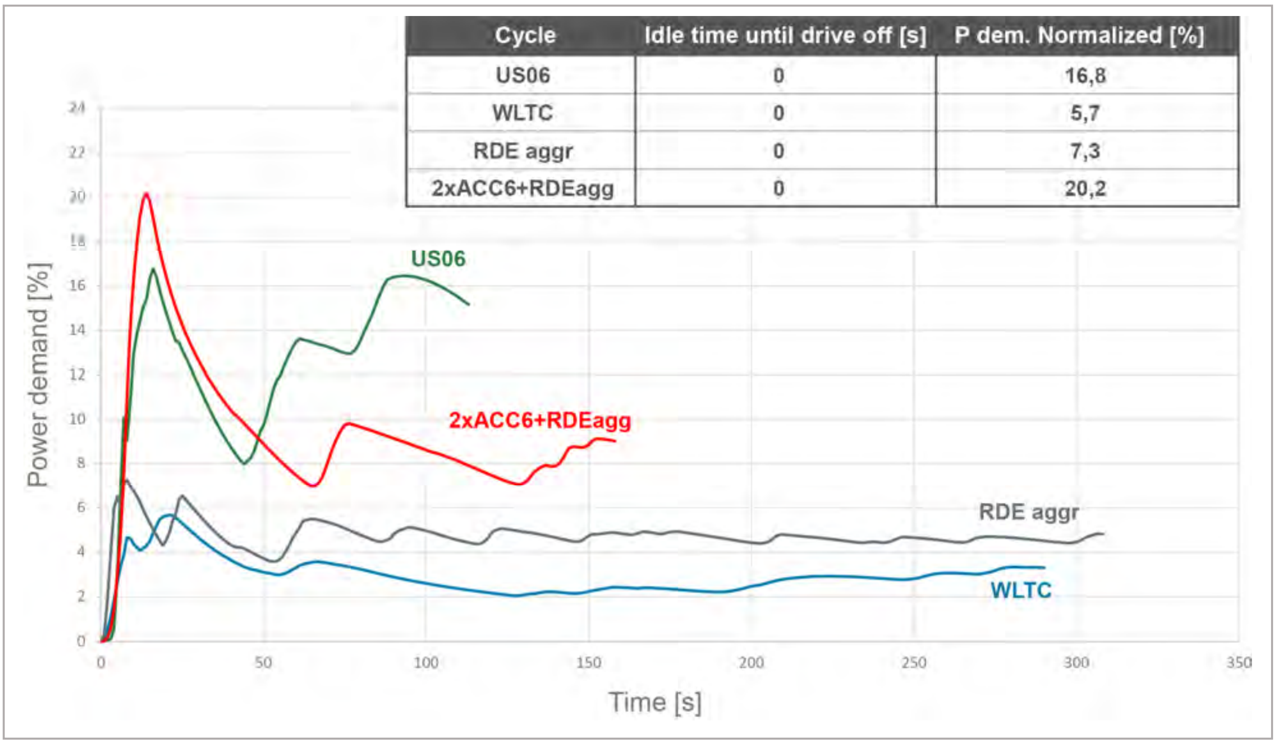


Figure 5b: Influence of idle time (0 seconds) on the moving average of the engine load in the first 2 km of different test cycles in a mid-range vehicle

2.2. Ambient temperature

As already mentioned, the tests were carried out on a dynamic engine test bench which is set up in a climatic chamber at the Emitec test center in Eisenach. With the catalytic converter system close to the engine, investigations were carried out at 20°C, 0°C (normal conditions) and -7°C (extended conditions). Figure 6 shows the influence of ambient temperature on NMHC- and NO_X-Emissions. The evaluation shows an increase of NMHC-Emissions by +93% at 0°C and +178% at -7°C relative to the 20°C measurements and accordingly -11% and -12% for NO_X-Emissions.

2.3. Idle time

The tests in 2.2. at different temperatures were done with 15 second idle times. In the next step the influence of shorter idle times was evaluated. Measurements with 5 seconds and 0 seconds idle were carried out at temperatures 20°C, 0°C and -7°C (Figure 7).

The evaluation shows dependent on the idle time an increase of NMHC-Emissions at 20° of 24% by shorten the idle time to 5 seconds and 72% with 0 second idle time. NO_X-emissions increase by 12% with 5 seconds idling and 42% with 0 seconds.

As shown in figure 5b the test used with 0 second idle time has a maximum average power of ~20% and thus being at the border between normal and extended driving conditions. Decreasing the temperature to 0°C would be still within the normal conditions.

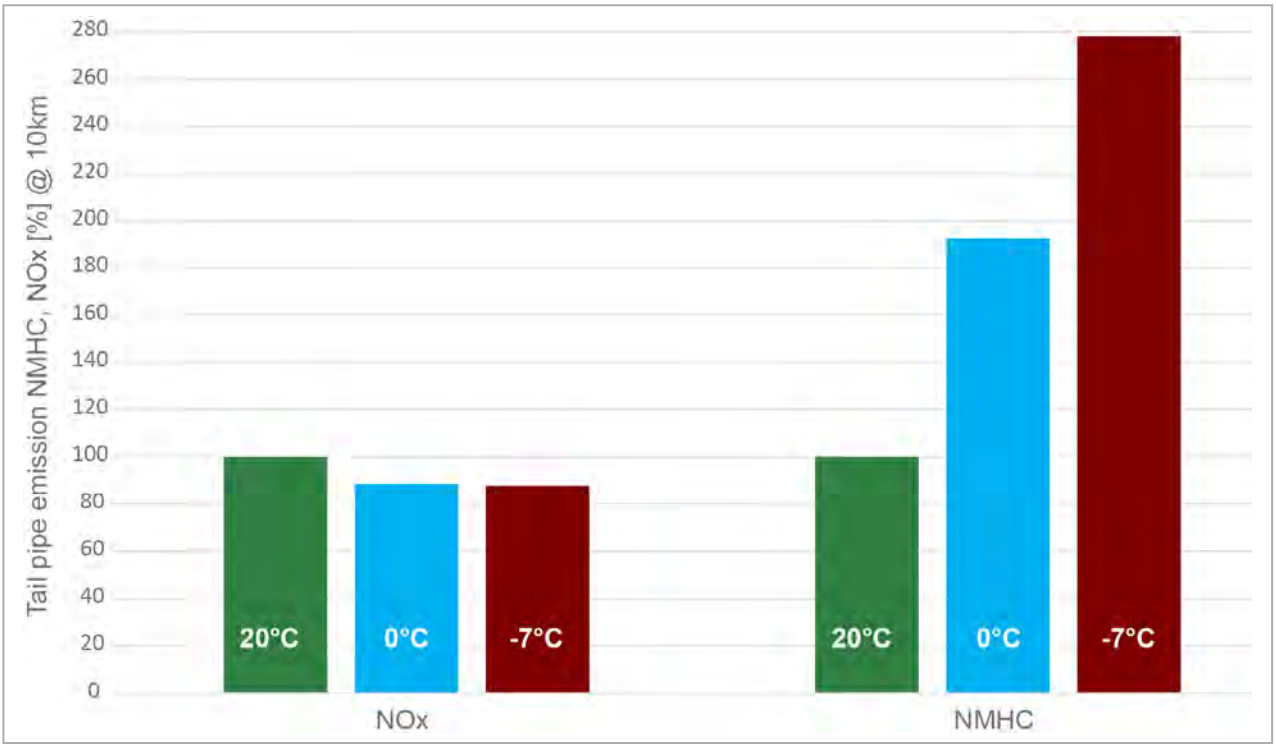


Figure 6: Tailpipe Emissions with an unheated close coupled catalyst system dependent on ambient temperatures, 15s idle time

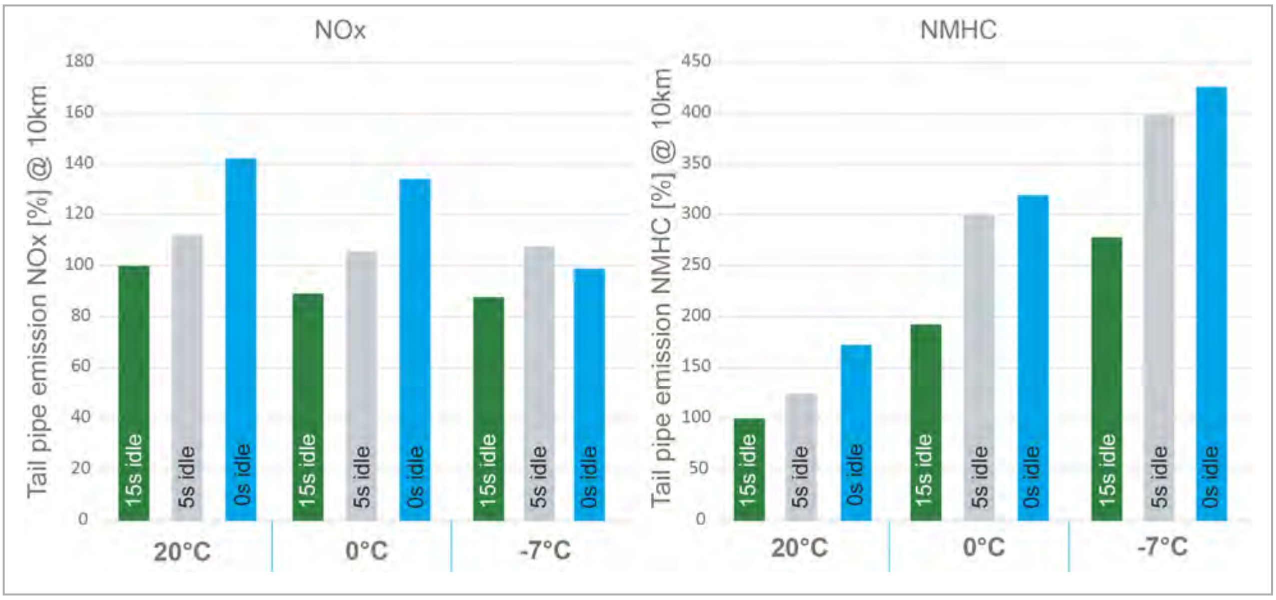


Figure 7: Tailpipe Emissions with an unheated close coupled catalyst system dependent on ambient temperature and idle time

Comparing the results for normal driving condition with 15 second idle times at 20°C and 0 second idle time at 0°C, an increase of NMHC tailpipe emissions of 220% and NO_X-Emissions of 34% can be recognized. It should be mentioned again that neither an adaption of the engine calibration nor a support from an electric motor (Hybrid) was used.

2.4 Trailer operation

The trailer operation corresponds to the extended boundary conditions but would not be valid according to the current state of discussion since 2 parameters i.e., trailer operation and increased load occur simultaneously. As already described above, this restriction makes no sense, because a trailer always brings an increased load with it. Figure 8 shows the influence of the trailer on the moving average of the engine load relative to the test without a trailer.

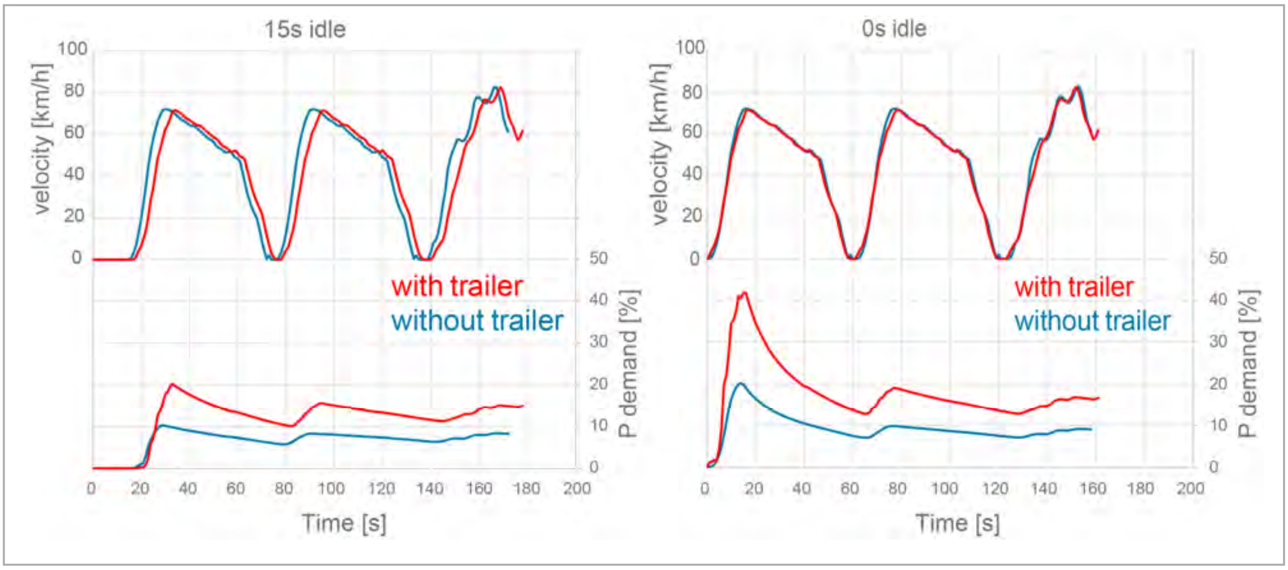


Figure 8: Moving average of the engine power in the first 2km of the test relative to the rated power

The maximum average engine power increased by ~100% for both idle times to ~20% and ~40% due to the additional load of the trailer. The trailer operation was simulated on the engine test bench only by increasing the “vehicle inertia”, additional influences on rolling resistance or aerodynamics were not considered. Trailer operation was also tested at ambient temperatures of 20°C, 0°C and -7°C with 15 and 0 seconds of idle time. Figure 9 shows the emission results.

The evaluation shows that with the additional trailer load at 20°C and 15 seconds idle load the NMHC-Emissions decreased by 18% and NO_X emissions increased by 2%. For extended conditions at -7°C and 0 second idle time conditions are the “worst” case in this study. With this boundary conditions the NMHC-Emissions increased by 446% and the NO_X-Emissions by 3%.

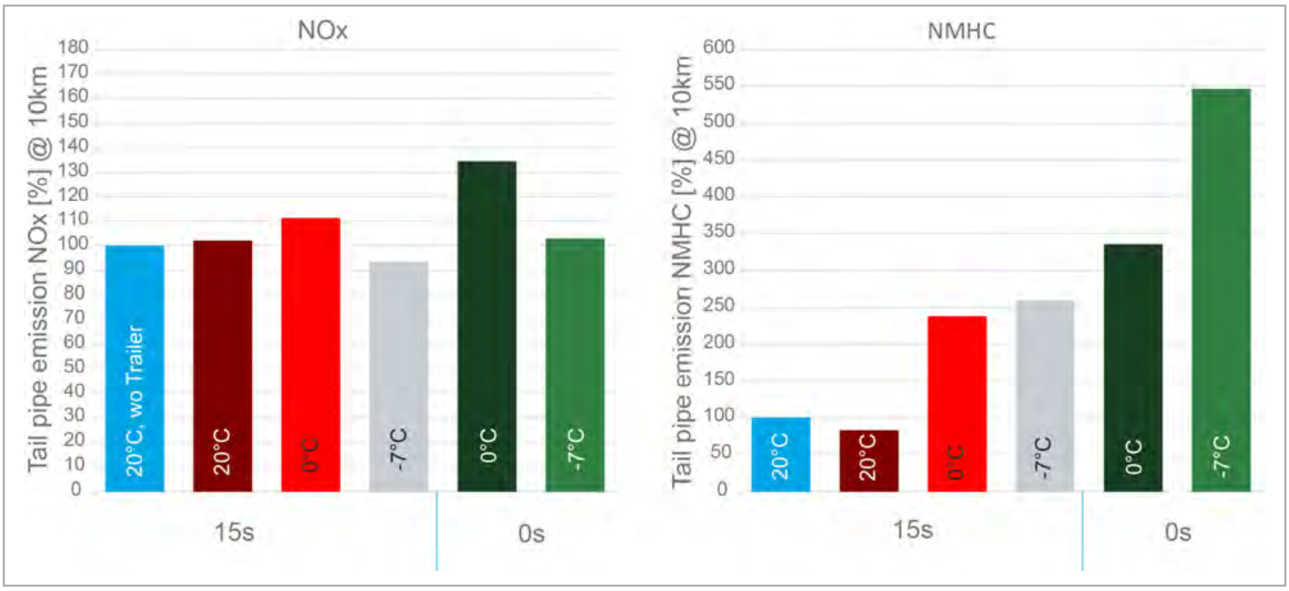


Figure 9: Tailpipe emissions as a function of trailer operation and ambient temperature

3. Emission results relative to the EU7 proposal

Figure 10 shows the results of the tests for the first 10 km after engine start relative to the EU7 normal and extended legislation. For the representation it was assumed that tests in which more than one parameter lies in the extended range are also valid. All results were run with the engine-related test system without additional heating and adjustment of the engine management

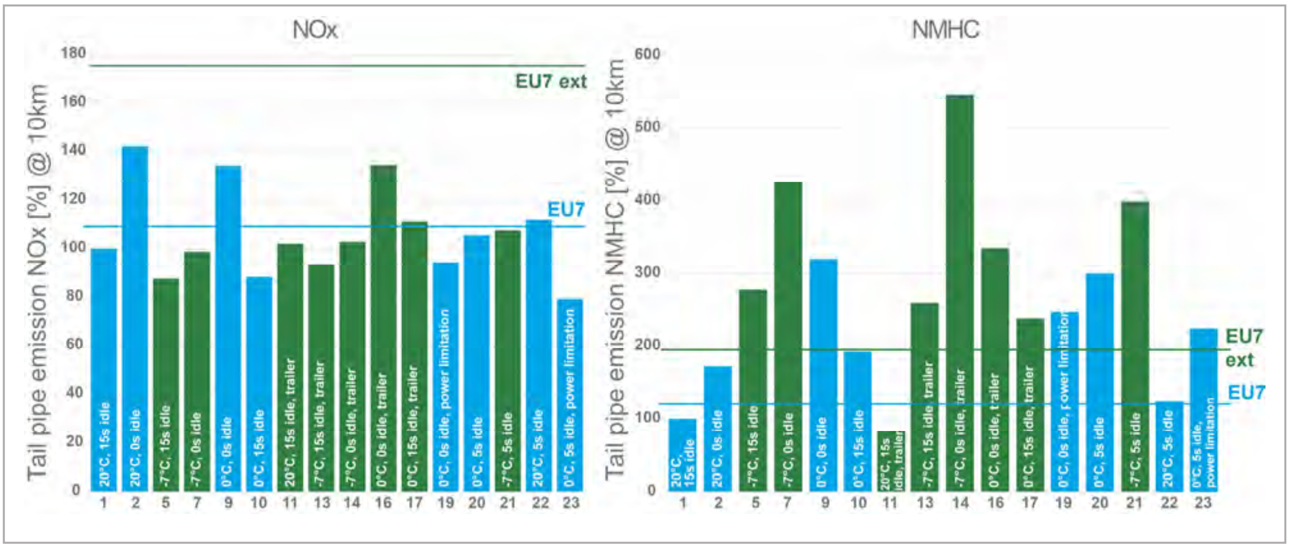


Figure 10: Emission results depending on load, idle time, ambient temperature, trailer operation after 10km relative to EU7-Limits

The results in figure 10 shows that, with the test engine used, NO_X-Emission results are critical especially with 0 seconds idle time at 20°C (Test 2) and at 0°C (Test 9). An increase of idle time to 5 seconds at 20°C (Test 22) already improved the NO_X emissions by 21%. For the extended driving conditions all NO_X results were within the proposed limits.

On the Non-Methan-Hydrocarbon (NMHC) results a different picture can be seen. All Tests at temperatures below 20°C are above the limits.
Taking a closer look to the air-fuel ratio during cold start it can be recognized that the engine at 0°C and -7°C is running for more than 14s below lambda 1 (Figure 11).

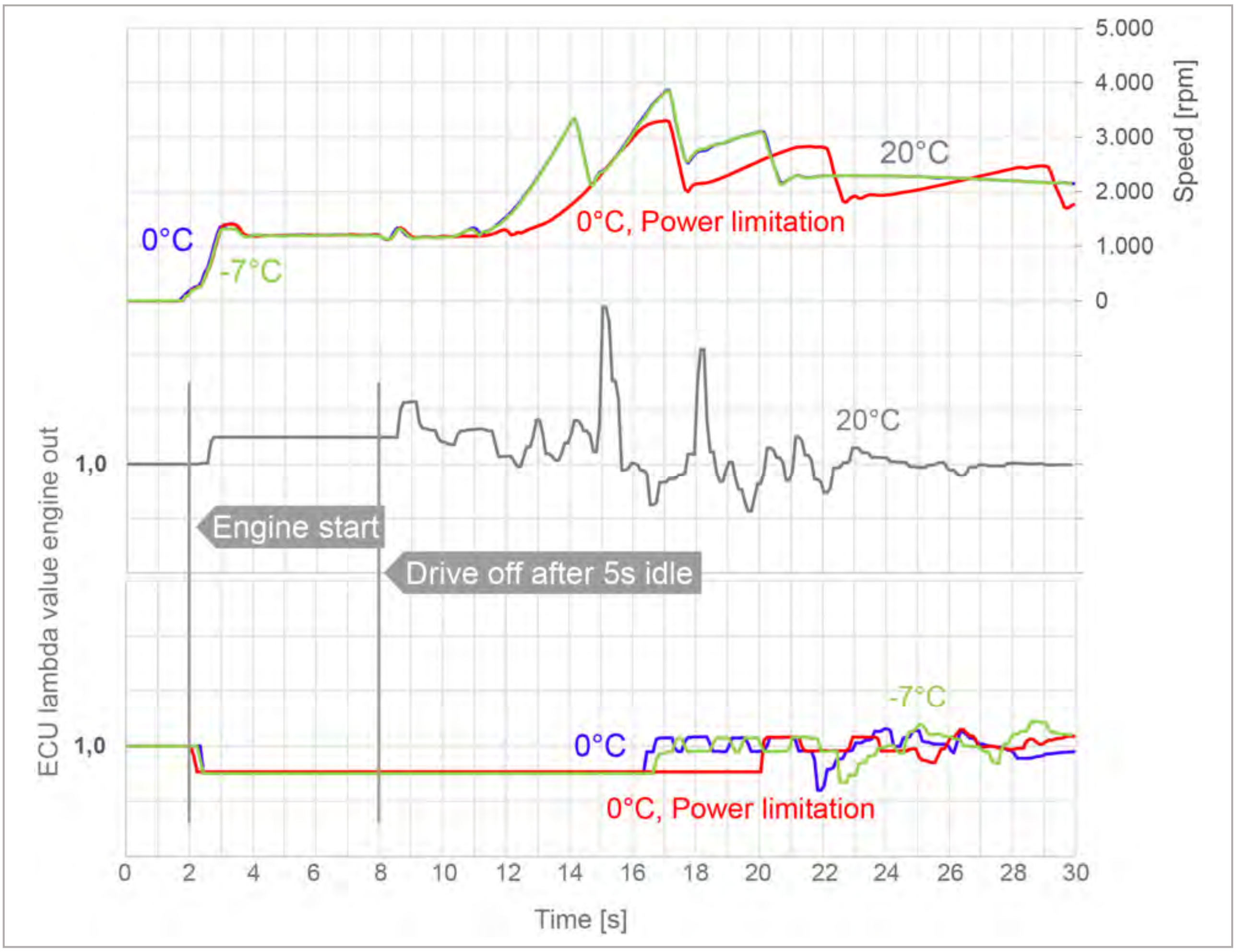


Figure 11: Air-Fuel mixture (lambda) at different temperatures with and with power limitation

As stated before, the engine management calibration was not modified for EU7 test conditions. It can be recognized that a reduction of torque has a negative influence on the duration on lambda <1 because the engine temperature increase is slower with lower load. With a modified calibration and/or secondary air injection the rich phase can be shortened or even eliminated.

3.1 Measures to improve emission results

In chapter 2.3 the influence of idle time on tailpipe emissions (Figure 7) was examined. Of course, it would be possible per definition to define a minimum idle time before the car starts moving. Assuming the different behavior of “real” drivers an enforced idle time of 5 seconds might be acceptable.
At the same time most of the future cars will have a 48V system and at least a mild hybrid function. With this it would be possible to even enlarge the idle time by using only the electrical motor for a few seconds and/or to reduce the engine load by delivering the driving

power needed by the motor. As mentioned, the tests were done without hybrid function. By that the reduction of power of the combustion engine without motor support would end in a slower acceleration during the first and 2nd acceleration phase. Figure 12 shows the effect of a power reduction of 70% during the first acceleration and 15% during the second acceleration hill.

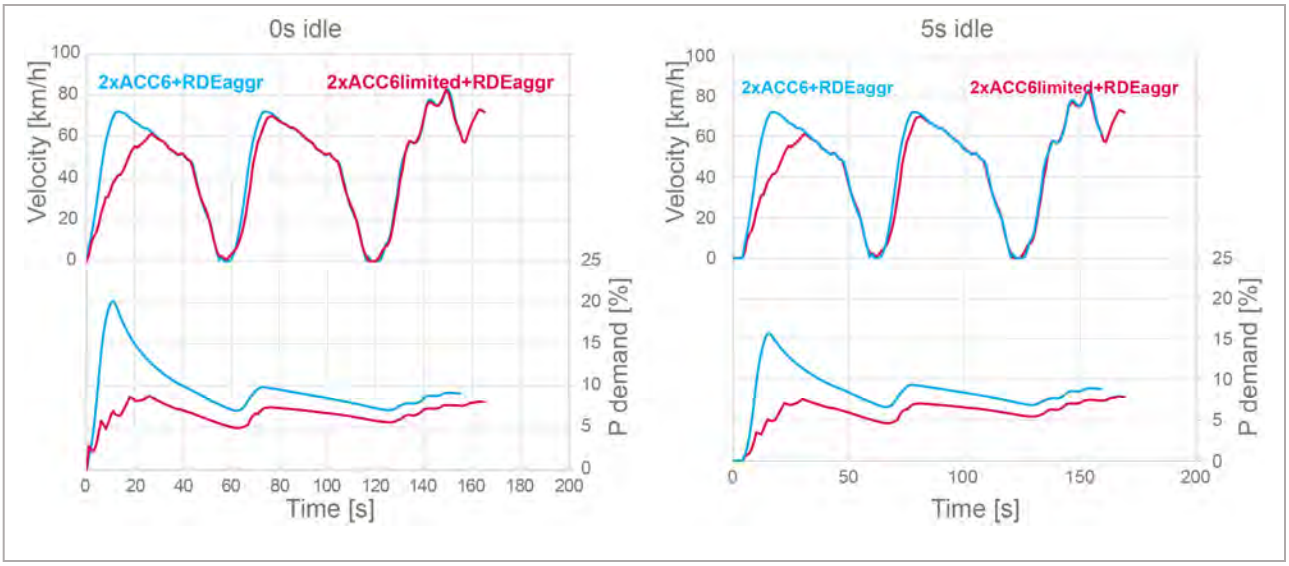


Figure 12: Moving average of the engine load for the first 2km with and without engine power limitation

The moving average power relative to rated power was reduced from ~20% down to ~8% by increasing the idle time to 5 seconds and limiting the power to 25kW during the first ACC 6 cycle and to 65kW during the second ACC 6 cycle. The comparison of tailpipe emissions is shown in figure 13.

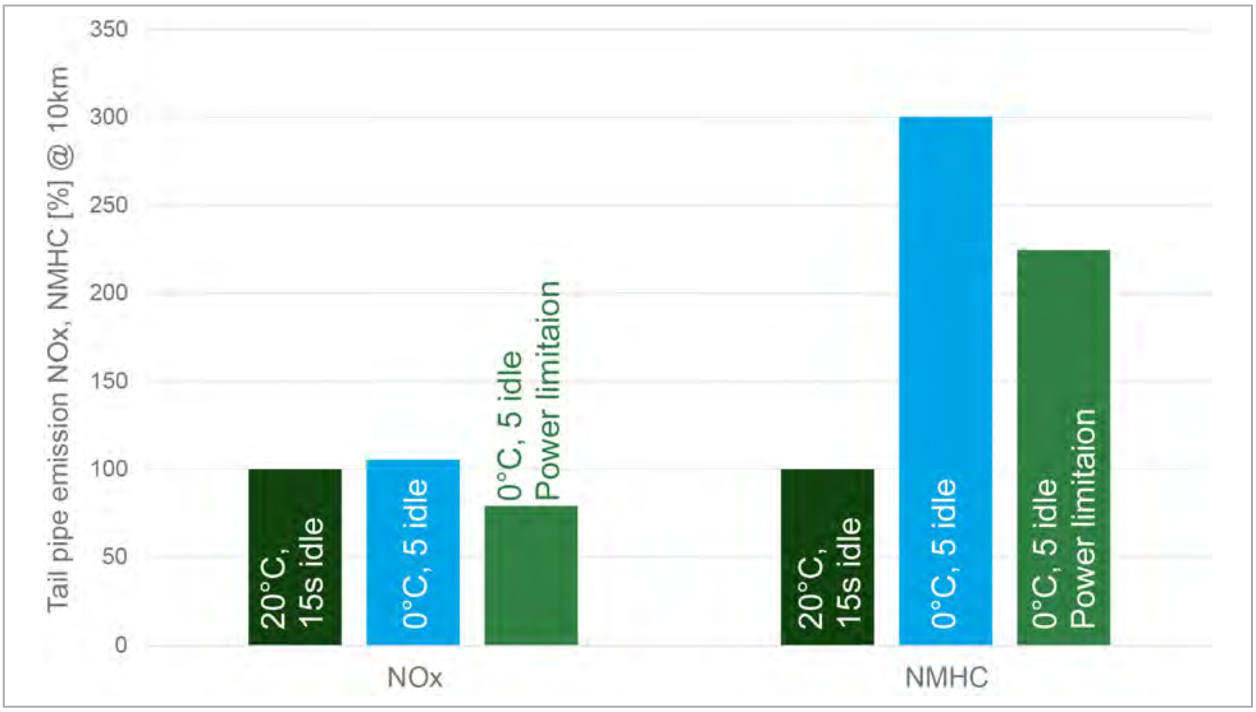


Figure 13: Comparison of NO_X- and NMHC-Emissions for normal driving conditions at 0°C with 5 seconds idle time and power limitation

The NO_X tailpipe emissions could be reduced by 24% and NMHC emissions by 25%. The reason for the relative small improvement for NMHC can be most likely seen in the longer time with lambda smaller than one for the test with reduced torque (Figure 11).

In order to examine the full potential of best available technologies, secondary air injection (SAI) was introduced, and the electrically heated catalyst (EHC) was activated with 5s preheating and 20s heating after engine start. The secondary air flow was applied into the inlet cone of the catalyst via a small bended tube and was switched on for 20s after engine cranking. The tailpipe emissions at 0°C and 5s idling without power limitation ("normal conditions") as second by second data are shown in figure 14.

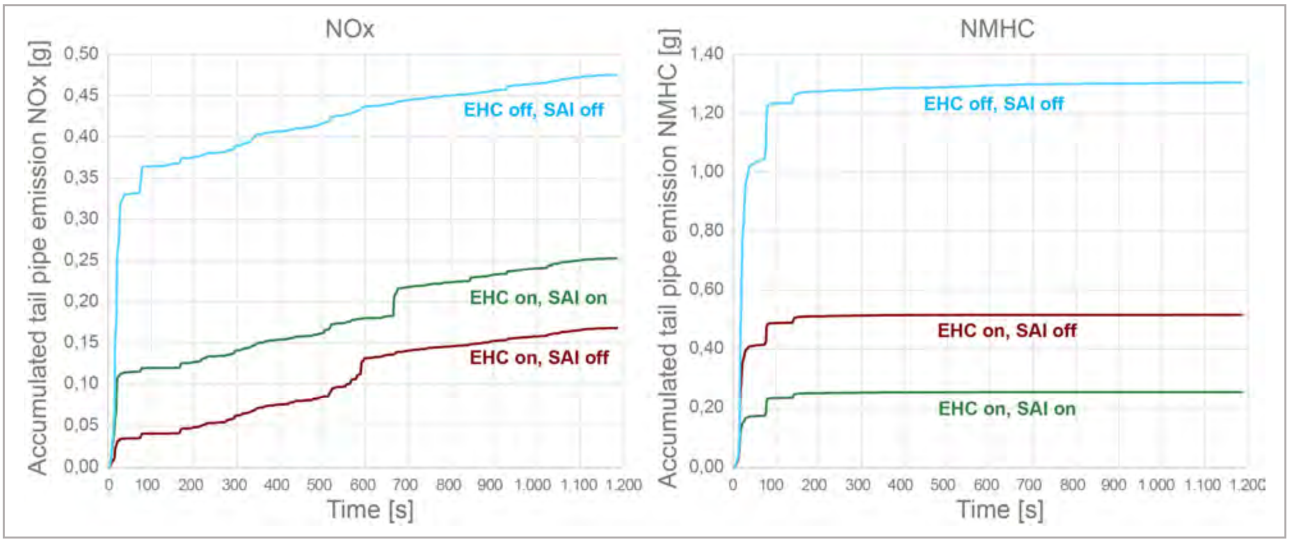


Figure 14: NO_X - and NMHC-Tailpipe emissions at 0°C, 5s idle, w/wo SAI, EHC on/off

The activation of the EHC improves the tailpipe emissions significantly by 65% in NO_X and 60% in NMHC. By using secondary air in addition, the NO_X advantage drops to 48 % but further improves the NHMC results to 81%.

For a direct comparison figure 15 shows the results after 10 kilometers also in comparison with the results at 20°C.

The technology of an electrically heated catalyst is well known and was in production for several vehicles with diesel engine in the last 10 years. According to current knowledge an electrically heated catalyst or at least a heater device is needed for Diesel vehicles to achieve EU 7 limits.
Using this technology for gasoline would support lower emission results and will be a solution in case the combination of several parameters for the extended driving conditions will be allowed.

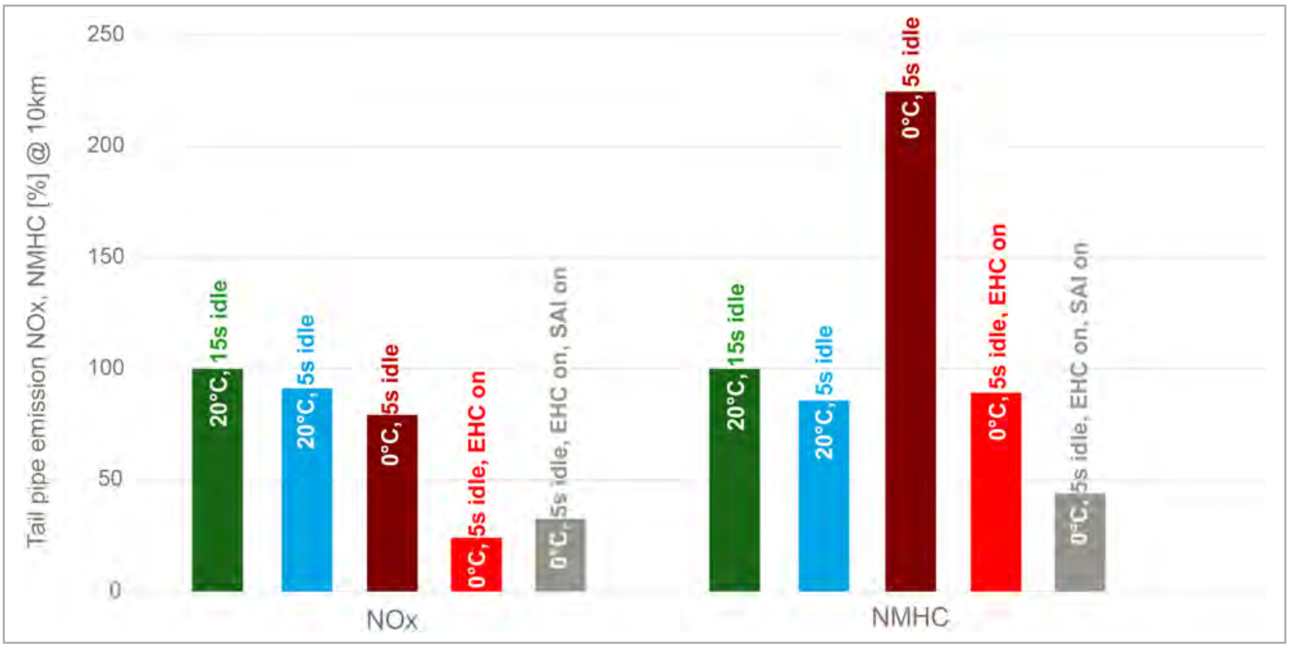


Figure 15: Comparison of NO_X - and NMHC-Emissions at 20°C and 0°C with 5 seconds idle time, w/wo SAI, EHC on/off after 10km

The today's assumption is that an active heating system is not needed for gasoline passenger car applications. The use of the electric drive and thus the possibilities to reduce engine power or longer idle times with high effective close coupled catalyst systems in combination with new engine technologies and control functions supports this assumption. Unfortunately, it also depends on the ongoing EU 7 discussion and the final requirements and boundary conditions for the valid tests.

Still the EHC would allow for a further safety margin and thus a more robust solution in case of borderline (according to the boundary conditions) emission tests and will be a solution in case the combination of several parameters will be allowed. Also, the question should be allowed about what the most cost-effective system is taking into account all costs and counting it separately. Means the 48V system for mild hybrids is mainly needed for reduced fuel consumption, but quite often calculated into the cost of an active heating device.

4. Conclusion

Based on the EU7 emission legislation proposal emission tests with different boundary conditions were carried out. The influence of ambient temperature, idle time, trailer operation and power limitation were examined. It can be stated that specially with hybrid vehicles tailpipe emissions can be positively influenced by using the motor to support the combustion engine to fulfill the driver torque request. Also, the introduction of a few seconds “forced” idle time has a positive impact. By that for normal driving conditions a passive catalyst system most likely will be able to fulfill the requirements. If such a close coupled Three Way Catalyst for gasoline vehicles will be sufficient to fulfill also the extended requirements, especially in case a combination of the different parameters would be allowed, cannot be finally concluded. Means the boundary conditions describing a valid or not valid test and also deciding if the test is according to normal driving or extended driving is still not finally settled.
If the public opinion would accept using again only part of the real driving spectrum for emission tests is questionable and might not support the positive image of the automotive industry.

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