Van Mourik Broekmanweg 6
2628 XE Delft
P.O. Box 49
2600 AA Delft
The Netherlands

www.tno.nl

[illegible]

TNO report

TNO 2015 R10858 v1

Emission performance of a diesel plug-in hybrid vehicle

Date	19 June 2015
Author(s)	Gerrit Kadijk Edo Buskermolen Jordy Spreen
Copy no	2015-TL-RAP-0100286662
Number of pages	25 (incl. appendices)
Number of appendices	1
Sponsor	Dutch Ministry of Infrastructure and the Environment PO Box 20901 2500 EX THE HAGUE The Netherlands
Project name	In use compliance program for light-duty vehicles
Project number	060.14432

Samenvatting

NO_x-emissie plug-in hybride dieselauto aanzienlijk hoger dan van plug-in hybride benzineauto's
In opdracht van het Ministerie van Infrastructuur en Milieu heeft TNO onderzoek gedaan naar het praktijkemissiegedrag van een Euro 5 plug-in hybride personenwagen die is uitgerust met een dieselmotor. Het onderzoek laat zien dat de NO_x-emissie van de geteste plug-in hybride Euro 5 dieselpersonenauto gemiddeld aanzienlijk hoger is dan de NO_x-emissie van plug-in hybride benzineauto's en die van gewone benzineauto's. De onderzochte plug-in diesel heeft een praktijk NO_x-uitstoot van gemiddeld 400 à 600 mg/km; een (plug-in) benzineauto stoot in de praktijk gemiddeld 20 mg/km NO_x uit.

De praktijk NO_x-emissies van moderne dieselmotoren zijn per kilometer tot wel 30 keer zo hoog als die van moderne benzinemotoren. Dit komt doordat de NO_x-emissies van Euro 5 dieselmotoren onder praktijkomstandigheden fors hoger zijn dan op grond van de Euro 5 norm voor diesel en de fabrieksspecificatie mag worden verwacht. Ook is de Euro 5 NO_x-norm voor diesels (180 mg/km) ruimer dan voor benzines (60 mg/km). Als gevolg hiervan is een plug-in hybride auto met dieselmotor gemiddeld genomen slechter voor de luchtkwaliteit dan plug-in hybride benzineauto's en gewone benzineauto's.

Net als bij conventionele dieselpersonenauto's zijn de gemiddelde NO_x-emissies van dit diesel plug-in hybride voertuig in dit testprogramma ongeveer drie tot vijf keer hoger dan de Euro 5 limietwaarden. De momentane emissies van het voertuig vertonen bovendien veel variaties; zij worden sterk beïnvloed door het oplaadgedrag en het gebruik van het voertuig. Het onderzoek laat zien dat gemiddeld tot 30% lagere NO_x-emissies mogelijk zijn als de hybride batterij via een laadpaal frequenter opgeladen zou worden (er kan meer elektrisch worden gereden). Voor praktijkritten van 40 km betekent dit dat de gemiddelde NO_x-uitstoot, waarbij met een volle batterij wordt gestart, circa 400 mg/km bedraagt. Als de hybride accu niet wordt opgeladen, bedraagt de NO_x-uitstoot gemiddeld 500 à 600 mg/km. Dit komt omdat de hybride accu dan leeg is en de dieselmotor het werk moet doen.

Ook praktijk-CO_2-emissies liggen hoger dan typekeuringswaarde
Uit het onderzoek blijkt dat, net als bij plug-in hybride auto's met een benzinemotor, de CO_2-uitstoot van de geteste plug-in diesel in de praktijk hoger ligt dan de opgegeven typekeuringswaarde. Dit wordt voornamelijk veroorzaakt doordat voor de typekeuringstest van een aanzienlijk hoger aandeel elektrisch rijden wordt uitgegaan dan tijdens gemiddeld praktijkgebruik.

Oplaadgedrag en ritafstand bepalen de praktijkemissies
Het oplaadgedrag van de berijder en de afstand per rit bepalen in hoge mate de gemiddelde NO_x- en CO_2-emissies van het voertuig. Plug-in technologie wordt beschouwd als een manier om auto's gemiddeld zuiniger en schoner te maken. Bij een frequent oplaadgedrag is hier inderdaad sprake van. Zodra de dieselmotor van dit Euro 5 plug-in voertuig werkzaam is, heeft het voertuig echter altijd een hoge momentane NO_x uitstoot van 500 tot 600 mg/km.

Wat is nodig voor de realisatie van lage praktijkemissies?
Dit onderzoek toont aan dat het geteste Euro 5 plug-in hybride dieselvoertuig in de praktijk aanzienlijk hogere NO_x-praktijkemissies heeft dan plug-in hybride benzineauto's en gewone benzineauto's. Dit kan worden verbeterd door berijders te stimuleren de hybride accu na iedere rit via het elektriciteitsnet op te laden. Dit zal ook leiden tot verlaging van de CO_2-praktijkemissies. Maar omdat de NO_x-uitstoot van Euro 5 diesels in de praktijk tot een factor 30 hoger is dan de NO_x-uitstoot van benzine-auto's, blijft ook bij veel laden de NO_x-uitstoot van de Euro 5 plug-in diesel aanzienlijk hoger dan die van een (plug-in) benzineauto. Voor het realiseren van lage NO_x-praktijkemissie bij plug-in diesels moet de NO_x-uitstoot van de dieselmotor aanzienlijk worden verlaagd. Pas dan levert een plug-in diesel een positieve bijdrage aan het verbeteren van de luchtkwaliteit.

Summary

NO_x emissions of diesel plug-in hybrid passenger car considerably higher than NO_x emissions of petrol plug-in hybrids

On behalf of the Dutch Ministry of Infrastructure and the Environment TNO conducted a study on the real-world emission performance of a Euro 5 diesel plug-in hybrid diesel passenger car. The study reveals that NO_x emissions of the tested vehicle on average are significantly higher than the NO_x emissions of plug-in hybrid petrol cars and conventional petrol cars. The tested plug-in hybrid diesel vehicle has a real-world NO_x emission that ranges from 400 to 600 mg/km, while a plug-in hybrid petrol car emits on average 20 mg of NO_x per kilometer.

The real-world NO_x emissions of modern diesel engine are up to 30 times higher than those of petrol engines. This is mainly caused by the fact that NO_x emissions of Euro 5 diesel engines are significantly higher under real-world conditions than would be expected on the basis of the Euro 5 type approval standard. Moreover, at 180 mg/km the Euro 5 NO_x limit value for diesels is less stringent than that for petrols, which lies at 60 mg/km. As a consequence, plug-in hybrids fitted with a diesel engine are less environmentally-friendly than plug-in hybrids with a petrol engine or conventional petrol cars.

As is true for conventional diesel passenger cars, the average real-world NO_x emissions of the tested plug-in diesel are approximately three to five times higher than the Euro 5 type approval limit value. Moreover, the NO_x emissions vary considerable over the tests and are strongly affected by charging behavior and vehicle usage. This research shows that NO_x emissions can be reduced by 30% if the hybrid battery is frequently charged from the mains. Starting a 40-kilometer trip with a fully-charged battery would results in a trip-average NO_x emission of around 400 mg/km. Executing the same trip with an uncharged hybrid battery results in a trip-average NO_x emission of 500 to 600 mg/km, due to the fact that in that case the vehicle is virtually propelled by the diesel engine alone.

Real-world CO_2 emission are also higher than type-approval CO_2 emission

The research shows that the real-world CO_2 emission of the tested plug-in hybrid diesel vehicle is higher than the type-approval CO_2 emission, as is the case with plug-in hybrid petrol vehicles. This is mainly caused by the fact that in the type-approval test procedure a larger share of electric driving is assumed than the share of electric driving in everyday use.

Real-world emissions strongly affected by charging behavior and trip distance

The driver's charging behavior and the trip distance have proved to have a large effect on the average real-world NO_x and CO_2 emissions of the vehicle. Plug-in hybrids technology is considered to be a way of making cars cleaner and more fuel efficient, and, when drivers frequently charge the hybrid battery from the mains, this is in fact the case. If the vehicle is not or seldom charged, however, the tested plug-in hybrid diesel is neither clean nor fuel efficient: when the diesel engine is running, its NO_x emission is high, ranging between 500 and 600 mg/km.

How can low real-world emissions be achieved for plug-in hybrid diesel cars?
This research shows that the real-world NO_x emissions of the tested Euro 5 plug-in hybrid diesel car are significantly higher than the real-world NO_x emissions of plug-in hybrid petrol cars and conventional petrol cars. The real-world NO_x emissions of the plug-in diesel can be reduced by charging the hybrid battery from the mains after every trip. As the real-world NO_x emissions of Euro 5 diesel engines are up to a 30 times higher than the real-world NO_x emissions of petrol engines, the real-world NO_x emissions of the Euro 5 plug-in diesel car will remain considerably higher than those of a (plug-in hybrid) petrol car – even in case the vehicle is frequently charged from the grid. For a low real-world NO_x emission of plug-in diesel vehicles the NO_x emission of the vehicle's diesel engine must be reduced considerably. Only in that case will a plug-in diesel car make a positive contribution to air quality.

Contents

1 Introduction

In recent years, light-duty vehicles with a diesel plug-in hybrid drive line have entered the market. The electric drive line with battery aims at reducing the emissions of the vehicle. In 2014, TNO investigated the fuel consumption of mainly *petrol* plug-in hybrid vehicles [TNO2014a]. Now, in order to get a view of the real-world emission performance of the applied *diesel* engine, a short emission test program on the road was carried out in March 2015.

TNO instrumented the vehicle with a Smart Emission Measurement System (SEMS) and subsequently performed several emission screening tests on the road.

The main objective of this test program is to investigate the real-world NO_x and CO_2 emission performance of the combustion engine of a diesel plug-in hybrid vehicle.

2 Test vehicle, equipment and trips

2.1 Test vehicle

Table 1 contains the main specifications of the tested vehicle.

Table 1: Specifications of tested plug-in hybrid vehicle.

Vehicle test code	[-]	Q1
Vehicle type	[-]	Estate
Vehicle mass	[kg]	1900-2000
Battery package mass	[kg]	300
Performance engines (diesel + electric)	[kW]	120+50
Emission class	[-]	Euro 5
Type Approval CO_2	[g/km]	48
Type Approval NO_x	[g/km]	<180
Diesel range	[km]	1200
Electric range	[km]	50
Energy content fuel tank	[kWh - MJ]	440 - 1585
Energy content hybrid battery	[kWh - MJ]	12 - 43
First registration date	[dd-mm-yyyy]	18-10-2013
Odometer	[km]	54.177
Date test period	[-]	March 2015

2.2 Test equipment

2.2.1 *Brief description of the Smart Emission Measurement System (SEMS)*

The TNO Smart Emission Measurement System (SEMS) was installed on the vehicle.

SEMS is an emission screening tool which contains an $NO_x - O_2$ sensor (Continental, UniNOx) and a thermocouple, which are installed in the tailpipe of the vehicle, and a data logger. It measures the exhaust gas temperature and the O_2 and NO_x volume concentrations in vol% or ppm. SEMS also measures geographical data and the CAN data of the vehicle with a measuring frequency of 1 Hz. On the basis of the measured O_2 readings and the carbon and hydrogen content of the fuel, CO_2 concentrations are calculated. In former projects, the accuracy and the reliability of the SEMS equipment and method has been proved [TNO2012, TNO2014]. However, the absolute emission results are calculated with data from the CAN bus of the vehicle. This may lead to deviations in the end results.

Calibration of the NO_x and O_2 sensors were performed before and after this test program.

In this project, the air mass rate of the vehicle CAN bus was applied for calculations of the NO_x and CO_2 mass flow rates [mg/km]. The quality of the air mass rate signal determines the accuracy of the NO_x mass emissions.

Figure 1, Figure 2 and Figure 3 show an example of a SEMS-instrumented vehicle.

Figure 1: NO_x sensor and thermocouple mounted in the vehicle's tailpipe.

Figure 2: Load packages (black box) and data logger of the SEMS (blue cradle).

Figure 3: The laptop used to monitor and control the SEMS equipment.

2.2.2 *Calculation of the NOx and CO_2 emissions*

SEMS measures and stores data from the installed sensors and signals available from the On-Board Diagnostic system. The CO_2 volume concentrations are based on the measured O_2 concentrations and fuel parameters, i.e. using the carbon balance method. The CO_2 and NO_x mass flow rates are based on data from the SEMS equipment, i.e. the mass air flow rate and measured/calculated volumetric emissions.

This test and data processing procedure contains the following steps:

1. The CO_2 volume concentration is determined from the measured O_2 volume concentration and the fuel C:H ratio.
2. The fuel mass flow rate is determined from the vehicle's Mass Air Flow signal, the fuel C:H ratio and the measured CO_2 concentration.
3. The exhaust flow rate is determined from the mass air flow rate and the fuel mass flow rate.
4. The CO_2 and NO_x mass flow rates are determined from the measured volume concentrations and the exhaust mass flow rate.

This analysis requires two input parameters:

- the C:H ratio of the fuel, which is assumed to be 1.95 for modern market-fuel diesel, and;
- the ambient oxygen content of air at 20.8% for on-road conditions. This is determined via calibration measurements.

The sensors of the SEMS equipment are calibrated. The quality of the OBD mass air flow signal is unknown.

It is noted that at very low NO_x concentrations, the SEMS sensor is less accurate for transient signals. However, in the range of concentrations of the current measurements, the correlation and calibration tests that have been carried out in the last four years provide a good evidence for accurate measurements.

2.3 Test trips

Table 2 contains the main characteristics of the executed test trips. All trips were started in Helmond, the Netherlands, and were carried out with minimum payload.

SEMS registers real-world conditions, vehicle data and emission concentrations. In order to be able to compare the individual real-world vehicle emissions with those of other vehicles, the TNO-designed 'reference trip' always forms part of the investigation. The reference trip consists of urban, rural and highway driving. Additionally, some other trips are performed: constant speed, urban driving and highway driving.

Table 2: Specifications of SEMS test trips

	TNO City route Helmond	TNO Reference route	Constant speed route Germany
Type	City	City, rural and highway	Highway
Cold/Hot start	Hot start	Cold and hot start	Hot start
Distance [km]	25.6	73.5	189
Duration [min]	57	89	119*
Average speed [km/h]	32 (excl. idle time)	55 (excl. idle time)	93 (total route)*
Load [-]	Driver + test equipment	Driver + test equipment	Driver + test equipment

*Constant speed measurements are part of this route. Constant speed tests have a duration of approximately 300 to 600 seconds.

Driving styles
The test driver received instructions for the required driving style. This can be 'economic', 'regular' or 'sportive'. Some vehicles are tested with more driving styles. The vehicle tested in this study was tested at economic, regular and sportive driving style, as shown in Table 3.

3 Test results

3.1 Test program

The duration of the test program was five days, including preparations and dismantling of the test equipment. Table 3 reports the sequence of the different test trips (routes) and boundary conditions of the test program. In order to get a broad view on the emission behaviour of the vehicle, different drive line modes, types of trips, driving styles and starting conditions were applied.

Before the first emission test the hybrid battery was fully charged. During the test program no battery charging has been applied.

Table 3: Test sequence, routes and conditions.

Day-trip no.	Powertrain Mode	Type of trip	Driving style	Comment
1-1	Hybrid	Reference	Regular	Cold start, battery fully charged
1-2	Hybrid	Reference	Regular	Hot start
1-3	Hybrid	Reference	Regular	Hot start
1-4	Hybrid	City	Regular	Hot start
2-5	Hybrid	Reference	Regular	Cold start, battery not charged
2-6	Power	Reference	Regular	Hot start
2-7	Power	Reference	Regular	Hot start
2-8	Hybrid	City	Economic	Hot start
3-9	Hybrid	Highway	Regular	Hot start
3-10	Hybrid	Constant speed	Regular	Hot start
3-11	Hybrid	Highway	Regular	Hot start
3-12	Hybrid	City	Sportive	Hot start
4-13	Power	Reference	Regular	Cold start, battery not charged

3.2 Test results

3.2.1 *Vehicle speed and engine speed*

Figure 4 shows the average combustion engine speeds in the different trips. In this test program the average engine speed is related to the average speed of the vehicle. In other words: in city trips the average engine speed is relatively low, because the average speed of the vehicle and the corresponding power demand is low. In this powertrain configuration the average engine speed is related to the average vehicle speed.

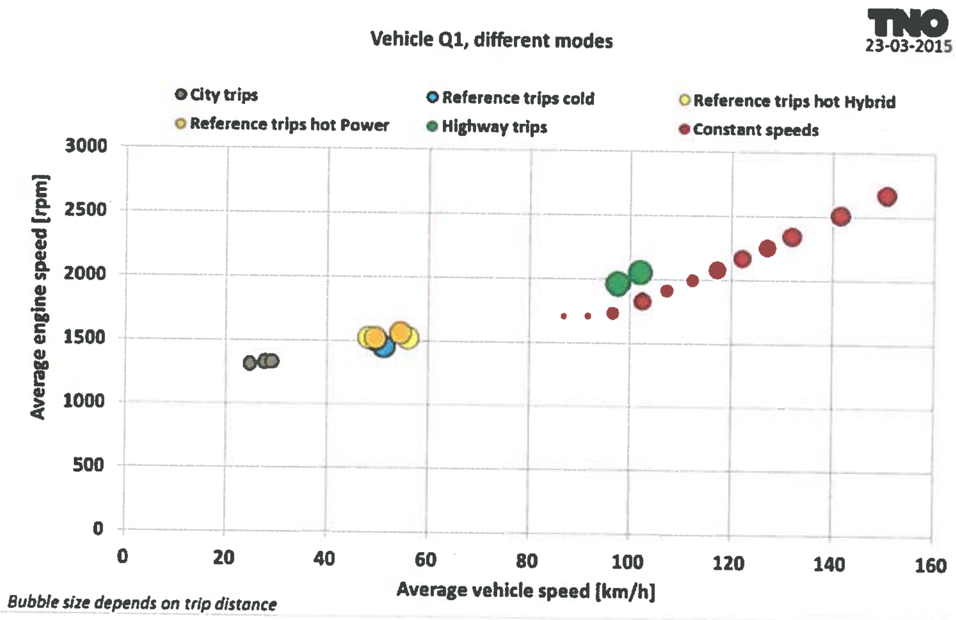

Figure 4: Average combustion engine speed at different trips

3.2.2 *CO_2 emissions*

In Figure 5, the average CO_2 emission per trip is plotted. Except for during the one cold reference trip, the hybrid battery had not been charged from the mains.
In city trips, an economic driving style reduces the CO_2 emission by approximately 30% (from 170 to 120 g/km) . Furthermore, in reference trips, compared to the power mode the hybrid mode of the powertrain reduces the CO_2 emission by approximately 10% (from 180 to 160 g/km).

Figure 6 shows the relationship between the share of engine operating time and CO_2 emission. This figure clearly shows that CO_2 emission is directly related to the share of engine operating time. In other words: a larger share of electric propulsion has a positive effect on the CO_2 emission of the vehicle.

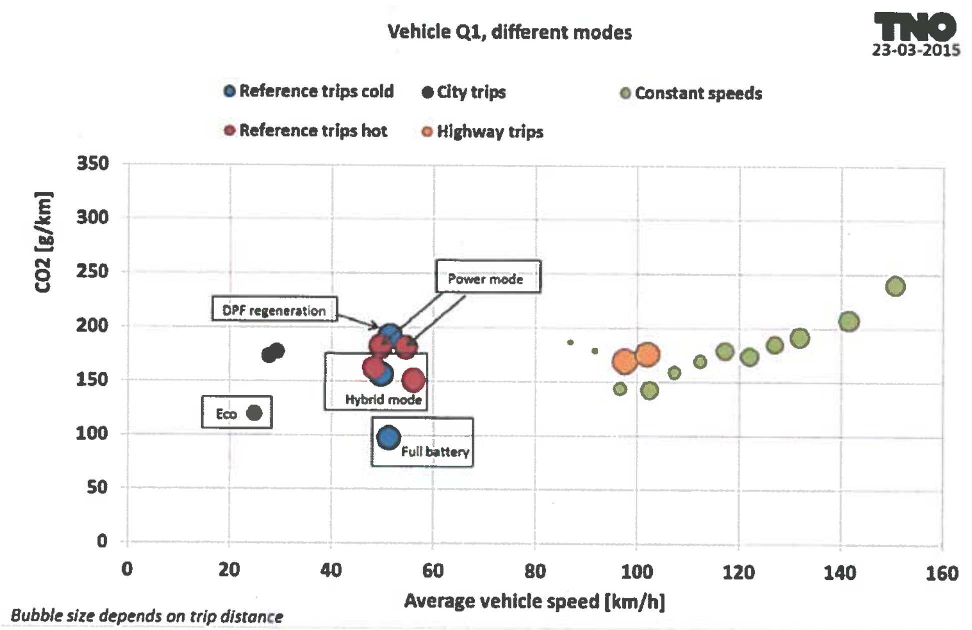

Figure 5: CO_2 emission in different trips.

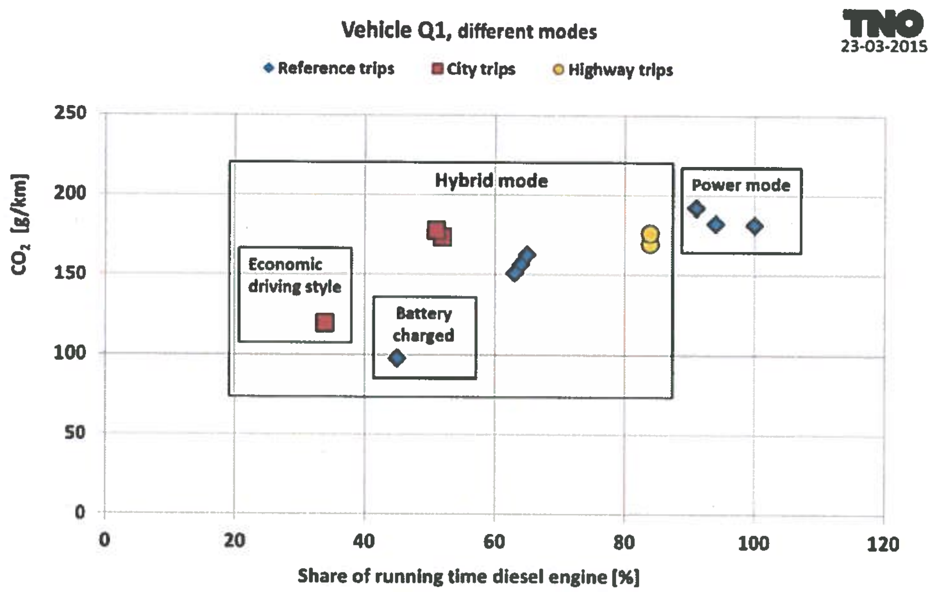

Figure 6: CO_2 emission versus share of running time diesel engine in different trips.

Figure 7 shows the effect of battery charging in the hybrid mode on the share of operation time of the diesel engine. Tests were performed with cold and hot starts. A full battery in the first test decreases the operation time of the diesel engine: during the first execution of the 72 km reference trip, the diesel engine operates approximately 45 % of the time. In the subsequent three reference trips, the diesel engine operates 62 to 65% of the trip time.

Confronting the type-approval CO_2 emission of 48 g/km with the measured real-world CO_2 emission range of 100 – 200 g/km in this test program, this seems to indicate that in the type approval test more full-electric operation is applied than in this on-road test program. The share of electric operation primarily determines the overall average CO_2 emission.

The reference trip is a combined trip of 72 km and has a duration of 90 minutes. In case of a shorter trip (e.g. 20 minutes), the share of full electric operation increases strongly and it is likely that the CO_2 emission in shorter trips with a low average speed reduces to 48 g/km. From these data it can be concluded that the CO_2 emission of a plug-in hybrid vehicle is mainly determined by the trip length and the actual battery state of charge.

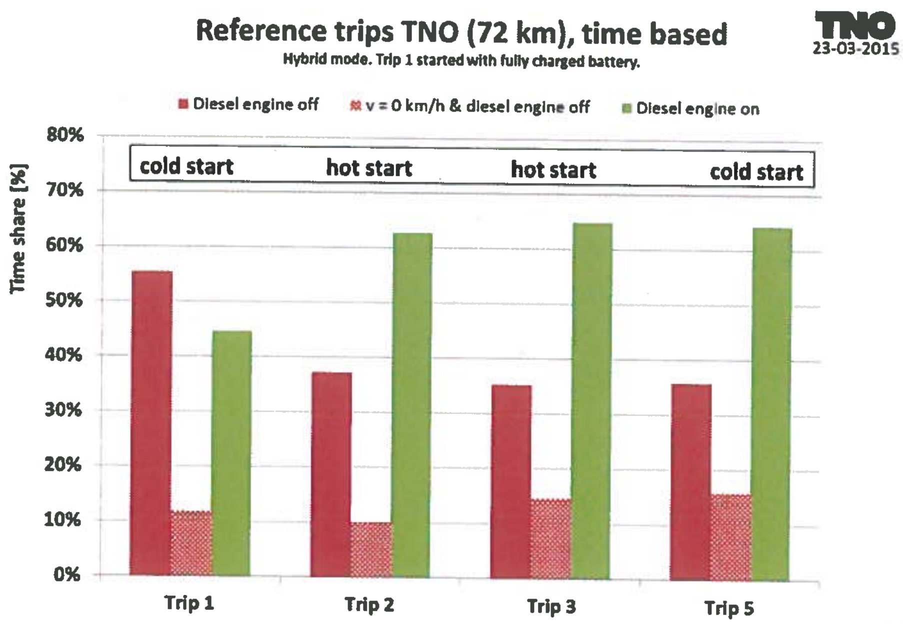

Figure 7: Effect of driving without charging the battery on the share of operation time of the diesel engine.

Figure 8 shows the share of the diesel engine operation time in the vehicle 'Power' mode. In these reference trips with uncharged hybrid battery and regular driving style the diesel engine is virtually always running. In hybrid mode, the diesel engine is running 65% of the time, against 90-100% of the time in power mode. This increase of engine running time in reference trips results on average in a raise of CO_2 emission of 16% (from 157 to 182 g/km).

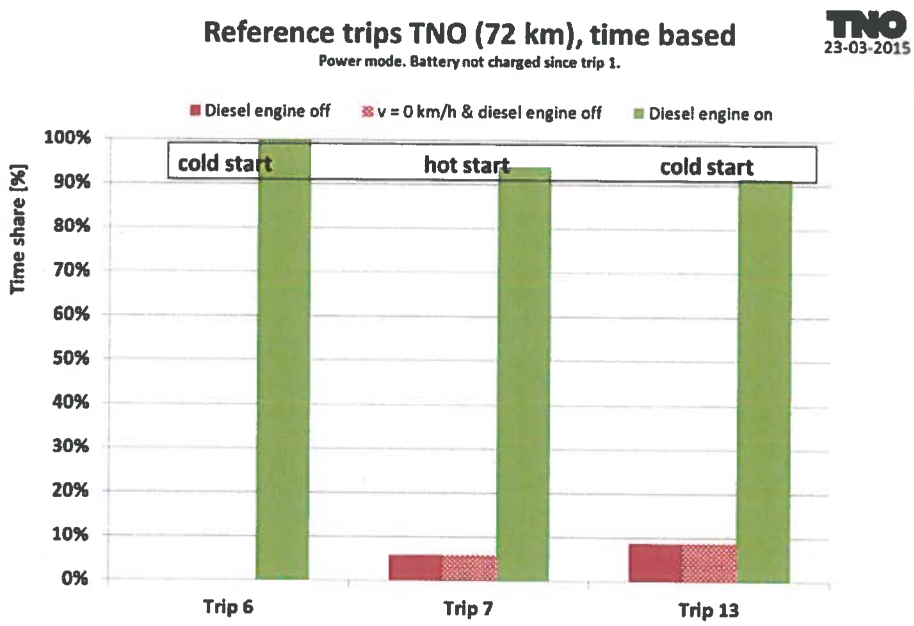

Figure 8: Effect of Power mode on the share of diesel engine operation time with uncharged battery.

3.2.3 *NO_x emission*

In Figure 9 the average NO_x emission of all trips are plotted. Except for during the one cold reference trip, the hybrid battery had not been charged from the mains. The measured NO_x emission in these tests ranges from 350 to 700 mg/km. In the reference trip, which was started with a full hybrid battery, and in the city trip with economic driving style, at approximately 350 mg/km the average NO_x emission is relatively low.

Figure 10 shows a relationship between NO_x emission and the share of engine running time; a reduced engine operation time, battery charging and an economic driving style result in a relatively low average NO_x emission.

The reference trip is a combined trip of 72 km and has a duration of approximately 90 minutes. In case of a shorter trip (e.g. 20 minutes) the share of full electric operation increases strongly and it is expected that the NO_x emission in shorter trips with a low average speed is less than the type-approval emission limit of 180 mg/km.

From these data it can be concluded that the NO_x emission of this plug-in hybrid vehicle is in the range of 350 – 700 mg/km.

The average NO_x emission in a trip is mainly determined by the share of electric propulsion. It is expected that the NO_x emission can be reduced to values below 180 mg/km by increasing the share of full electric operation.

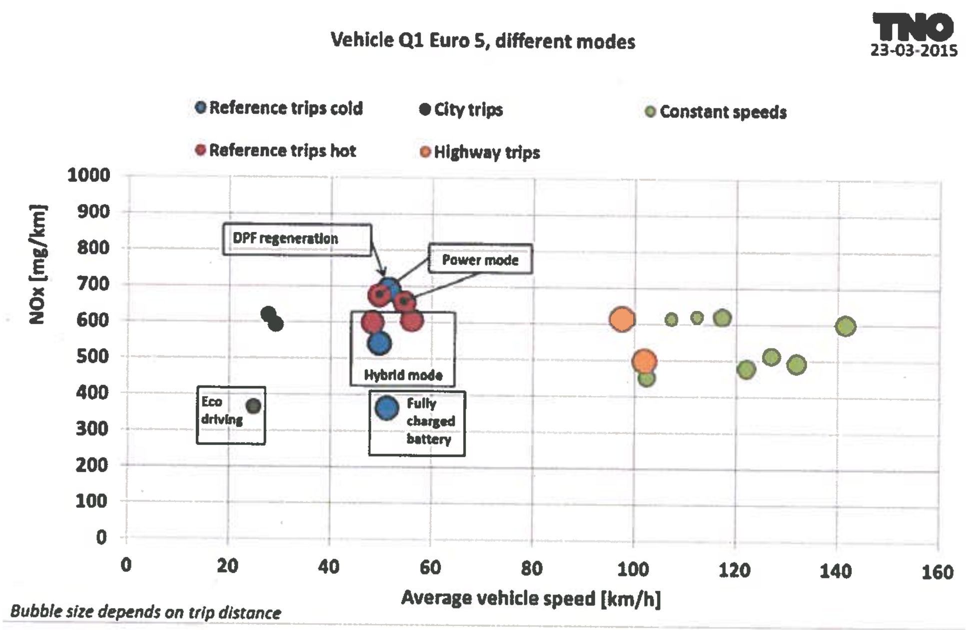

Figure 9: NO_x emission in different trips.

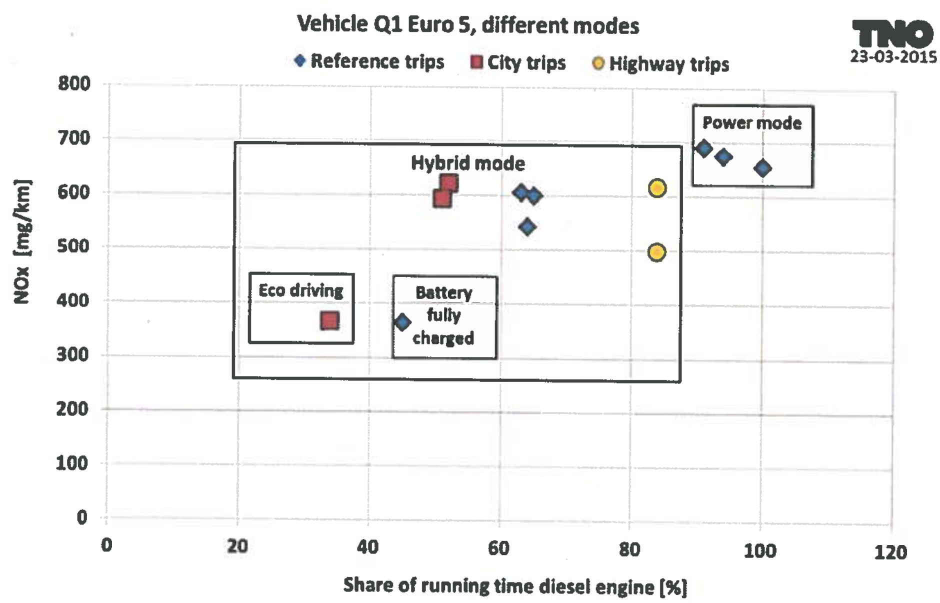

Figure 10: NO_x emission versus share of diesel engine running time in different trips.

Figure 11 shows the NO_x emission of a reference trip with cold start and with fully charged hybrid battery. The results of the trip have been split into five sectors (A – E) and are chronologically plotted. Per sector the average NO_x emission of the vehicle in hybrid operation and the average actual NO_x emission of the combustion engine is plotted. In the first sector (A) the relative share of combustion operation is large. Obviously, the combustion engine is warming up. After this warming-up, the average NO_x emission of the vehicle in the sectors B, C and D is lower because the propulsion is mainly electric. However, in the sectors D and E, the hybrid battery is empty and the emission gradually increases because the relative share of the propulsion of the combustion engine increases.
Due to the pre-charged battery at the start of the test the combustion engine is not continuously running in this trip. Consequently, the average NO_x emission in the sectors varies between 180 and 700 mg/km and on average the NO_x emission is 380 mg/km. The momentary NO_x emission of the vehicle with running combustion engine (diesel operation) varies between 550 and 720 mg/km.

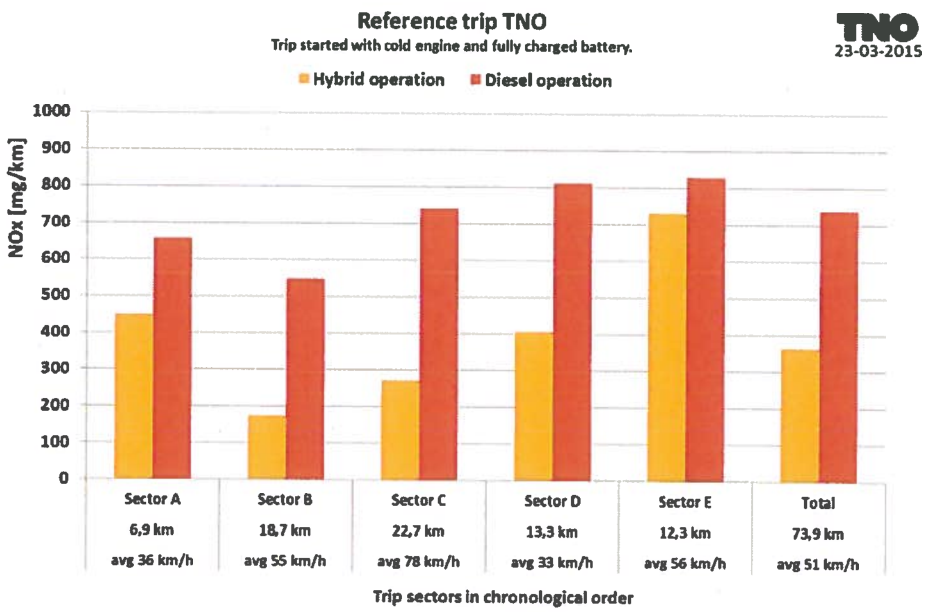

Figure 11: NO_x emission (per sector and total average) in a reference trip (74 km) with cold start and with 100% charged plug-in hybrid battery.

Figure 12 shows the NO_x emission of a reference trip with cold start and with uncharged hybrid battery. The average NO_x emission in this trip is 530 mg/km. Due to the non-pre-charged battery at the start of the test, the combustion engine is running more or less continuously in the sectors A, B and C of this trip. In every sector, the average NO_x emission is high, ranging from 500 to 700 mg/km.

The results in Figure 11 and Figure 12, depicting the trips with charged and uncharged battery respectively, show that the momentary NO_x emission of this plug-in hybrid vehicle with an operating diesel engine in the different trip sectors is between 550 and 820 mg/km. The average NO_x emission ranges from 180 to 720 mg/km and very dependent on the share of electric vehicle propulsion.

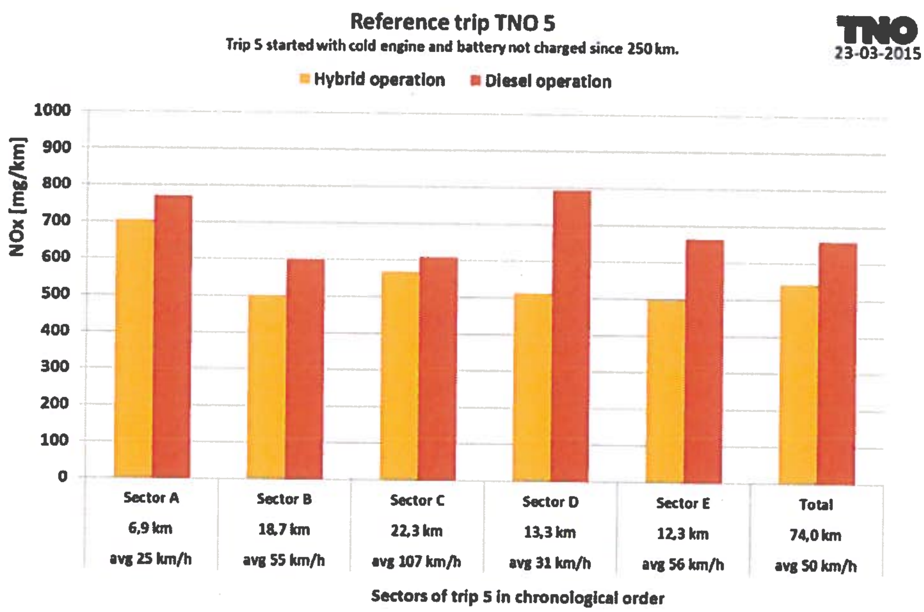

Figure 12: NO_x emission (per sector and total average) in a reference trip (74 km) with cold start and with uncharged plug-in hybrid battery.

Figure 13 shows the NO_x emission of a reference trip with hot start and with uncharged hybrid battery. Due to the non-pre-charged battery at the start of the test, the combustion engine is running more or less continuously in this trip. In every sector, the average NO_x emission is high, ranging from 500 to 1030 mg/km. On average, the NO_x emission is 600 mg/km.
The NO_x emission results of the reference trips with uncharged battery with cold and hot start (see Figure 12 and Figure 13 respectively) differ slightly. This indicates a stable strategy of the NO_x emission control, independent of the engine temperature.

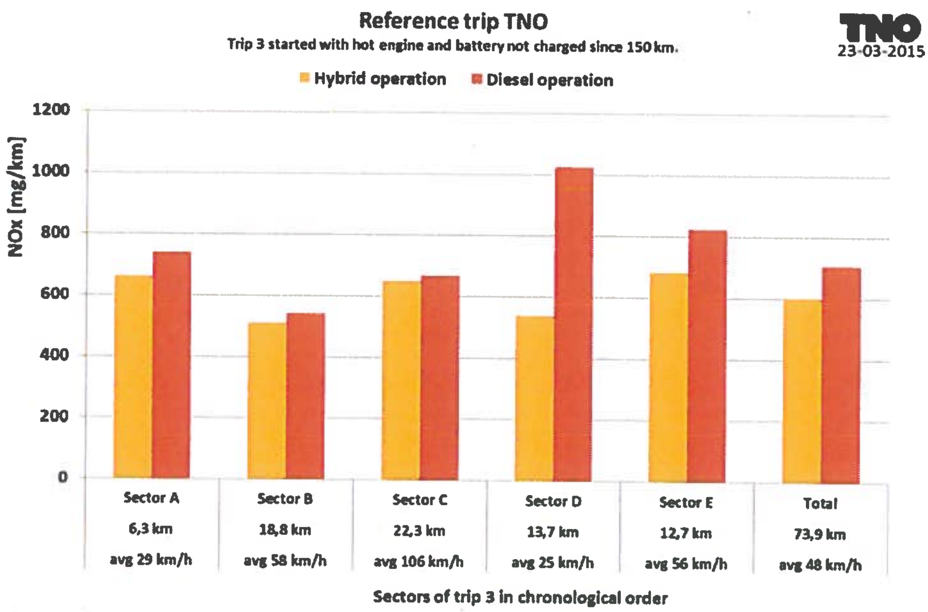

Figure 13: NO_x emission (per sector and total average) in a reference trip (74 km) with hot start and with uncharged plug-in hybrid battery.

4 Discussion

How do real-world emissions of this diesel plug-in hybrid vehicle relate to type approval emissions?
According to the type approval documents, this vehicle has a CO_2 emission of 48 g/km and the NO_x emission is below 180 mg/km. It seems that these numbers may be reached at most favourable conditions in a trip with a length of 21 km.
The NO_x and CO_2 on-road test results of the executed program vary widely and are very dependent on the state of charge of the hybrid battery. In this test program, the CO_2 emission ranges from 100 to 200 g/km; the NO_x emission is between 550 and 800 mg/km. Full electric operation of the powertrain results in a zero-emission vehicle. In real-world conditions, however, the electric range is limited to 50 km. Moreover, at higher vehicle speeds the performance of the electric powertrain is not sufficient and the diesel engine is activated. This vehicle configuration enables a low emission vehicle in urban areas at shorter trips. When the vehicle is used with an uncharged hybrid battery on longer trips (> 50 km) however, the diesel engine operates more or less continuously. In that case, on average the NO_x emissions are 2 to 5 times higher than the type approval values.

AECC [AECC2013] and CE&TNO [CE2014] report the NO_x emission performance of a petrol hybrid vehicle. On average the NO_x emission of a petrol plug-in vehicle does not exceed 20 mg/km.

In comparison to a conventional diesel vehicle (no hybrid), the real-world emission of plug-in hybrid vehicles may vary far more because full electric propulsion does not yield vehicle pollutants.

Observing these results, it is obvious that real-world emissions of plug-in hybrid vehicles strongly depend on the behavior of the driver. More charging of the hybrid battery from the mains directly reduces the average CO_2 and NO_x emission. Research has shown, however, that users of plug-in hybrids do not often charge the battery from the mains: 70-85% of the distance travelled is not covered by the energy charged through the electricity network [TNO2014a]. Finally, the applied powertrain mode, i.e. electric, hybrid or power, which can be chosen by the driver, also strongly affects the emission.

5 Conclusions

The real-world NO_x and CO_2 emissions of a plug-in hybrid vehicle with a diesel engine have been determined in an on-road emission test program. Different test routes, driving styles and battery charging regimes were applied. From these tests the next conclusions can be drawn:

1. In this test program, the average real-world NO_x emission of this plug-in hybrid vehicle in different trips ranges from 350 to 700 mg/km and depends on the share of electric propulsion in a trip. This emission level is in line with the current Euro 5 NO_x emission factor of passenger cars. It is expected that the average NO_x emission of this vehicle can be decreased to the type-approval emission limit of 180 mg/km by increasing the share of full-electric operation to over 75% of the distance travelled.

2. The average CO_2 emission of this plug-in hybrid vehicle is in the range of 100 to 240 g/km and is 2 to 5 times higher than the type approval specification of 48 g/km. A real-world CO_2 emission of 48 g/km can probably only be achieved with a 100%-charged hybrid battery, an electric powertrain propulsion mode, a low average vehicle speed, an economic driving style, short trips and battery charging after each trip.

3. Due to (de)activation of the combustion engine in the different test trips, the actual NO_x and CO_2 emissions are 0 mg/km in case of electric propulsion, and emissions up to 4 to 5 times the type approval limit value in case the combustion engine is switched on. This results in a 'digital' vehicle emission behaviour, i.e. the actual emissions are either zero or at a constant high level. Consequently, a decrease of the average emissions is only possible by an increase of the share of electric propulsion. This large variation in actual vehicle emissions of this new powertrain technology will result in emission factors with more bandwidth.

4. In the Netherlands, the reduction potential of emissions of vehicles with diesel plug-in hybrid technology is mainly neutralised because 70-85% of the distance is not covered by the energy charged through the electricity network.

6 References

[TNO2012]	A smart and robust NOx emission evaluation tool for the environmental screening of heavy-duty vehicles, Vermeulen et.al. 2012, TNO and Ministry of Infrastructure and the Environment, the Netherlands. (TAP conference 2012, Thessaloniki, Greece)
[TNO2014]	SEMS operating as a proven system for screening real-world NOx and NH3 emissions, Vermeulen et.al. 2014, TNO and Ministry of Infrastructure and the Environment, the Netherlands. (TAP conference 2014, Graz Austria)
[TNO2014a]	Update analysis of real-world fuel consumption of business passenger cars based on Travelcard Nederland fuelpass data. TNO and Ministry of Infrastructure and the Environment, the Netherlands. Report TNO 2014 R11063
[AECC2013]	Exhaust Emissions from European Market- Available Passenger Cars Evaluated on Various Drive Cycles, Cecile Favre et. al., SAE paper 2013-24-0154
[CE2014]	Brandstoffen voor het wegverkeer. Factsheets CE & TNO 2014

7 Signature

Delft, 19 June 2015 TNO

Jordy Spreen
Project manager

Gerrit Kadijk
Author

A Test trip results

Trip		Part	Speed	Duration	Distance	Nox tailpipe	CO2	Temp after cat	Engine speed
			[km/h]	[s]	[km]	[mg/km]	[g/km]	[degC]	[rpm]
150303_01_V60_REF_REG_C.V2	1	Total	51.2	5196	73.9	364	98	68	1451
150304_05_V60_REF_REG_C.V2	4	Total	49.6	5363	74.0	542	157	96	1509
150303_02_V60_REF_REG_W.V2	2	Total	56.0	4739	73.7	606	151	106	1522
150303_03_V60_REF_REG_W.V2	3	Total	48.3	5511	73.9	600	163	105	1522
150304_06_V60_REF_REG_POWER_W.V2	5	Total	54.5	4811	72.8	656	182	117	1561
150304_07_V60_REF_REG_POWER_W.V2	6	Total	49.6	5332	73.4	675	182	110	1522
150303_04_V60_CITY_REG_W.V2	7	Total	27.7	3499	27.0	621	173	88	1323
150304_08_V60_CITY_ECO_W.V2	8	Total	24.8	3873	26.7	366	119	71	1308
150305_12_V60_CITY_SPORT_W.V2	9	Total	29.2	3275	26.5	593	177	91	1327
150304_13_V60_REF_REG_POWER_C.V2	13	Total	51.4	5198	74.2	691	192	112	1508
HELM_DUITSLAND_W	10	Total	97.4	3182	86.1	615	169	138	1965
DUITSLAND_HELM_W	11	Total	101.9	3020	85.5	498	176	147	2054
Constant speed	12	Total	86.8	128	3.1	1172	186	147	1708
Constant speed	12	Total	91.6	171	4.4	1126	178	148	1711
Constant speed	12	Total	96.6	775	20.8	628	144	131	1737
Constant speed	12	Total	102.4	1493	42.5	452	143	137	1825
Constant speed	12	Total	107.2	701	20.9	615	159	139	1915
Constant speed	12	Total	112.3	666	20.8	621	169	152	1998
Constant speed	12	Total	117.2	1292	42.1	621	179	201	2078
Constant speed	12	Total	122.1	1312	44.5	478	174	152	2171
Constant speed	12	Total	127.0	1127	39.8	513	185	157	2256
Constant speed	12	Total	131.9	1416	51.9	492	192	161	2344
Constant speed	12	Total	141.6	1404	55.2	600	207	172	2513
Constant speed	12	Total	150.6	1171	49.0	2194	240	208	2672