Earth, Life & Social Sciences
Princetonlaan 6
3584 CB Utrecht
P. O. Box 80015
3508 TA Utrecht

www.tno.nl

T +31 88 866 42 56

TNO report

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In-use compliance and deterioration of vehicle emissions

Date	8 July 2015
Author(s)	Dipl. Ing. P.S. van Zyl (TNO) Dr. N.E. Ligterink (TNO) Ing. G. Kadijk (TNO) J. Borken-Kleefeld PhD (IIASA) Yuche Chen PhD (IIASA)
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Summary

Vehicle pollutant emissions deteriorate in the course of the vehicle lifetime, e.g., due to wear and low maintenance. Due to the different nature of pollutants, applied technologies, vehicle use and real world conditions the spread in deterioration is expected to be wide. This deterioration of vehicle emissions has been established in the Netherlands about ten years ago and used within the national inventories (see Task Force Traffic and Transport of the National Emission Inventory), however, from recent study by IIASA there are indications that the supposed deterioration is an underestimation of the actual effect. Moreover, most of the deterioration studies are a few cars, with limited statistics. In the emission test database at TNO are a number of accidental recurrences, of vehicles used for different test programs. The data is matched to generate pairs of the same vehicle on the same test for different mileages. This provided more data than was used in the past.

The increase in emissions due to deterioration is set to stop at nine years in Dutch emission inventory. In the Emission Inventory Guidebook, it is capped at 120 000 km. In this report the nine years is maintained, to keep the method in line with the current approach. However,measurements are limited beyond nine years and 120 000 kilometres, to warrant a change. The IIASA data shows and further increase, however, one would expect the increase to be capped at Euro-0 levels by some basic technological and physical principles.

The approaches in emission deterioration are not completely arbitrary. These are related to similar factors, mileages and duration in the emission legislation. The duration factors and in-use compliance became more stringent over the years. The approaches in the inventories have not altered yet.

The aim of this report is to (re-)evaluate the effect of in-use compliance and deterioration of petrol and diesel vehicle emissions (CO, THC, NO_2/NO_x, PM10 and NH_3) in the course of the vehicle lifetime.

National, international and specifically European data dealing with vehicle emissions deterioration and risks of failing technology have been assessed and vehicle aging effects have been estimated based on the probability and significance factor.

The results have led to the conclusion that currently used cold deterioration factors used by TNO should about double for CO, HC and NOx by from 50% to 100% increase in 9 years. PM emissions do not deteriorate, as there is not yet a clear trend visible. A suggestion for adaptation has been made and is shown below (see Table 1 and Table 2). Hot emissions remain unchanged, since there is not sufficient evidence for change. Diesel vehicles have no deterioration factors as yet. However, there a large number of risks for emission increase, especially on the more modern diesel vehicles. There is no underlying data, hence to deterioration is proposed. However, it is important to monitor deterioration as it is expected as the more sophisticated emission control from Euro-2 vehicles onwards have a higher risk of deterioration, with higher associated emissions as well.

Table 1 Updated deterioration factors of Euro 1 and 2 petrol vehicles (NEDC cycle with cold start).

vehicle lifetime	0	1	2	3	4	5	6	7	8	9+
CO	1.00	1.09	1.18	1.26	1.35	1.44	1.53	1.61	1.70	1.79
THC	1.00	1.05	1.11	1.16	1.21	1.27	1.32	1.37	1.42	1.48
NOx	1.00	1.11	1.21	1.32	1.43	1.54	1.64	1.75	1.86	1.97
PM10	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table 2 Updated deterioration factors of Euro 1 and 2 petrol vehicles (hot).

vehicle lifetime	0	1	2	3	4	5	6	7	8	9+
NOx	1.00	1.12	1.24	1.36	1.49	1.61	1.73	1.85	1.98	2.1

It is recommended to study deterioration of vehicle emissions in more detail because current measuring data is restricted or not representative. The data is mostly based on measuring data of Euro 1 and Euro 2 vehicles and cover only the deterioration of emissions of older vehicles. Moreover the deterioration of Euro 3-6 vehicles probably differs strongly because deterioration is mainly determined by the performance of the catalysts.

Although, a different approach, the deterioration factors are more or less in line with the final deterioration at nine years and beyond as specified Emission Inventory Guidebook. In the guidebook, after 120,000 kilometres, which corresponds to about nine years of operation, the emissions of CO, THC, and NOx, Euro-1 and Euro-2 petrol vehicles are doubled with respect to the test results. There is no distinction in cold start and hot start emissions in the Guidebook, which is an essential difference with the approach in this study. The absolute numbers are not necessarily comparable, as the vehicle categories are different and the approach for handling the effect on emissions of road-types and congestion is incomparable.

Contents

1 Introduction

1.1 Background

Vehicle emissions deteriorate in the course of the vehicle lifetime, e.g., due to wear and low maintenance. This deterioration of vehicle emissions has been established in the Netherlands about ten years ago (see Task Force Traffic and Transport of the National Emission Inventory), however, there are indications that the supposed deterioration is an underestimation of the actual effect. Since the analysis was performed before the Euro 5/V was introduced, for modern vehicles, there are few insights into the deterioration of vehicle emissions.

Higher emissions of modern vehicles are mainly the result of technology failure, for example due to a broken diesel particulate filter (DPF), a stuck exhaust gas recirculation (EGR) valve, a faulty sensor or similar. Even though the chance of technology failure is low, the effect on additional emissions are high and for this reason cannot be disregarded.

1.2 Aim and approach

The aim of this report is to (re-)evaluate the effect of in-use compliance and deterioration of vehicle emissions in the course of the vehicle lifetime.

<u>The following approach will be taken:</u>
1. An overview is provided of currently-used deterioration factors for vehicle aging effects as used in the Task Force Traffic and Transport of the National Emission Inventory.
2. Collect International and specifically European data dealing with vehicle deterioration.
3. Estimation of vehicle aging effects based on the probability and significance factor.
4. Estimation of level of risks of failing technology based on the extra emissions.
5. Recommendation for possible adjustments and further study.

1.3 Scope

The deterioration of vehicle emissions will be expressed in deterioration factors as the percentage of emissions at a vehicle lifetime x years in comparison to a vehicle lifetime of 0 years. Deterioration factors are documented for the first nine years. Above nine years, the correction factors are expected to remain on the same level as for nine years. The assumption of nine years is based on the legal durability requirements and the relevant age of vehicles. However, modern vehicles have a longer average lifetime, doing more distance. Currently, petrol vehicles are scrapped after about 280 000 kilometres on average.

1.4 Structure of the report

Each step described in the approach above is dealt with in a separate chapter.

2 Inventory deterioration per emission component

Up to now, there is very limited information available on the failure of modern emission reduction technology. The high NO_x emissions of modern diesel vehicles cannot be considered a failure as it occurs for many vehicles with no apparent malfunction. In the next paragraphs the risks per fuel type and emission component is discussed.

Carbon monoxide (CO):
Petrol: The CO emission increase can be caused by incomplete combustion or deterioration of the catalyst. Incomplete combustion is a very scarce phenomenon because drivers do not tend to drive with vehicle with less engine performance. It is expected that a small amount of older vehicles is a high emitter (low risk). Deterioration of the catalyst is a very slow and steady process, possibly accelerated by the use of poor fuel quality, e.g., outside Europe. Therefore it is expected that the CO emission slowly increase over time.
Diesel: Direct injected diesel engines without oxidation catalyst tend to have increasing CO-emissions because fuel injectors deteriorate. In modern engines this increase of CO-emission is neutralized by the oxidation catalyst.

Carbon dioxide (CO_2):
Due to increased internal engine friction which can be caused by a lack of maintenance the CO_2 emission of vehicles can increase over time. Furthermore, Diesel Particulate Filters of diesel vehicles tend to regenerate more frequently in time, this results in a slightly higher CO_2 emission. Moreover, clogged DPF generate more back pressure associated with increased fuel consumption.

Hydrocarbons (THC):
Petrol: The most prominent increase of THC emissions of petrol engines is caused by deterioration of the three-way catalyst. The light-off temperature of the catalyst increases over the life time; therefore THC emission at cold engine operation increases, and warm emission will increase. Also here incomplete combustion may play a role high emissions.
Diesel: Direct injected diesel engines without oxidation catalyst tend to have increasing THC-emissions because fuel injectors and engines deteriorate. In modern engines (Euro 2 onwards) this increase of THC-emission is neutralized by the oxidation catalyst.

Nitrogen Oxides ($NO + NO_2$):
Petrol: The most prominent increase of NOx emissions of petrol engines is caused by deterioration of the three-way catalyst and or lambda sensor. The light off temperature of the catalyst increases over the life time or the operating window of a lambda sensor shifts to lean operation.
Diesel: Direct injected diesel engines tend to have increasing NOx-emissions because EGR-systems deteriorate. Diesel engines without EGR-systems are less sensitive and have a more stable NOx performance over their life time. The NO_2 fraction in NO_x will decrease with the aging of the oxidation catalysts commonly used from Euro 2 vehicles.

Particulate Matter (PM):
Petrol: PM emissions of petrol engines are very low and have a low tendency for deterioration. The main cause for this relative small deterioration is the increase of burnt lubrication oil.
Diesel: Direct injected diesel engines without wall flow diesel particulate filter (DPF) tend to have increasing PM-emissions because fuel injectors and turbo chargers deteriorate. In modern engines this increase of PM-emission is neutralized by the DPF. For this category the PM-deterioration is mainly caused by failing DPFs or DPF removals.

NH_3 emissions:
Petrol: NH_3 emissions are typically associated with older three-way catalysts, i.e., petrol and LPG vehicle after 1991. This is consistent with the current findings for NH_3 emissions, and the earlier emission tests on Euro-1 and Euro-2 vehicles. Previously, in 2002-2004, the NH_3 emission were substantially lower than recent Remote Emissions Sensing (RES) measurements in the UK [DEFRA2013]. Probably the increased engine out THC-emission leads to more oxidation of these hydrocarbons which results in higher NH_3 emission. It is assumed that both results are correct and representative for the vehicle fleet. Consequently the NH_3 emissions have increased threefold in the last ten years. Modern vehicles (Euro-3 and newer) seem to have lower baseline NH_3 emissions and less deterioration.
Diesel: Apart from possible deterioration light-duty vehicles with SCR-technology have a risk of NH_3 emission because these emissions are not regulated. Furthermore the deterioration of these SCR-catalysts may lead to increased NH_3 emission.

3 Current deterioration factors & conditions

Vehicle emissions deteriorate in the course of the vehicle lifetime. =The current approach to include deterioration effects has been established in the Netherlands in 2009 by the Task Force Traffic and Transport of the National Emission Inventory. In this chapter, the legal deterioration factors, to which manufacturers must comply are provided as a function of the vehicle lifetime in years.

3.1 Currently used deterioration factors

Currently used emission factors are based on Boulter [Boulter, 2009]. Boulter performed a meta-study of the available studies on emission deterioration. However, since Euro-4 was introduced in around that time, the study concerns only older legislation classes. The study is also an important basis for the Emission Inventory Guidebook. Figure 1 to Figure 8 show the deterioration factors for the emissions CO, THC, NOx, PM10. It is differentiated between different Euro-classes as well as hot and cold emissions of petrol and LPG vehicles. No information is documented on the deterioration factors of Diesel fuel vehicles. Correction factors are displayed as a percentage of the emissions a newly registered vehicle at a lifetime of zero years.

3.2 Emission deterioration parameters in European directives

In Table 3 and Table 4 the history of the European deterioration parameters of light-duty vehicles are briefly reported. From these data it is clear that the deterioration requirements become more stringent in time. The Euro 5 and 6 vehicles must perform over a longer lifetime at relatively low emission levels than former Euro classes. Consequently vehicle manufacturers have had to design vehicles with increasing durability requirements and emission control systems need to be more robust. I.e. Euro 6 vehicles need more accurate emission control systems which last longer than lower Euro class vehicles. From this point of it is expected that vehicle emission deterioration of Euro 5 and 6 vehicles is less than older vehicles because the emission control systems of Euro 5 and 6 vehicles have a higher quality. The shift in increased emissions is more in terms of failure risk than slow and known deterioration.

Table 3 European deterioration factors of petrol vehicles.

	Emission Class					
	1	2	3	4	5	6
70/220/EEC + ammendm.	X	X	X	X	-	-
EC 715/2007 EC 692/2008	-	-	-	-	X	X
Distance [km]	80.000	80.000	80.000 or 5 yrs.	100.000 or 5 yrs.	160.000	160.000
CO	1,4	1,5	1,2	1,2	1,5	1,5
THC and NMHC	1,4	1,5	1,2	1,2	1,3	1,3

NOx	1,4	1,5	1,2	1,2	1,6	1,6
PM	-	-	-	-	1,0	1,0
EOBD	No	No	No	Yes	Yes	Yes

Table 4 European deterioration factors of diesel vehicles.

	Emission Class					
	1	2	3	4	5	6
70/220/EEC + ammendm.	X	X	X	X	-	-
EC 715/2007 EC 692/2008	-	-	-	-	X	X
Distance [km]	80.000	80.000	80.000 or 5 yrs.	100.000 or 5 yrs.	160.000	160.000
CO	1,1	1,1	1,1	1,1	1,5	1,5
HC+NOx	1,0	1,0	1,0	1,0	1,1	1,1
PM	1,2	1,3	1,2	1,2	1,0	1,0
EOBD	No	No	No	Yes	Yes	Yes

3.3 Conclusions

Deterioration correction factors for the Dutch vehicle fleet are currently available:

- for light-duty vehicles,
- for the fuel types petrol and LPG,
- for the Euro-classes 0 to 4,
- for the emissions CO, THC, NO_x and PM10.

In general, it is assumed that

- deterioration factors increase over time,
- hot emissions need stronger correction than cold emissions,

newest Euro-classes require smaller deterioration factors.
The longer monitoring mileages, from 80 000 kilometres to 160 000 kilometres are likely to ensure more robustness in emission control technology, than the leniency in the associated durability factors in the legislation. This may be the reason why the observed deterioration for newer vehicles is lower.

There are several reasons why emissions change over the lifetime of a vehicle and thus why deterioration factors are required. In chapter 4, the development of emission factors over time is analyzed at hand of emission measurements from TNO and RES performed in Zurich and analyzed by IIASA.

In Figures 1 to 7 are the current deterioration factors used in the Netherlands for different vehicle categories of passengers cars, and the different pollutant emissions.

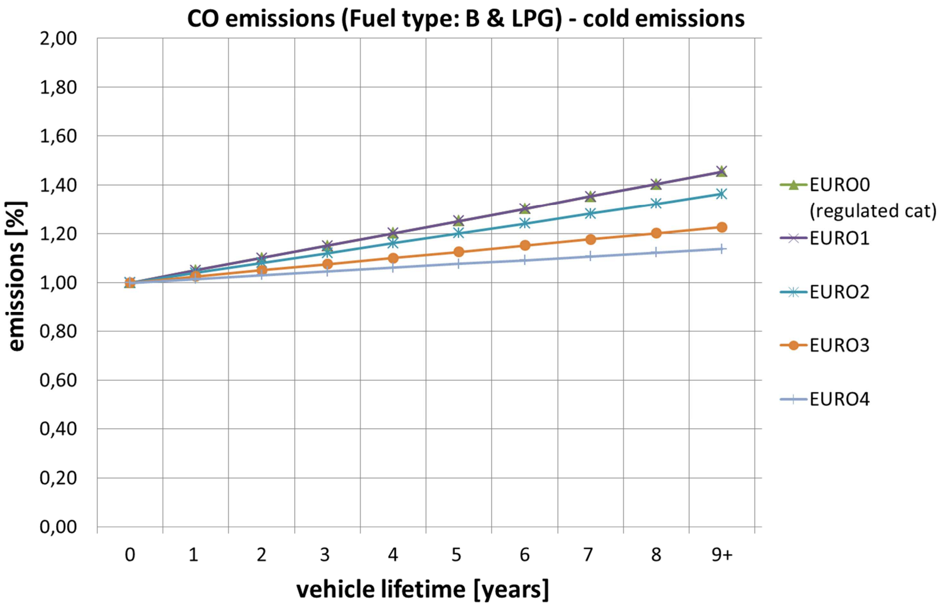


Figure 1 CO deterioration factors for cold start emissions, petrol vehicle (1=100%) (markers do not indicate measuring points).

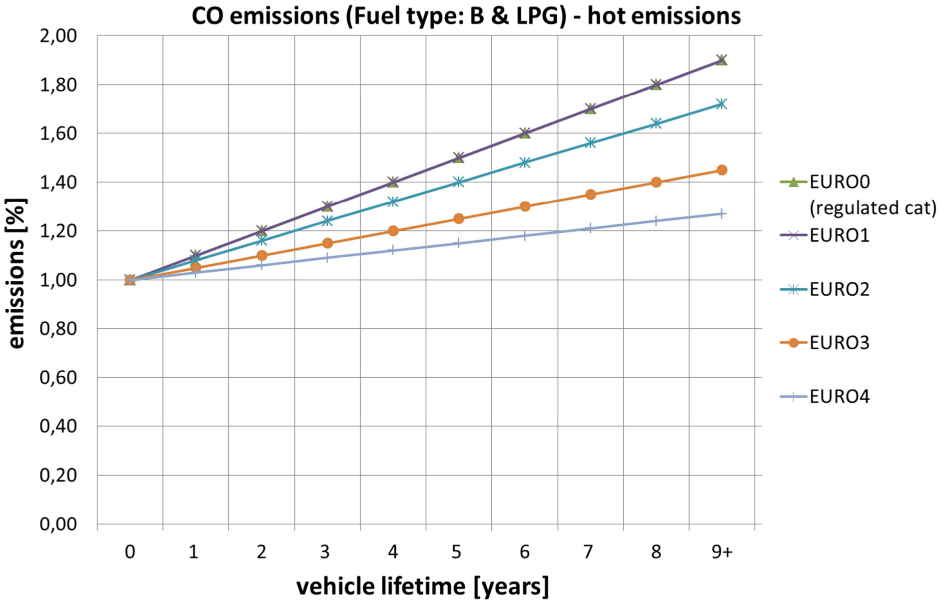


Figure 2 CO deterioration factors for hot MVEG cycle emissions, petrol vehicle (1=100%) B = Petrol.

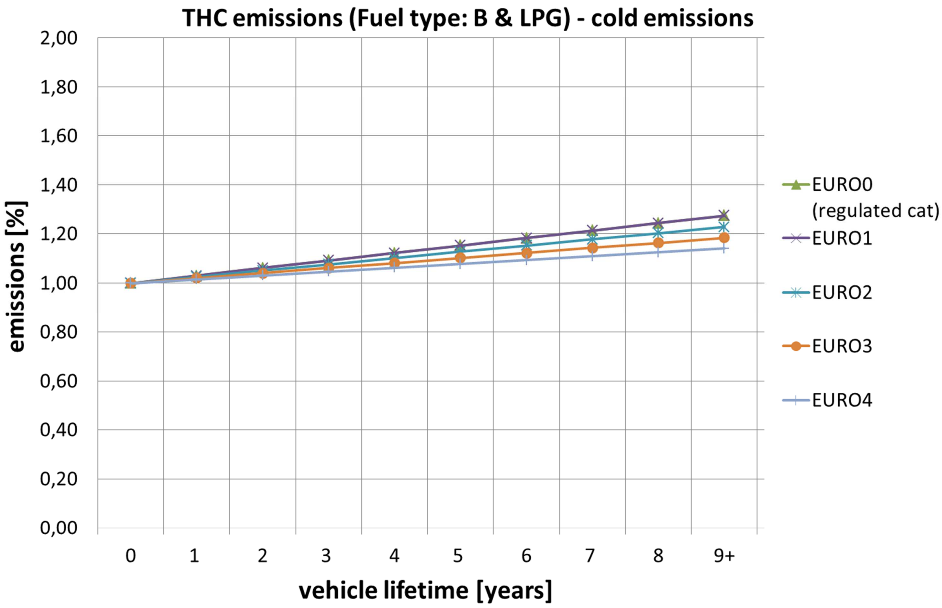


Figure 3 THC deterioration factors for cold start emissions, petrol vehicle (1=100%).

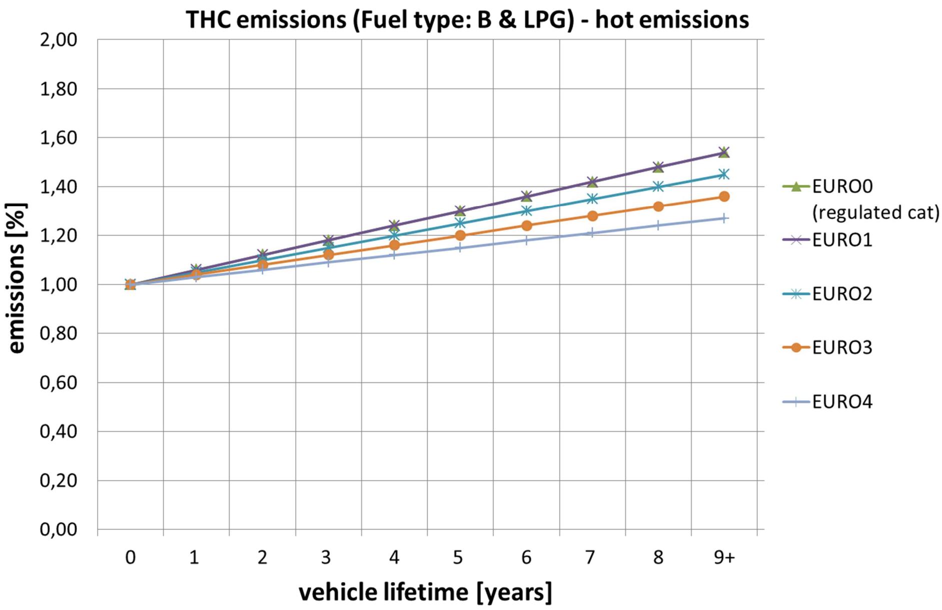


Figure 4 THC deterioration factors for hot emissions, petrol vehicle (1=100%).

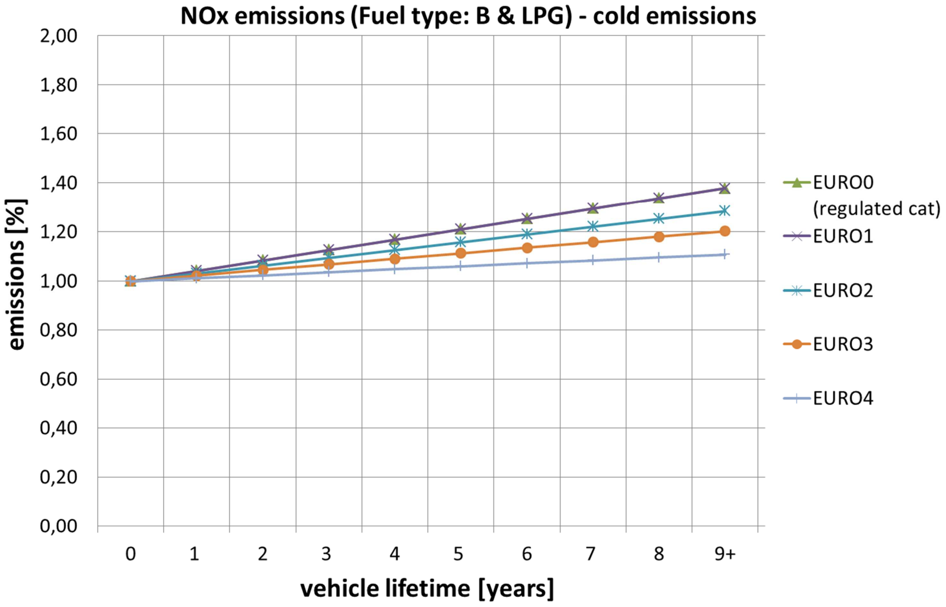


Figure 5 NOx deterioration factors for cold start emissions, petrol vehicle (1=100%).

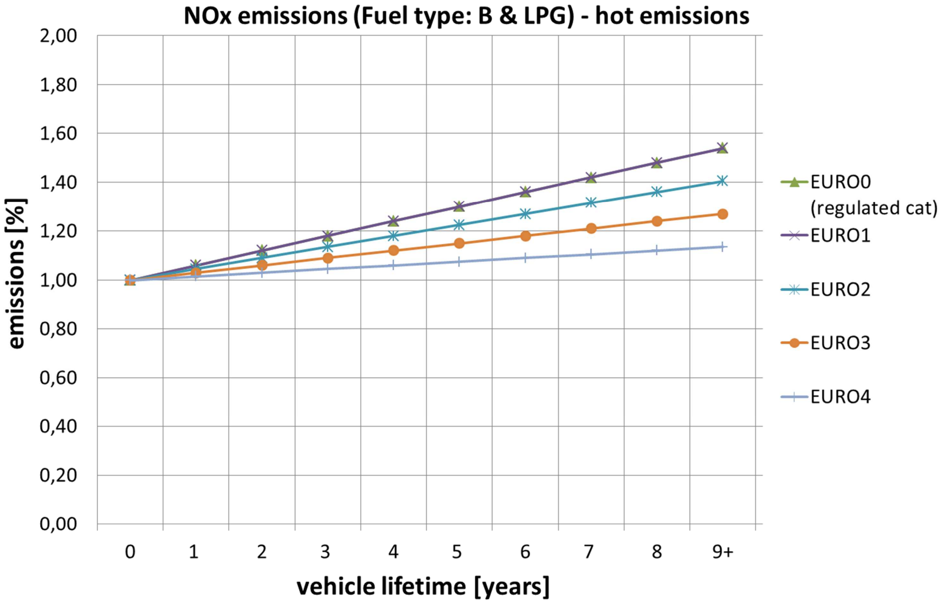


Figure 6 NOx deterioration factors for hot emissions, petrol vehicle (1=100%).

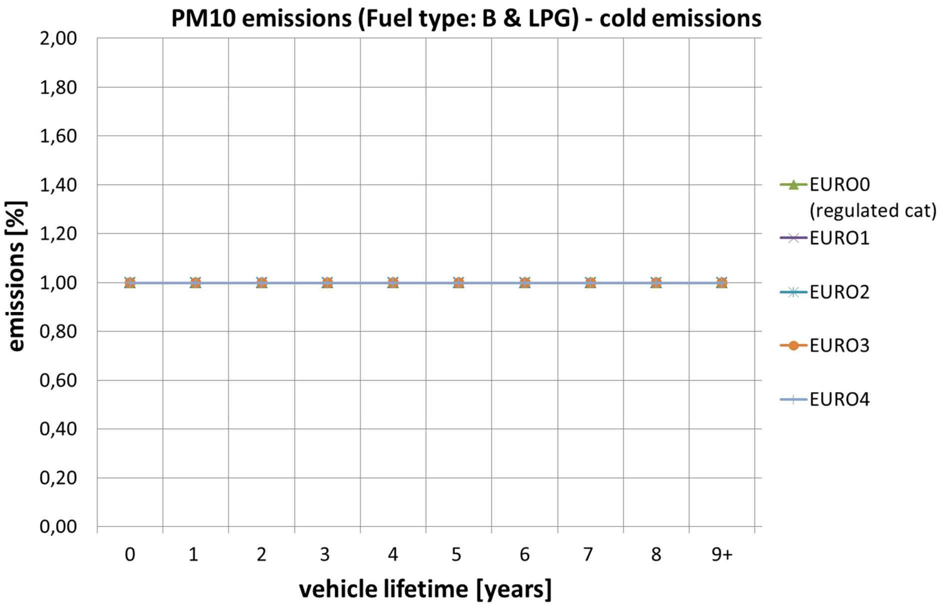


Figure 7 PM10 deterioration factors for cold start emissions, petrol vehicle (1=100%).

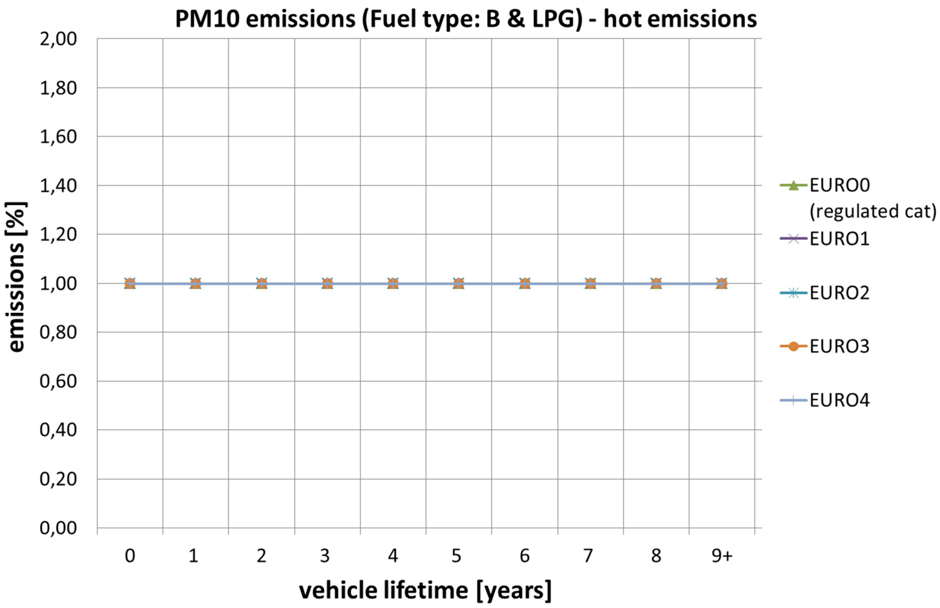


Figure 8 PM10 deterioration factors for hot emissions, petrol vehicle (1=100%).

4 International and specifically European data dealing with vehicle deterioration

In this chapter, data on vehicle deterioration is collected and compared with the aim to derive more accurate and up-to-date deterioration factors. Data was gathered from:

- TNO in-house emission measurements,
- Zurich remote emission sensing (RES) measurements (analysed by IIASA).

Both data sets include measurements of several vehicles monitored over several years. The data is analysed in terms of the emission deterioration over time and distance travelled.

In the next two subsections, the measurements from TNO and IIASA are dealt with separately in more detail. Based on the measurements, updated deterioration factors are introduced subsection 4.3. Of specific interest are the NOx emissions and THC emissions for petrol vehicles, however for completeness all emission measurements will be displayed and discussed.

4.1 TNO emission measurements and deterioration rates

TNO's data collection comprises a set of in total 168 vehicles (24 different brands, 96 different models) which were measured over a period of several years. Data of 22 different test cycles (mostly CADC) were used from diesel and petrol vehicles covering Euro 0 to Euro 4. An overview of all measurements is given in Table 5.

Table 5 Overview of vehicles tested by TNO on the same test at different mileages.

Fuel type	Euro-class	Number of vehicles tested
Petrol	0	106
	1	4
	2	24
	4	1
Diesel	0	7
	1	7
	2	16
	3	3

The measurements were analysed in terms of CO, CO_2, THC and NO_x emissions . Results are discussed separately for:

- different fuel types,
- different Euro-classes,
- hot and cold measurements.

In order to condition the data, mean values were determined at specific bin values. The bin values were chosen as the average mileage of vehicles in the Netherlands at a specific vehicle age.
The average mileage was taken from CBS [CBS, 2014], see Table 6.

Table 6 Average mileage per year [CBS, 2014].

Years	<1	1 and 2	3 and 4	5 and 6	7 and 8	9 and 10	10+
Petrol	9213	15109	12848	11280	11098	10801	8703
Diesel	20490	33199	26616	23066	21940	20022	16173

Table 7 Cumulative mileage per year in km x 1000 [CBS, 2014].

Years	<1	2	3	4	5	6	7	8	9	10
Petrol	9.2	24.3	39.4	52.3	65.1	76.4	87.7	98.8	109.9	120.7
Diesel	20.5	53.7	86.9	113.5	140.1	163.2	186.3	208.2	230.1	250.2

4.1.1 Petrol vehicle measurements

For petrol vehicles, it is observed that only limited amount of measurements is available for Euro-1 and Euro-4 vehicles throughout the lifetime of the vehicle. It therefore remains difficult to observe any kind of trend in the data. The same is true for Euro-0 cold measurements. Euro-0 hot measurements show a downward trend in all emissions. A possible explanation for this are the different catalyst stimulation programs for Euro-0 when Euro-1 was introduced, therefore leading to reduced emissions at higher lifetime.

Clear trends in cold and hot emissions can be observed for Euro-2 passenger cars with emissions being on average higher at high mileage (80,000 – 100,000 km) in comparison to the first measurement at low mileage. This is particularly true for NOx emissions where cold emissions are nearly 1- to 3-times as high as the reference value and hot emissions are between 2.5- to 4-times the reference value.

Figure 9 to Figure 12 show measured emission levels of petrol vehicles at different mileages as a percentage of the first measurement (at low mileage). The same figures are shown in Figure 13 to Figure 16 for diesel vehicles.

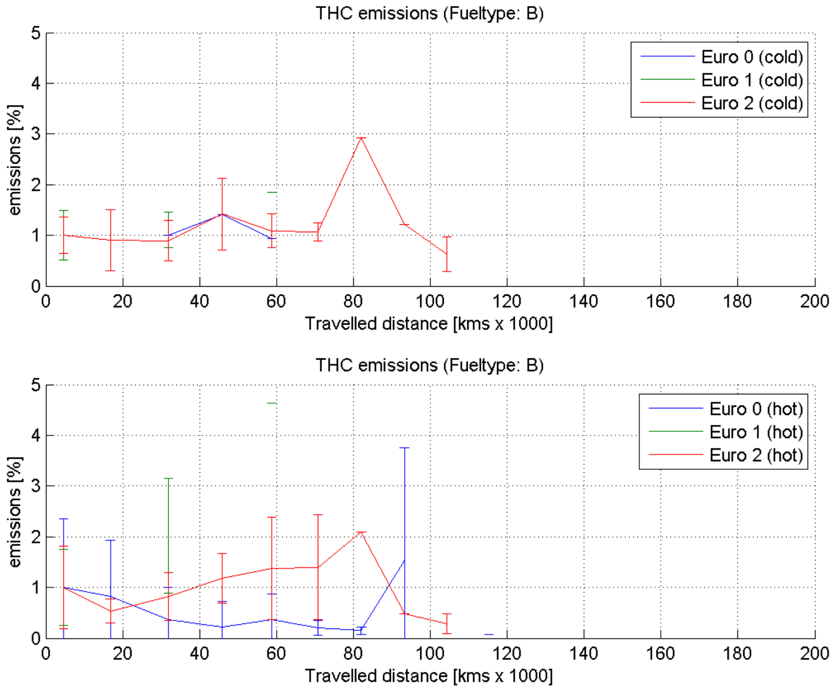


Figure 9 THC results of petrol vehicles as a function of the vehicle distance travelled (1=100%).

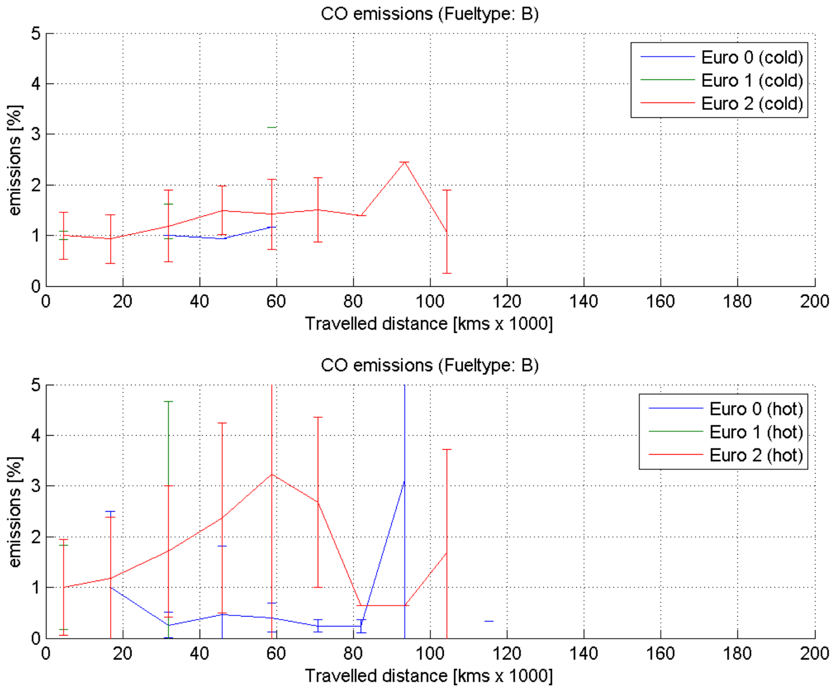


Figure 10 CO results of petrol vehicles as a function of the vehicle distance travelled (1=100%).

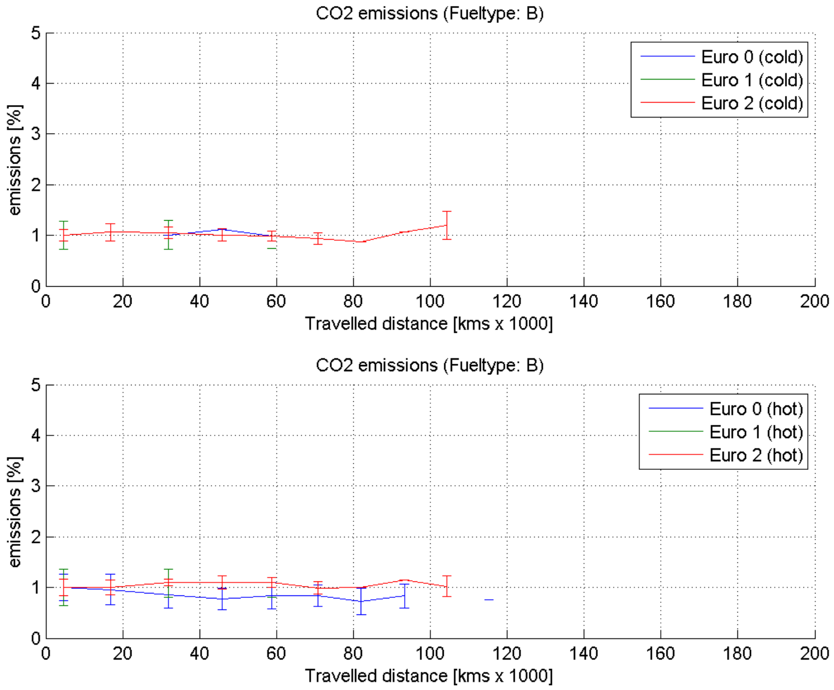


Figure 11 CO_2 test results of petrol vehicles as a function of the vehicle distance travelled (1=100%).

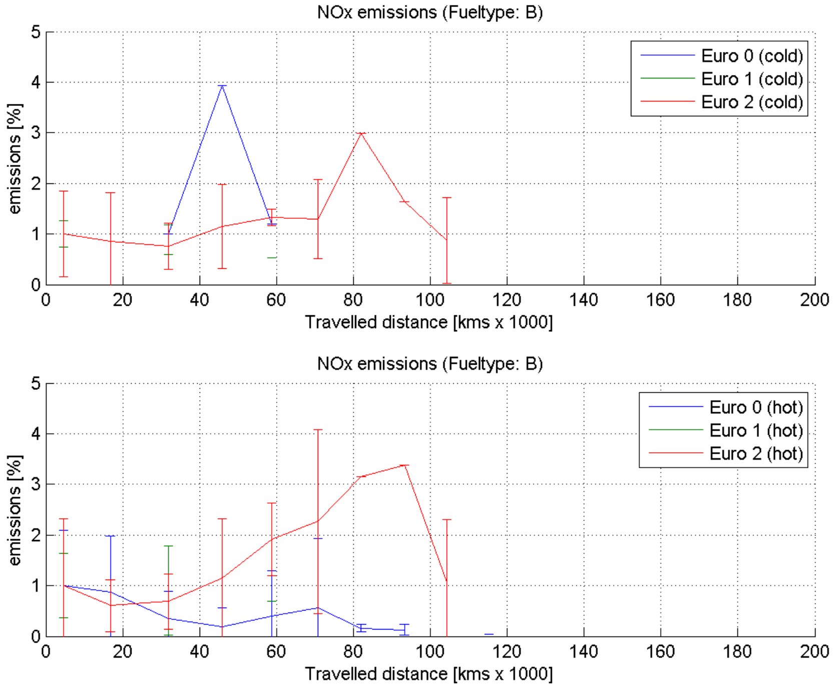


Figure 12 NO_x test results of petrol vehicles as a function of the vehicle distance travelled (1=100%).

4.1.2 *Diesel vehicle measurements*

For diesel vehicles, clear trends can be observed for Euro-1, Euro-2, Euro-3 for hot and cold emissions. However, for Euro-0, the number of cold emission measurements are too limited to discover any trend.

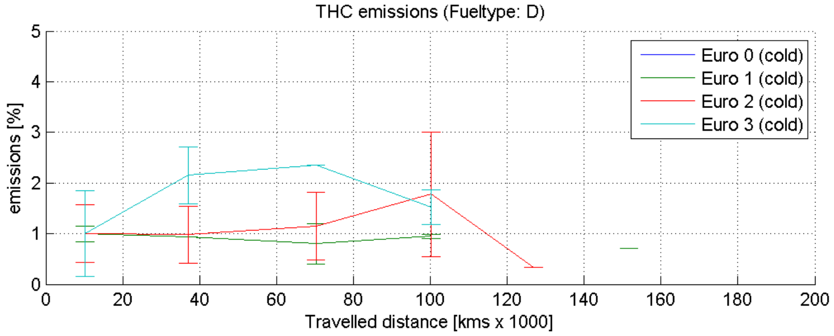
Generally, it can be seen that in many cases diesel emissions (hot and cold) for all Euro-classes hardly change over time. The following exceptions are however observed:

- CO hot emissions for Euro-3 vehicles strong increase is observed at 70000 km which also correlates with the increase for Euro-3 THC emissions.
- THC hot emissions for Euro-0 increases to nearly 5-fold at 150000 km, whereas THC hot emissions for Euro-2 increases to nearly 3-fold at 130000 km and plummets again to 50% at 150000 km. The reasons for this Euro-2 emission behaviour might be connected to a failure in the diesel injection, however, the data does not provide any conclusive evidence.

NOx emissions tend to be more or less stable up to 100,000 km, however, some vehicles show a 50% increase at 100,000 km. The limited available data at 120,000 km (only for Euro 2 and Euro 3 vehicles) show a NOx increase of 70% to 80%.

For PM emissions not enough data is available to warrant any analysis. As noted before the data for the other emissions is limited in the case of diesel vehicles.

Furthermore, for diesel vehicles the cold NEDC tests have in general limited relvance for the real-world emissions of these vehicles. Therefore, a switch was made to perform cold starts on a CADC test, to acquire cold start data. However, also here the emissions are inconsistent.



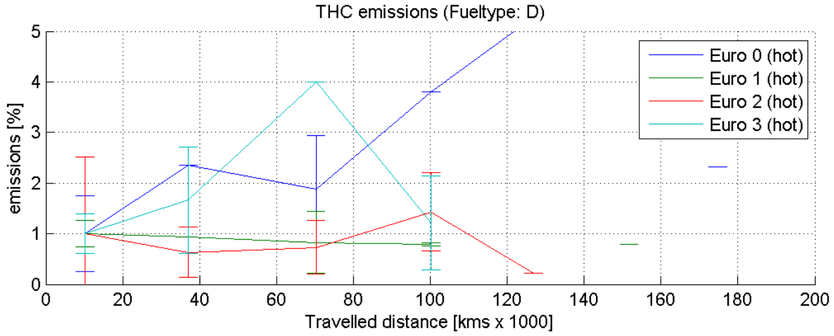


Figure 13 THC test results of diesel vehicles as a function of the vehicle distance travelled; respectively cold and hot NEDC cycle (1=100%).

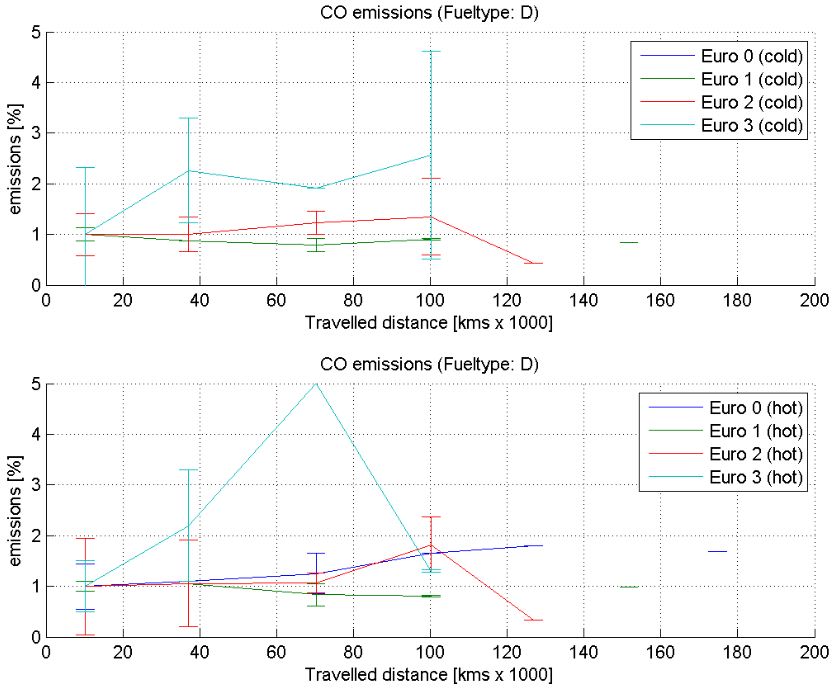


Figure 14 CO test results of diesel vehicles as a function of the vehicle distance travelled (1=100%).

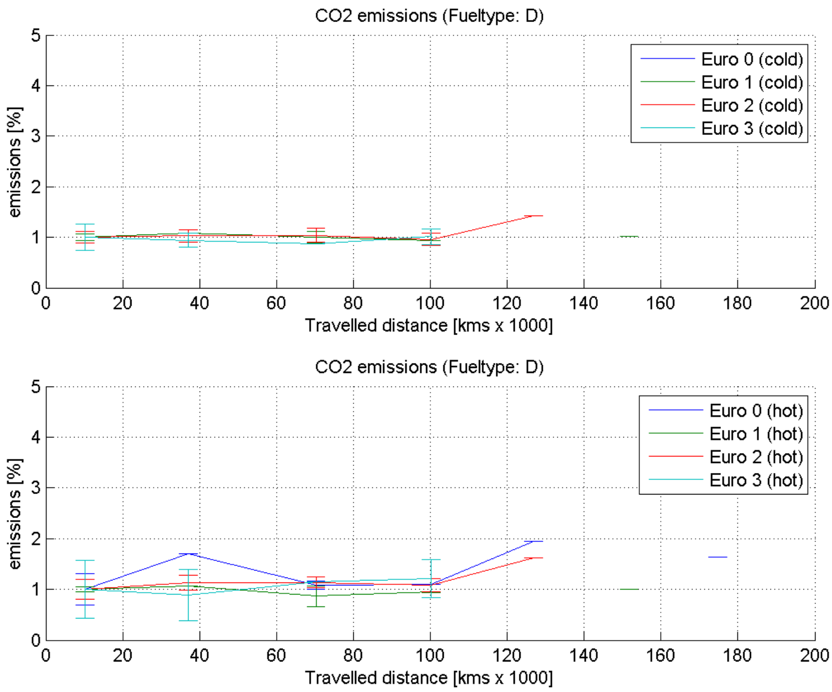


Figure 15 CO_2 test results of diesel vehicles as a function of the vehicle distance travelled (1=100%).

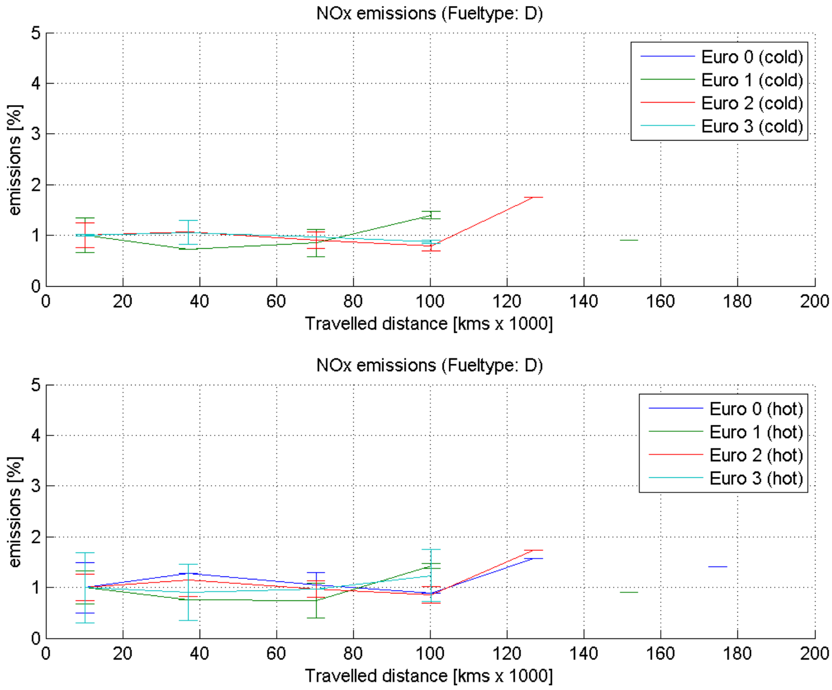


Figure 16 NO_x test results of diesel vehicles as a function of the vehicle distance travelled (1=100%).

4.1.3 *Resulting deterioration rates*

Deterioration rates for the different emissions are determined through fitting a straight line through the binned measurements as shown above.
Since Euro-2 measurements provide the most robust data and only limited measurements are available for Euro-0 and Euro-1 classes, Euro-2 development trends are also used for Euro-1. Since diesel vehicle emissions hardly change over time, no deterioration rates are determined for diesel vehicles. However, it is expected this is no longer the case for more modern diesel vehicles with EGR NOx emission reduction, which is prone to malfunctioning.

Deterioration factors for cold and hot (start) NEDC emissions for petrol vehicles are displayed in the following figures, Figure 17 to Figure 22. It is seen that CO, THC and NOx deterioration factors increase by a factor 2 and more. PM10 emissions remain unchanged.

With a linear fit no trend for emission deterioration is determined for CO and HC hot emissions. In fact, the linear fit indicates a slight reduction of emissions over the lifetime of the vehicle. This is not to be expected though and is explained by the low average emission at a mileage of 80 and 100 thousand kilometers (see Figure 9 and Figure 10). At somewhat lower mileage, a steep increase of the emissions can be observed, however due to the low average emission measurements at 80 and 100 thousand kilometers, the overall slope of the fit is negative. The hot NEDC cycle emissions of NOx increase by a factor 3 over a lifetime of 9 years.

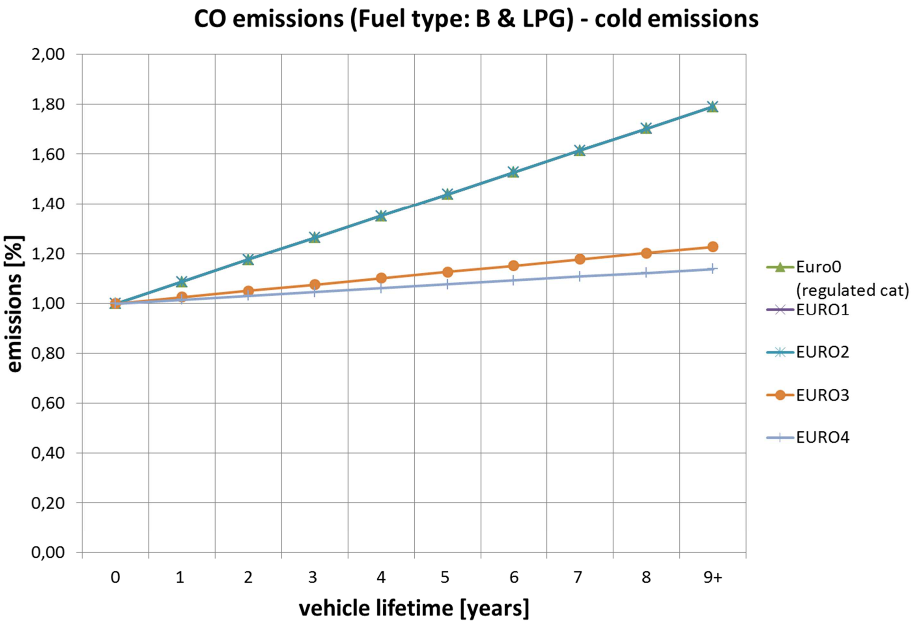


Figure 17 CO deterioration factors based on cold emission measurements, petrol vehicle (1=100%).

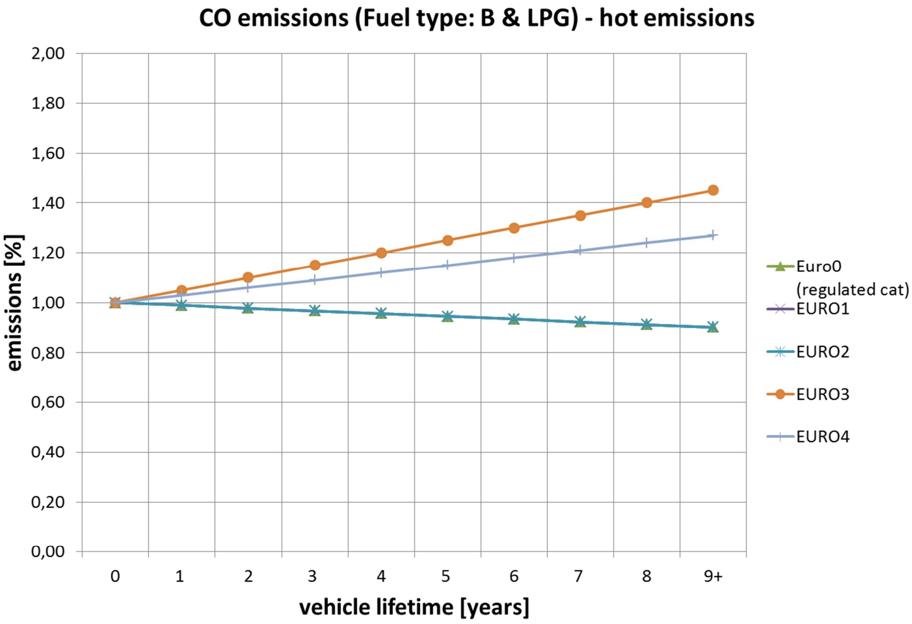


Figure 18 CO deterioration factors based on hot emission measurements, petrol vehicle (1=100%).

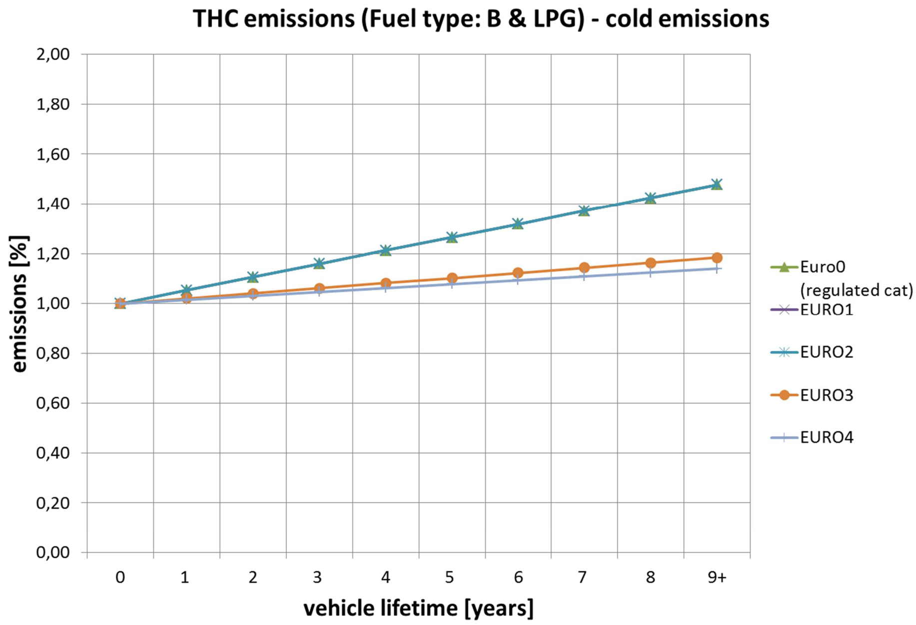


Figure 19 THC deterioration factors based cold emission measurements, petrol vehicle (1=100%).

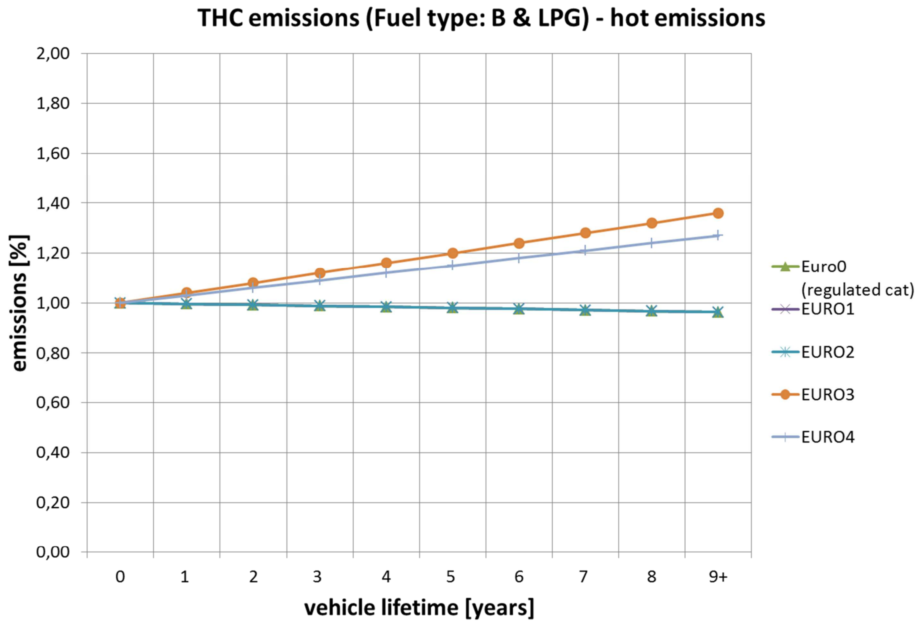


Figure 20 THC deterioration factors based on hot emission measurements, petrol vehicle (1=100%).

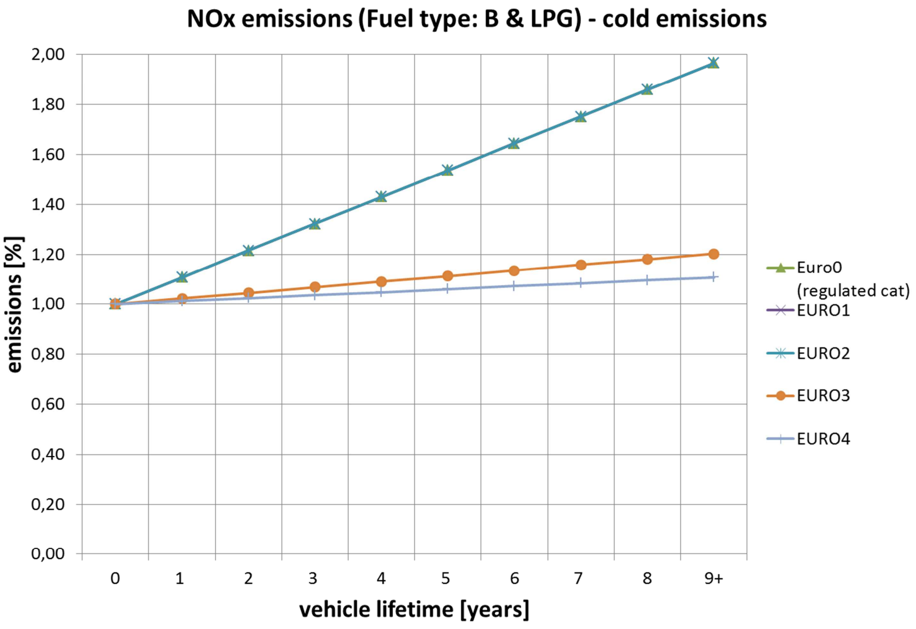


Figure 21 NOx deterioration factors based on cold emission measurements, petrol vehicle (1=100%).

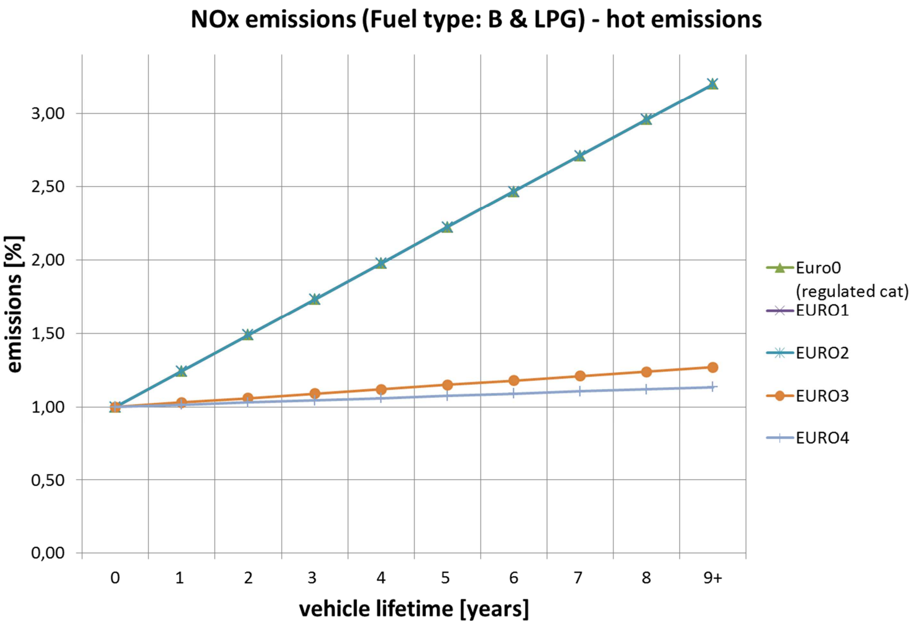


Figure 22 NOx deterioration factors based on hot emission measurements, petrol vehicle (1=100%).

The curves of the figures 18 t/m 22 represent the newly adapted deterioration factors for the average Dutch vehicles emissions.

4.2 Remote sensing emission measurements and deterioration rates

IIASA has determined deterioration factors based on long-term on-road Remote Emission Sensing measurements (RES) in Zurich. An overview of all measurements is given in Table 8 [IIASA, 2014].

Table 8 Overview of vehicles measured by RES and analysed by IIASA [IIASA, 2014].

Fuel type	Euro-class	Number of vehicles tested
Petrol	1	31229
	2	25356
	3	21191
	4	35345

The data set consists of a representative amount of petrol passenger cars spanning vehicle age from one to 15 years and across Euro norms 1 to 4. Vehicle emissions have been measured successively at the same location in Switzerland for a period of thirteen years (from 2000 to 2013). At the test location the uphill grade of the road is 9%, the average speed of the vehicles is 45 km/h and the average acceleration is 0,06 m/s^2. For all vehicles the measured data cover a momentary emission of the vehicle which covers a very restricted engine operating area.

RES measurements have been compared with current TNO emission factors and TNO emission measurements as discussed above. The TNO test data are based on chassis dynamometer tests which contain a broad variety of engine speed and load points.

Below,**the focus is on Euro 1 and Euro 2 cars**, as these older cars have the highest absolute emissions and hence their deterioration is most important to the total. TNO chassis dyno and RES emission measurements are placed in context: For this purpose, the average TNO emission factors for motorways are overlaid with the RES data for both zero mileage and 120’000 km. In between the standard deterioration rate is applied linearly.

The measurements results are presented below in Figure 23 for CO, THC and NO_x emissions. The analysis is limited to Euro-1 and Euro-2 hot emissions, since there are relatively limited amount of TNO measurement data available for comparison on other Euro-classes.

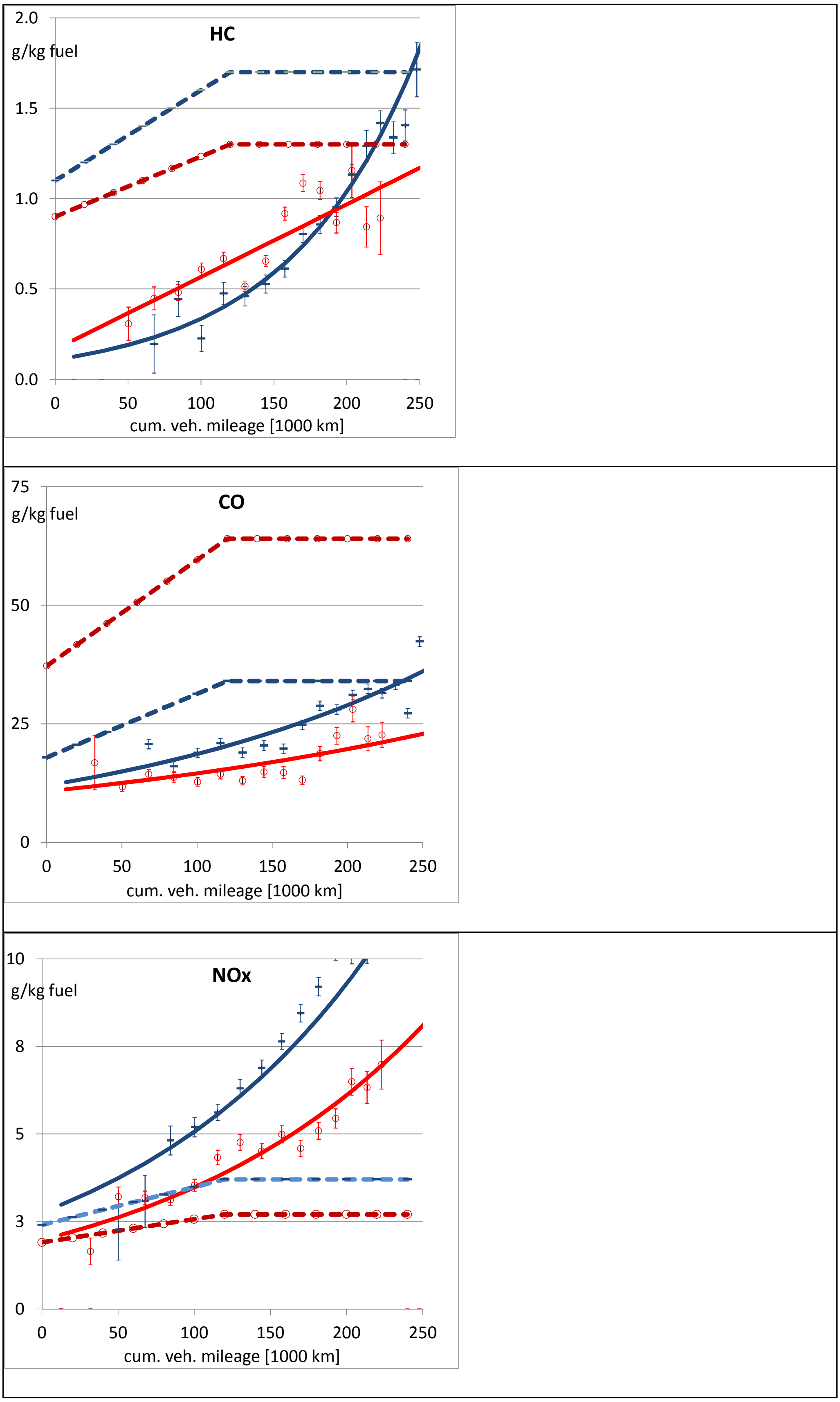


Figure 23 Petrol hot emissions [IIASA, 2014] (the sold lines) in comparison with current TNO emission factors (dashed lines), Euro 1 (blue), Euro 2 (red).

Some clear differences in emission factors are observed when comparing TNO emission factors with RES measurements:

- TNO emission factors of CO and THC are higher than IIASA factors;
- TNO emission factors of NOx are lower than IIASA factors.

Large differences are observed in CO and THC emissions
In Figure 23, it is observed that except for HC Euro-2, all IIASA hot emissions increase exponentially over time. CO emissions remain relatively stable up to 120000 km at which point the emissions seem to deteriorate increasingly. Compared at a mileage of 120000 km (equivalent to a lifetime of roughly 9 years), TNO emission factors of THC are roughly 1.5- to 3 times larger and CO emissions roughly 4-times larger than determined by RES. The high absolute difference in HC emissions indicates towards different operating conditions.

It is assumed that HC in TNO measurements is high because the result is produced in a chassis dynamometer test with cold starts and the RES-results are only based on stable high engine loads in a certain engine speed area. Catalyst ageing therefore makes only a small contribution to increase emissions. The same is true for CO emissions, however, here the change rates are not very different anyhow. For the reasons given above and since HC and CO have no relevance for air quality, there is no conclusive evidence to warrant the adjustment of HC and CO emissions.

In RES measurements, due to the upslope gradient of the road, engine loads are on average higher than measured on a flat road. For petrol vehicles this might lead to a specific engine control strategy (rich air-fuel mixture) which severely effects the performance of the three-way catalyst. Consequently the NOx emission is very low at rich air-fuel mixtures and CO- and HC-emission is relatively higher. In the chassis dynamometer tests the engine loads are relatively low and the control strategy of the engine sticks on stoichiometric combustion which is favourable for the three-way catalyst.

TNO hot emission measurements shown above are measured at mileages lower than 120000 km. Based on the approach taken by [Boulter, 2009], these measurements provide sufficient data if emissions are assumed to remain stable at higher mileages. As shown by IIASA, there is little evidence to make such an assumption. According to the RES measurements deterioration rates of hot emissions increase (exponentially) over the total lifetime of the vehicle. Since TNO measurements are limited to mileages below 120000 km, it is not possible to compare the emission levels with IIASA at higher mileages.

TNO NO_x emission factors are about a factor 2 smaller than IIASA factors at a vehicle mileage of 120.000km. This difference increases at higher mileages, since the currently used deterioration rate remains stable, while emission measurements from RES increase with time. Due to the theoretical average life time of older vehicles (9 years) the deterioration factors for older vehicles (> 9 yrs) are considered to be stable. IIASA data also covers deterioration of these older vehicles It that case, it can be considered to take over deterioration rates or slopes of IIASA in future emission factors. This would also imply that it is not good to limit deterioration to 120.000 km, since the deterioration trend is continuous up to 250.000 km.

With Euro-0 NOx emissions at about 1.7-2.7 g/km, this would be the likely end-point for deterioration. In that case there is still a long way to go in increasing deterioration.

The differences between the emission measurements from chassis dynamometer tests and the RES measurements from Zurich are probably due to different operating conditions. This can be understood from the cause of the emissions: TNO averages over cycles include occasional high emission events from rich operation under dynamic conditions and accelerations. RES is the average over snapshots under more stable engine operating conditions at relative high engine loads.

Especially with Euro-1 and Euro-2, if high power was demanded from the engine, typically at accelerations, the control strategy deviated from the stoichiometric operation, which is necessary for the three-way catalyst to function. During accelerations the engine operates with rich air-fuel mixtures (lambda < 1) with additional CO and HC emissions as a result. In the TNO emission factors, such rich engine operation are included. Consequently, hot HC and CO emission are higher than in the type-approval test.

RES measurements have low hot HC and CO emissions, and higher NOx, compared with chassis dyno averages. Probably the high engine load and rich operation occur frequently at the location of the RES. Hence, cycle averaged HC and CO emissions of Euro-1 and Euro-2 petrol vehicles (see TNO) are probably dominated by rich operation, such that the aging of the catalyst has little consequence. For NOx emission the picture is different. The dynamic driving over a cycle does not lead to higher NOx emissions from rich operation, as with limited oxygen the NOx emission is low. Therefore, in this case the aging will contribute to a significant increase in the hot NOx emissions, as shown in the results from RES. Its effect is therefore to be included in the new hot emission factors.

Regarding operating conditions and test types IIASA and TNO have tested differently. IIASA data are based on momentary emissions of vehicles which run uphill and the TNO test results are based on chassis dynamometer test results. These different conditions and test types probably are the main cause for differences in test results. However both data sets contain important views on deterioration which can be applied for future updates of emission factors.

The deterioration factors derived from remote sensing are compared for 120.000 km with the factors from TNO's chassis dynamometer tests see Table 9.

Table 9 Comparison of deterioration factors of petrol vehicles from TNO chassis dynamometer tests vs. remote sensing data at a mileage of 120.000 km.

Deterioration factors @ 120k	Euro-class	THC	CO	NOx
TNO current	Euro-1	1.5	1.9	1.5
TNO new	Euro-1	1.0	0.9	3.2
RES	Euro-1	3.9	1.7	2.1
TNO current	Euro-2	1.45	1.7	1.4
TNO new	Euro-2	1.0	0.9	3.2
RES	Euro-2	3.9	1.4	2.0

TNO current TNO new RES	Euro-3 Euro-3 Euro-3	1.4 n/a 1.0	1.45 n/a 1.3	1.3 n/a 1.6
TNO current TNO new RES	Euro-4 Euro-4 Euro-4	1.3 n/a 0.4	1.3 n/a 1.6	1.1 n/a 1.5

Further research, specifically the following activities, could contribute to the development of more distinguished deterioration factors:

- Increased number of vehicle measurements under comparable conditions;
- Continuation of monitoring program, i.e. performing emission measurements at higher vehicle lifetime and mileage;
- Differentiation between different drive cycle emission measurements.

4.3 Concluding remarks and recommended adjustments of deterioration factors

Based on the analysis shown above for cold and hot emissions, it is decided to adjust the deterioration rates handled by TNO as follows:

- Cold emissions are adjusted to be in-line with the TNO emission measurements shown above.
- Hot NOx emissions are adjusted to be in-line with results from IIASA.

Presented below in Table 10 and Table 11 are the updated deterioration factors for cold emission factors. The values are representative for Euro-classes 0 (with cat), 1 and 2.

Table 10 Updated deterioration factors for Euro-0, Euro-1 and Euro-2 petrol vehicles (cold emissions).

vehicle lifetime	0	1	2	3	4	5	6	7	8	9+
CO	1.00	1.09	1.18	1.26	1.35	1.44	1.53	1.61	1.70	1.79
THC	1.00	1.05	1.11	1.16	1.21	1.27	1.32	1.37	1.42	1.48
NOx	1.00	1.11	1.21	1.32	1.43	1.54	1.64	1.75	1.86	1.97

Table 11 Updated deterioration factors for Euro-0, Euro-1 and Euro-2 petrol vehicles (hot emissions).

vehicle lifetime	0	1	2	3	4	5	6	7	8	9+
NOx	1.00	1.12	1.24	1.36	1.49	1.61	1.73	1.85	1.98	2.1

5 Estimation of vehicle aging effects based on the probability and significance factor

The results in the previous chapter underline once again that vehicle emissions change with the lifetime of the vehicle. The most important reason for this is the failure of certain emission control technologies. When technologies fail, their efficiency is reduced and therefore specific emissions can increase or decrease.

For more modern technology there are no deterioration factors as yet. However, from the risk estimation below, it is clear that monitoring emissions throughout the vehicle lifetime has become more important rather than less important for modern vehicles, Euro-4 and beyond. The increase in emission, with failure and aging, are much higher as the difference between the baseline, engine-out emissions with no emission control and the reduced emissions are typically much larger.

In this chapter, a short overview is given on the risk factors of different emission control technologies. This overview is a preliminary inventory in the absence of proper data on deterioration of modern vehicles. The following technologies are regarded:

- Diesel and petrol
    - Three-way catalytic converter (TWC)
    - Engine cylinder
    - Exhaust gas recirculation (EGR)
- Diesel only
    - Diesel oxidation catalyst (DOC)
    - Diesel fuel injector
    - Selective catalytic reduction (SCR)

The risk factors are expressed in terms of the probability and significance of failure. The higher the risk factor, the more important it becomes to have strict checking periods in order to detect a failing technology on the road.

5.1 Diesel particulate filter (DPF)

A DPF is designed to remove particulate matter, consisting mostly of soot, elementary carbon and other small particles.

Risk factor
- failing mechanism: wear
- effect of failing mechanism: increased PM emissions
- probability of failure: 2 – 5%
- significance of failure: 99%

5.2 Diesel fuel injector

The fuel injection admits fuel into the engine. Fuel injection generally increases the engine fuel efficiency, there less fuel is required for the same power output. Precise fuel metering also leads to cleaner exhaust gas emission.

Risk factor

- failing mechanism: clogging e.g. with biofuels deposits (plant oil)
- effect of failing mechanism: increased CO, THC and PM emissions
- probability of failure: <5% (for EN590 Diesel)
- significance of failure: no measurement data available (estimate 20%)

5.3 Three-way catalytic converter (TWC)

A three-way catalytic converter has three simultaneous tasks, the reduction of NOx to O_2 and N_2, oxidation of CO to CO_2 as well as the oxidation of HC to CO_2 and water.

Risk factor

- failing mechanism: (heat) aging, lambda sensor failure, (sulphur) poisoning
- effect of failing mechanism: increased NOx, CO and THC emissions
- probability of failure: <1%
- significance of failure: 80%

5.4 Diesel oxidation catalyst (DOC)

The oxidation catalyst works together with the DPF in order to remove pollutant in the exhaust stream, specifically through oxidation of CO and HC.

Risk factor

- failing mechanism: (heat) aging, (low temperature) DPF clogging
- effect of failing mechanism: increased PM, lower NO2/NOx ratio
- probability of failure: unknown
- significance of failure: unknown

5.5 Engine cylinder

The engine cylinder is the combustion chamber of a vehicle. Through wear and lubricant burning particulate emissions can be increased.

Risk factor

- failing mechanism: wear, lubricant burning
- effect of failing mechanism: increased PM
- probability of failure: unknown
- significance of failure: unknown

5.6 Selective catalytic reduction (SCR)

SCR reduces NOx into N_2 and water with the aid of a catalyst.

Risk factor

- failing mechanism: e.g., urea crystallization on the injector
- effect of failing mechanism: increased NOx
- probability of failure: <1% for modern vehicle (regulated in the OBD)

- significance of failure: SCR-Euro-V = 80%, SCR-Euro-VI = 90% (depending on Euro-class)

5.7 Exhaust gas recirculation (EGR)

EGR is a NOx reduction technology in which a portion of the exhaust gas is recirculated into the engine cylinders.

Risk factor
- failing mechanism: clogging
- effect of failing mechanism: increased NOx
- probability of failure: 10 – 15%
- significance of failure: EGR-Euro-V = 70%, EGR-Euro-VI = 40/50%

6 Discussion and conclusion

Deterioration is a main cause for increase of vehicle emissions in time. Due to the different nature of pollutants, technologies, vehicle use and real world conditions the spread in deterioration is expected to be wide and the extent of deterioration is relatively unknown. Furthermore representative vehicle testing is very expensive. With data of different sources deterioration factors can be estimated for the Dutch emission inventory program: www.emissieregistratie.nl.

This report deals with an update of deterioration factors. For this purpose a number of emission measurements from TNO and RES have been considered and analyzed. The emissions CO, THC and NOx have been regarded separately for cold and hot MEVG cycle emissions, different Euro-classes as well as petrol and diesel engines.

The deterioration factors are almost doubled for many of the emission components. Moreover there is concern that a cap on the deterioration at nine years is not appropriate. However, there at the moment insufficient data to support an actual proposal to alter the current methodology at this point. From first principles, it is to be expected that the deterioration of emission of petrol cars will only stop once the high levels of Euro-0 are reached.

The evaluated data sets consisted of a limited number of about 70 vehicles that were monitored over several years at different mileages. The development of the emission factors over time and mileage were used to derive deterioration factors for specific emissions.

The results have led to the conclusion that currently used cold deterioration factors used by TNO should be increased. A suggestion for adaptation has been made and is shown below (see Table 12 and Table 13).

Hot emissions and deterioration factors remain unchanged, since there is not sufficient evidence for change.

Table 12 Updated deterioration factors of Euro 1 and 2 petrol vehicles (cold).

vehicle lifetime	0	1	2	3	4	5	6	7	8	9+
CO	1.00	1.09	1.18	1.26	1.35	1.44	1.53	1.61	1.70	1.79
THC	1.00	1.05	1.11	1.16	1.21	1.27	1.32	1.37	1.42	1.48
NOx	1.00	1.11	1.21	1.32	1.43	1.54	1.64	1.75	1.86	1.97
PM10	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table 13 Updated deterioration factors of Euro 1 and 2 petrol vehicles (hot).

vehicle lifetime	0	1	2	3	4	5	6	7	8	9+
NOx	1.00	1.12	1.24	1.36	1.49	1.61	1.73	1.85	1.98	2.1

Although, a different approach, the deterioration factors are more or less in line with the final deterioration at nine years and beyond as specified Emission Inventory Guidebook. In the guidebook, after 120,000 kilometres, which corresponds to about nine years of operation, the emissions of CO, THC, and NOx, Euro-1 and Euro-2 petrol vehicles are doubled with respect to the test results. There is no distinction in cold start and hot start emissions in the Guidebook, which is an essential difference with the approach in this study. The absolute numbers are not necessarily comparable, as the vehicle categories are different and the approach for handling the effect on emissions of road-types and congestion is incomparable.

Another important difference with the Guidebook is the data underlying the deterioration factors. In this study only data from the same vehicles at different mileages is used. The variability between vehicle is large and very likely to generate a bias due to the selection of vehicles across the years. Moreover, data from outside Europe is not considered relevant.

7 Recommendations

Future update deterioration:

1. The current deterioration factors are based on outdated engine technologies. Furthermore exhaust after-treatment systems are hardly taken into account and deterioration behaviour of catalysts deviate strongly from deterioration of engines. Consequently, it is recommended to carry out a desk study which deals with the following deterioration factors: deterioration of engines, deterioration of emission control technologies and operating conditions. The study must be based on the deterioration factors which will be studied separately. In this way a modular system (a model) of deterioration can be built.
2. Current measuring data (RES and chassis dynamometer tests) cover partly deterioration of emissions of vehicles. In a future update, these data can be combined and implemented in the deterioration model and/or emission factors.

8 References

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9 Signature

Name and address of the principal
RIVM
W. van der Maas
Postbus 1
3720 BA Bilthoven

Names and functions of the co-operators
Dr. N.E. Ligterink (TNO)
Dipl. Ing. P.S. van Zyl (TNO)
Ing. G. Kadijk (TNO)
J. Borken-Kleefeld PhD (IIASA)
Yuche Chen PhD(IIASA)

Date upon which, or period in which the research took place
July 2014 – June 2015

Name and signature reviewer

Ir. R.P. Verbeek

Signature:

Ir. R. Dröge
Projectleader

Release:

Ir. R.A.W. Albers MPA
Research Manager