Atmospheric Environment 43 (2009) 996–1007

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Cold start extra emissions as a function of engine stop time: Evolution over the last 10 years

Jean-Yves Favez*, Martin Weilenmann, Jan Stilli

EMPA, Laboratory for Internal Combustion Engines, Überlandstrasse 129, 8600 Dübendorf, Zuerich, Switzerland

ARTICLE INFO

Article history:
Received 6 September 2007
Received in revised form 10 March 2008
Accepted 14 March 2008

Keywords:
Relative cold start extra (excess) emissions
Stop (parking) time
Long-term evolution
Extra emission estimation
Gasoline passenger cars

ABSTRACT

Cars with catalysts show a significant increase in exhaust emissions at engine start. These extra emissions are expressed as the difference, over a particular driving cycle, between emissions generated when the vehicle is started and when the engine or the catalyst are stably warm. Experimental data, suitable for the assessment of cold start emissions, are usually available for completely cooled engines. Most results originate from tests at ambient temperature of 20–30 °C and with an engine stop time of at least 12 h. On the other hand, data including shorter stop times are very rare.

The present work investigates the influence of exhaust emissions with shorter stop times, i.e. 0.5, 1, 2 and 4 h. The main goal consists in the comparison of emissions exhausted by recent car models (Euro-4) against emissions assessed in the framework of a similar campaign 10 years ago (FAV1/Euro-1 vehicles).

A short survey of the current extra emission estimation methods is presented in this paper. It is shown that some methods are not suited for providing correct estimations in all cases. We discuss the fact that different estimation methods can show either similar or completely different results depending on the evolution behaviour of the hot emissions.

Due to new technologies, e.g. the catalyst and improved engine control algorithms, emissions have been considerably reduced over the last 10 years. In this study it is determined how the relative extra emissions, i.e. extra emissions relative to the extra emissions for the standard stop time of 12 h, expressed as a function of stop time have changed. We may claim with caution that for medium stop times of 0.5–4 h the average relative extra emissions of Euro-4 vehicles are well below the average of the relative extra emissions of Euro-1 vehicles.

1. Introduction

Since catalysts are effective only at high temperature (the 'light-off temperature' which is above 200 °C), emissions are far more significant during the initial part (cold phase) of a trip when engine and catalyst are cold. Catalysts have become so effective in the last 15 years that it is even becoming difficult to measure the regulated pollutants, i.e. CO, HC and NO_x, when the catalyst has reached its light-off temperature. Nowadays, due to catalyst improvements the most significant part of the total emission during a trip, especially for short trips (<10 km), takes place during the cold phase. Therefore, the analysis of additional emissions during the cold phase, referred to as the cold start extra (or excess) emissions, has gradually gained significance in improving emission models and thus emission inventories.

Cold start extra emissions can be subdivided into two parts: (i) excess emissions due to the starting of the engine and (ii) excess emissions during the warming-up process of the engine and the catalyst. In this study only the sum is discussed. An exhaustive survey of research carried out in the past concerning cold start emissions is given in the

* Corresponding author. Tel.: +41 44 823 4622; fax: +41 44 823 4044.
E-mail address: jeanyves.favez@empa.ch (J.-Y. Favez).

1352-2310/$ – see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.atmosenv.2008.03.037

Table 1
Four gasoline vehicles which are considered for the Euro-1 campaign

Vehicle no.	Make	Model	Eng. capacity (cc)	Power (kW)	Mileage (km)	Gearbox type
1-1	BMW	325i	2493	125	133,264	Manual 5
2-1	BMW	320i	1989	95	154,662	Autom. 4
3-1	Opel	Vectra GT	1997	85	65,912	Manual 5
4-1	VW	Golf CL	1595	51	31,134	Manual 5

report by André and Joumard (2005). We can sum up past research by stating that it focuses on the characterisation of cold start emissions as a function of the following five parameters: (i) technology or emission standard (FAV1/ Euro-1 … Euro-4), (ii) average vehicle speed, 9 (iii) ambient temperature, (iv) travelled distance and (v) engine stop time (also called parking time). Large amounts of data and research results are available for the first four parameters, while suitable data for stop time analysis are very rare, since the measurement procedures required for such investigations are time consuming and costly. Previous stop time investigation results have been presented in Hammarström (2002), Schweizer et al. (1997), Hausberger (1997) and Sabate (1996). In the present work we focus on stop times of 0, 0.5, 1, 2, 4 and 12 h by using 15 repetitive IUFC (Inrets urbain fluide court, i.e. short free-flow urban) cycles (André et al., 1999).

This paper presents a brief survey of current extra emissions estimation methods. We show that some methods are not suited for providing correct estimations in all cases. It is found that we have to distinguish between different hot phase emission classes, which have to be considered for the choice of the estimation method. We discuss the fact that different estimation methods can show either similar or completely different results depending on the hot phase emission class.

The main goal of this work is to describe the relative cold start extra emissions as a function of stop times. We assume therefore, as in André and Joumard (2005), that a stop time longer than 12 h is sufficient to cool the engine and catalyst down to ambient temperature of 20–30 °C. Thus, the cycle after a stop time of 12 h is considered as the fully cold-started cycle. The emissions of cycles with shorter stop times are normalised by dividing by the emissions of the fully cold-started cycle. This results in a relative extra emission as a function of stop time. We present a comparison of relative extra emissions in a recent campaign with Euro-4 gasoline passenger vehicles against relative extra emissions assessed in the framework of a similar campaign 10 years ago with FAV1/Euro-1 gasoline passenger vehicles (Schweizer, 1997). Moreover, we compare the relative extra emissions of both campaigns with the INRETS model proposed by André and Joumard (2005).

2. Preliminaries

2.1. Experimental setup

The test fleet is composed of vehicles which reflect the Swiss fleet distribution with regard to engine size, chassis type and manufacturer of the single vehicle classes at the time of selection. The cars are obtained from volunteer private owners and are not serviced before the test. All cars were tested on a chassis dynamometer test bench. Temperature and humidity are kept at reference values using a closed-loop controller system. The exhaust gas composition is determined in two different ways. Firstly, the gas is analysed in accordance with European Council Directive 70/220/EEC for passenger cars (Council Directive 70/220/EEC, 1970), insofar as included. Under this procedure the exhaust gas has to be diluted with a constant volume sampling (CVS) system and gas samples of the diluted exhaust and the ambient air are collected in bags for each section of the measured driving cycle. Secondly, undiluted (raw) online gas analysis measurements are carried out at the tailpipe at 10 samples s^{-1}. These measurements allow a more detailed analysis of the correlation between the driving pattern of the car and pollutant emissions and, for the purpose of this paper, are required for the subcycle analysis method.

The Euro-1 campaign was strictly speaking a FAV1 campaign. But since the Swiss legislation FAV1 corresponds to the Euro-1 legislation we refer to as a Euro-1 campaign. The gasoline vehicles considered in this campaign are listed in Table 1. All four cars are equipped with a three-way catalyst. The cycle considered is the T50 cycle which has a length of 6.5 km, a duration of 830 s and an average speed of 28 km h^{-1}. This cycle is a city-centre cycle which is not repetitive, i.e. there is no identical driving pattern which is repeated several times. The ambient temperature is set at 25 °C and the ambient relative atmospheric humidity at 50%.

Table 2
Six gasoline vehicles which are considered for the Euro-4 campaign

Vehicle no.	Make	Model	Eng. capacity (cc)	Power (kW)	Mileage (km)	Gearbox type
1-4	Opel	Agila 1.2	1199	55	46,492	Manual 5
2-4	Fiat	Stilo 1.6	1596	76	77,801	Manual 5
3-4	VW	Sharan 1.8	1781	110	101,065	Manual 6
4-4	Toyota	Avensis 2.0	1998	108	37,700	Autom. 4
5-4	Ford	Mondeo 2.5	2495	125	42,412	Manual 5
6-4	Audi	A4 3.0	2976	162	49,938	ECVT

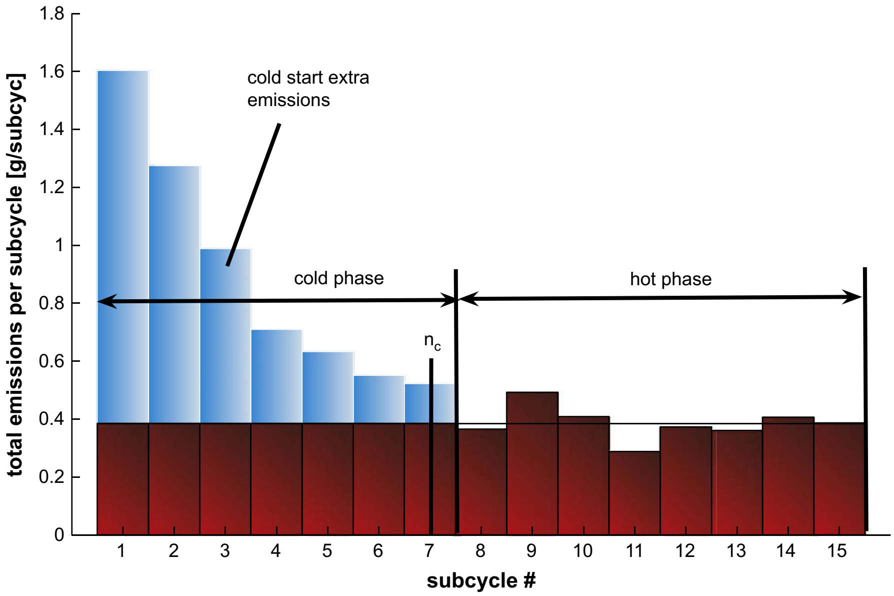

Fig. 1. Evolution of emissions as a function of subcycle. Separation of the cycle into a cold and a hot phase.

Remarks: According to the report of André and Joumard (2005), the T50 cycle might be too short to capture all the cold phase emissions. This statement seems to contradict results in the same report: for Euro-1 vehicles with an ambient temperature of 25 °C and an average speed of 28 km h^{-1} cold distances (i.e. the distance of the cold phase) of 5.11 km for CO, 6.63 km for HC, 3.87 km for NO_x and 6.1 km for CO_2 are given. Thus, these suggested cold distances are below the cycle length of 6.5 km, except for HC for which it is slightly above the cycle length. These are, of course, averaged cold distances and some cars could evidently show longer cold distances. But there is another fact that validates the use of T50 cycles for cold start emission estimations. The results of our Euro-4 campaign show that almost all cold distances are about 1 km with an absolute cold distance maximum of 3 km (see Fig. 4, where the cold distances are about one IUFC cycle long). On the other hand, the averaged cold distances for Euro-4 vehicles suggested in André and Joumard (2005) are clearly above 1 km, i.e. with similar values as for the Euro-1 vehicles. This leads to the conclusion that the T50 cycle seems to be appropriate to capture most of the cold phase emissions.

The characteristics of the gasoline Euro-4 test fleet vehicles are listed in Table 2. The cycle considered is the IUFC15 cycle, which is a repetition of 15 IUFC cycles (André et al., 1999). Only the first IUFC cycle includes the emissions due to the starting of the engine. There is no engine cut off during the subsequent IUFC cycles. One IUFC cycle has a length of 0.999 km, a duration of 189 s and an average speed of 19 km h^{-1}. In what follows, the IUFC cycle is referred to as the subcycle of the IUFC15 cycle. The ambient temperature is set at 23 °C and the ambient relative atmospheric humidity at 50%.

For each vehicle and stop time only one set of data, i.e. data of a unique driving cycle (IUFC15 or T50), is collected.

2.2. Cold start extra emissions estimation methods

For this work we consider following 4 cold start extra emissions estimation methods.

2.2.1. Subcycle analysis method

To apply this method a repetitive cycle, such as the IUFC15, is required. Fig. 1 illustrates this cycle as example with 15 subcycles. We have to separate the cycle into a warm up phase, referred to as the cold phase, and a hot stabilised phase, referred to as the hot phase. Thus, we first have to determine which subcycles belong to the cold phase. In the case of Fig. 1 the seventh subcycle could be considered as the last subcycle of the cold phase, referred to

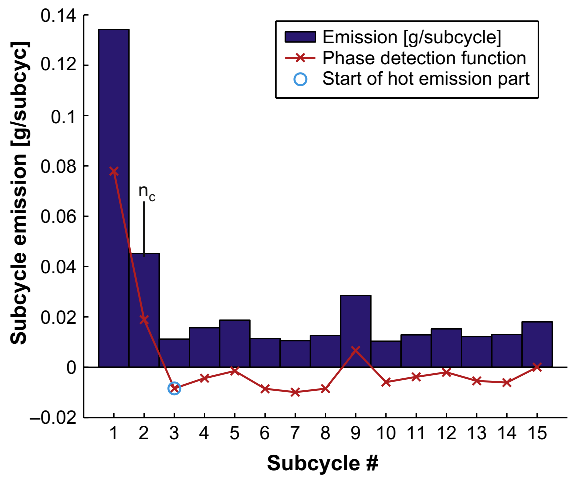

Fig. 2. Variations of the phase detection function as a function of subcycles.

as subcycle number n_c. Following methods for determining n_c can be considered:

(a) It can be affected graphically "by hand" by analysing the total subcycle emissions as a function of the chronologically succeeding subcycles, which corresponds to a discretized time line.
(b) It can be computed by the standard deviation method developed at INRETS (see André and Joumard, 2005). It consists in computing the standard deviation backward, i.e. on the last two subcycles, then on the three last subcycles and then on all the following consecutive subcycles. It is considered that during the hot phase the emissions are stable, except some small variations in the emissions. In this case the standard deviation decreases as a function of the increasing number of subcycles considered. However, as soon as cold start emissions appear the standard deviation increases more distinctly. Thus, at a certain subcycle a minimum standard deviation emerge. This subcycle is defined as the first hot subcycle, numbered as n_c+1, which leads to n_c. During the present work it turned out that this method does not work in all cases. This is due to the fact that the cold start extra emissions are not emphasised sufficiently after short stop times to permit accurate detection. We therefore developed a more robust method to determine n_c.
(c) This more robust method, referred to as the "enhanced standard deviation method", requires the computation of the backward subcycle emission standard deviation (similar as for the INRETS standard deviation method described above) and the backward subcycle emission average. The backward standard deviation is given by the index function

$$\sigma(n) = \begin{cases} \sqrt{\frac{1}{15-n}\sum_{i=n}^{15}(E(i)-\mu(n))^2} & \text{if } n \in \{1,2,\dots,14\} \\ 0 & \text{if } n = 15 \end{cases}$$

where

$$\mu(n) = \frac{1}{16-n}\sum_{i=n}^{15} E(i), \forall n \in \{1,2,\dots,15\}$$

is the index function of the backward average. The variable n represents the number of the subcycle. With both index

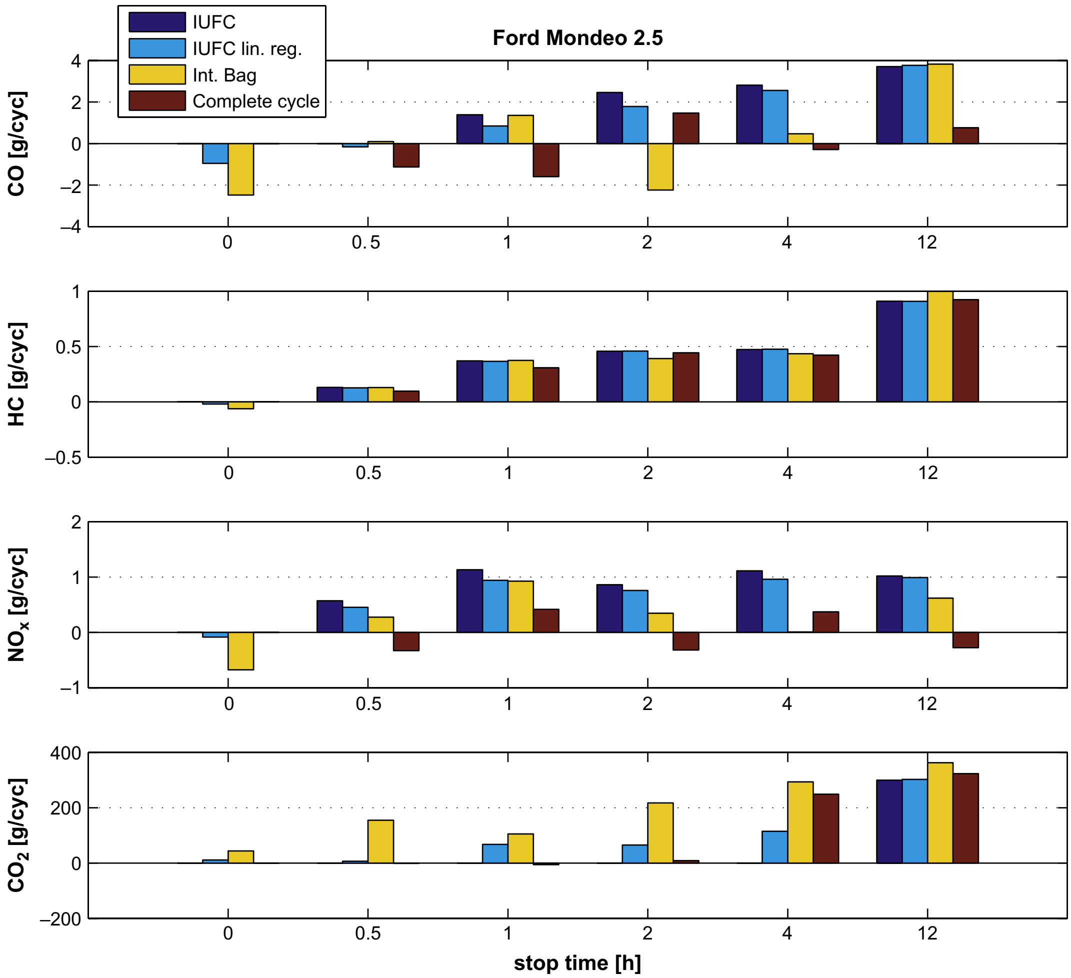

Fig. 3. Extra emission as a function of stop time estimated by 4 different methods for vehicle 5-4 (Ford Mondeo).

functions and the emissions as a function of subcycles a phase detection function is defined as follows:

$$f(n) = \begin{cases} E(n) - (\mu(n) + \sigma(n)) & \text{if } n \in \{1,2,\ldots,15\} \\ 0 & \text{if } n = 0 \end{cases}$$

By means of this function n_c is computed by determining the first subcycle, referred to as n_0, for which $f(n_0) \geqslant 0$, while the subsequent subcycle, referred to as n_0+1, satisfies $f(n_0+1)<0$. Mathematically, this can be expressed by a set

$$N = \{n \in \{0,1,2,\ldots,14\} : f(n) \geqslant 0 \text{ and } f(n+1) < 0\}$$

and by $n_c = \min(n)$, $\forall n \in N$

Note that for cycles for which no cold phase can be detected n_c is equal to 0. These are cycles for which the power train and the catalyst are completely warmed-up from beginning.

Fig. 2 illustrates as an example the variations of the phase detection function as a function of subcycles. For this example the set N has two elements $N=\{2,9\}$. By taking the smallest element of N, n_c is equal to 2.

The idea behind this method is similar to that of the INRETS standard deviation method. It is based on detecting increased emissions (when $f(n)>0$) compared to the hot phase emissions, which is incorporated in $f(n)$ by $\mu(n)$, which refers to the average of the hot phase emissions, and by $\sigma(n)$, which refers to the variations of the hot phase emissions. It has to be emphasised that no mathematical proof has been derived so far in order to show that this method has a high confidence level for detecting n_c correctly. But at least it gives a deterministic procedure, in contrast to the "by hand" method, and in comparison to the INRETS standard deviation method it works well with the analysed set of data. Therefore, solely this method has been used for the estimation of cold start extra emissions. Note that in presence of small hot phase emission variations, an error of one subcycle in the estimation of n_c has only small effect on the cold start extra emissions estimation. Thus, the other methods would give similar results.

Once n_c is determined the cold start extra emission of the subcycle method is given by

$$EE_{\text{cold}} = E_{\text{cyc}} - E_{\text{hot}} = \sum_{i=1}^{15} E(i) - \frac{15}{15 - n_c} \sum_{i=n_c+1}^{15} E(i)$$

where $E(i)$ is the total emission of subcycle i, E_{cyc} is the total emission of the cycle and E_{hot} is the sum of the hot emission part of the cycle.

2.2.2. *Subcycle analysis by linear regression method*

The second subcycle method consists of computing the continuous cumulative emission from the start of the cycle. Linear regression of these cumulative emissions is

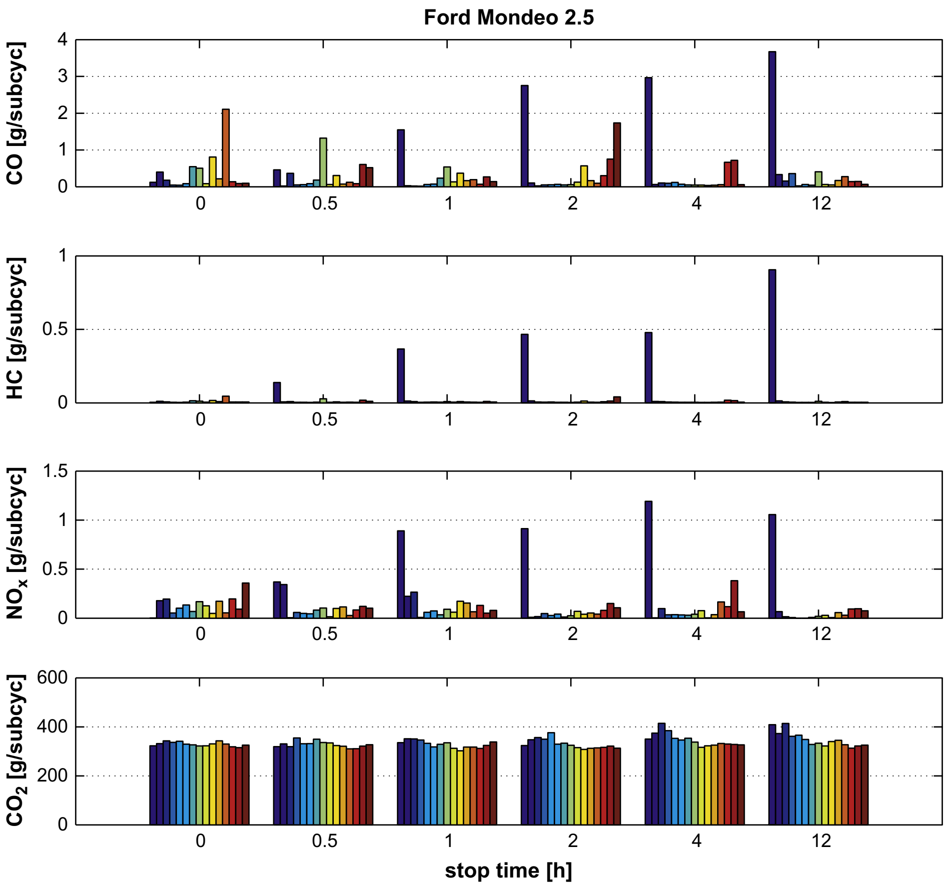

Fig. 4. Total subcycle emissions as a function of chronologically succeeding subcycles for each stop time for vehicle 5-4 (Ford Mondeo).

calculated uniquely on the basis of the hot phase part. Thus, again n_c is required and it is determined with the enhanced standard deviation method presented above. Having computed the linear regression as a function of subcycles, the estimation of the cold start extra emission is given by evaluating the linear regression at the first subcycle (start of the cycle). A detailed discussion of this method is provided in Weilenmann (2001) and in André and Joumard (2005).

2.2.3. Bag analysis method

Some laboratories measure emission factors using bags only. At EMPA a complete cycle is subdivided into three bag measurements. In the case of an IUFC15 the total emission of subcycles 1–5, 6–10 and 11–15 correspond to the bags 1, 2 and 3, respectively. By assuming that the cold phase ends before the start of the third bag (first 10 subcycles) the emission is given by

$$EE_{cold} = E_{bag1} + E_{bag2} - 2E_{bag3}$$

2.2.4. Cycle analysis method

If only the total emission of a whole cycle, referred to as E_{cyc}, is available, we additionally need to measure the emissions of a fully hot cycle, referred to as E_{hotcyc}. The cold start extra emission is given by

$$EE_{cold} = E_{cyc} - E_{hotcyc}$$

A fully hot cycle starts with a completely warmed-up power train and a catalyst above light-off temperature. A cycle after zero stop time can typically be considered as a fully hot cycle, if the engine start is not included in the considered cycle. Unfortunately, the engine start is included in the IUFC15 and the T50 cycles. For these cycles the cold start extra emissions can be slightly underestimated due to the excess emissions during the engine start. Note that in the framework of this study no excess emissions due to the engine start could be observed.

This is the sole method which can be applied to non-repetitive cycles like the T50 cycle. But it can be as well applied to repetitive cycles like the IUFC15 cycle.

3. Comparison of the different extra emission estimation methods

Fig. 3 illustrates the estimated cold start extra emissions of vehicle 5–4 (Ford Mondeo). The extra emissions are

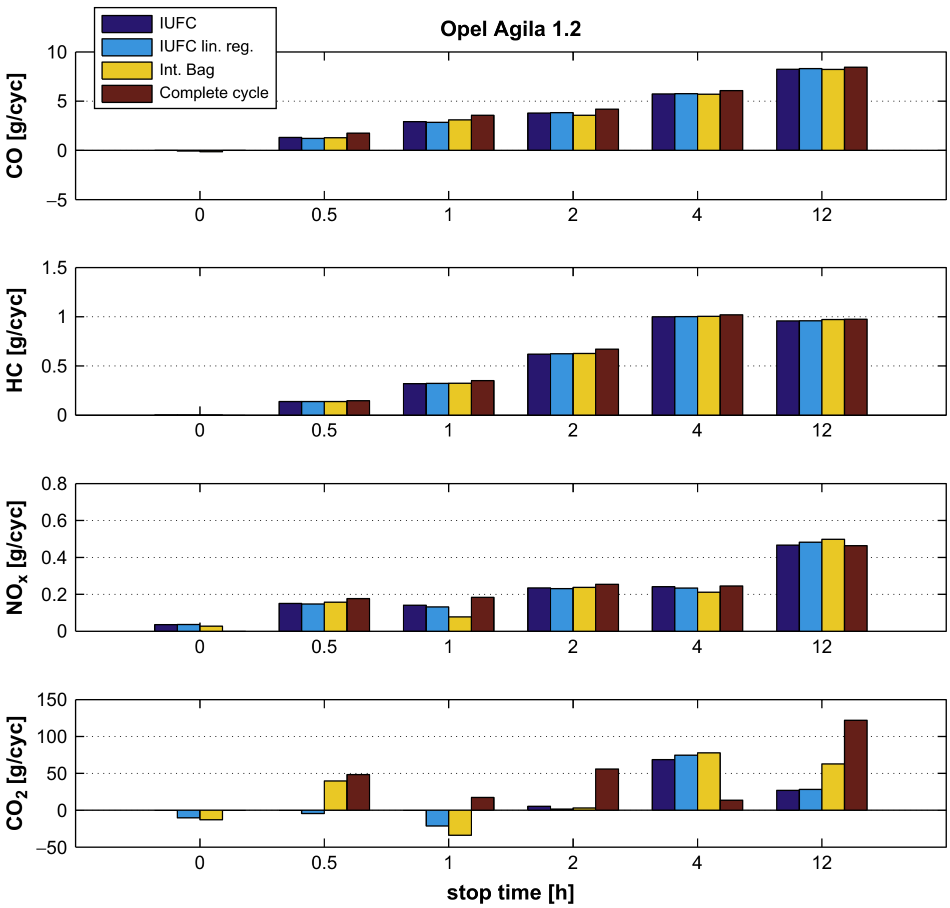

Fig. 5. Extra emission as a function of stop time estimated by 4 different methods for vehicle 1-4 (Opel Agila).

expressed as a function of stop time and are estimated with the four different estimation methods by using data of IUFC15 cycles. The extra emission of HC shows similar values for all methods, while for CO and NO_x only the subcycle methods provide similar extra emissions which qualitatively correspond to the evolution that can be expected. On the other hand, the bag and cycle methods provide widely varying and oscillating extra emission evolutions.

These odd results can be explained by analysing the evolution of the subcycle emissions. Fig. 4 depicts the total subcycle emissions as a function of the chronologically succeeding subcycles for each stop time. With the focus only on the CO emissions, the first subcycle can be assigned to the total cold start extra emissions. The cycles corresponding to stop times of 0 and 2 h show a considerable excess of emissions in the last part of their hot phases, i.e. subcycles 10–15 (third bag), for which it is assumed that the catalyst light-off temperature is already reached (especially for the 0 stop time cycle), and thus distinct lower emissions are expected. This emission excess therefore leads to negative emission estimations for the bag analysis method. A similar observation can be established for the cycle analysis method: Due to the excess emission during the last five subcycles of the zero stop time cycle (fully hot cycle) the hot phase emission E_{hotcyc} is overestimated compared to the hot phase emissions of the other cycles. This inevitably leads to an underestimation of the extra emissions particularly for the cycles corresponding to stop times of 2 and 4 h.

In general, it is expected to detect excess emissions for cycles with a stop time of 0 due to the starting of the engine. In our study this effect cannot be established. At least we claim that such an effect cannot be detected by inspecting the emissions as a function of subcycles (see Fig. 4).

Both subcycle analysis methods are in general more robust, especially for cycles (such as the zero stop time cycle considered) for which no cold phase can be determined, i.e. n_c=0. This robustness results from the fact that the hot phase emissions are averaged over several subcycles. In our considered case the cold phases end in subcycle one for stop time longer than 0 h, and thus the hot phase emissions are averaged over 14 subcycles, providing representative hot phase emissions. We conclude that the estimation accuracy can be improved by increasing the hot phase length: either by appending supplementary subcycles or by measuring a cycle with the same stop time several times.

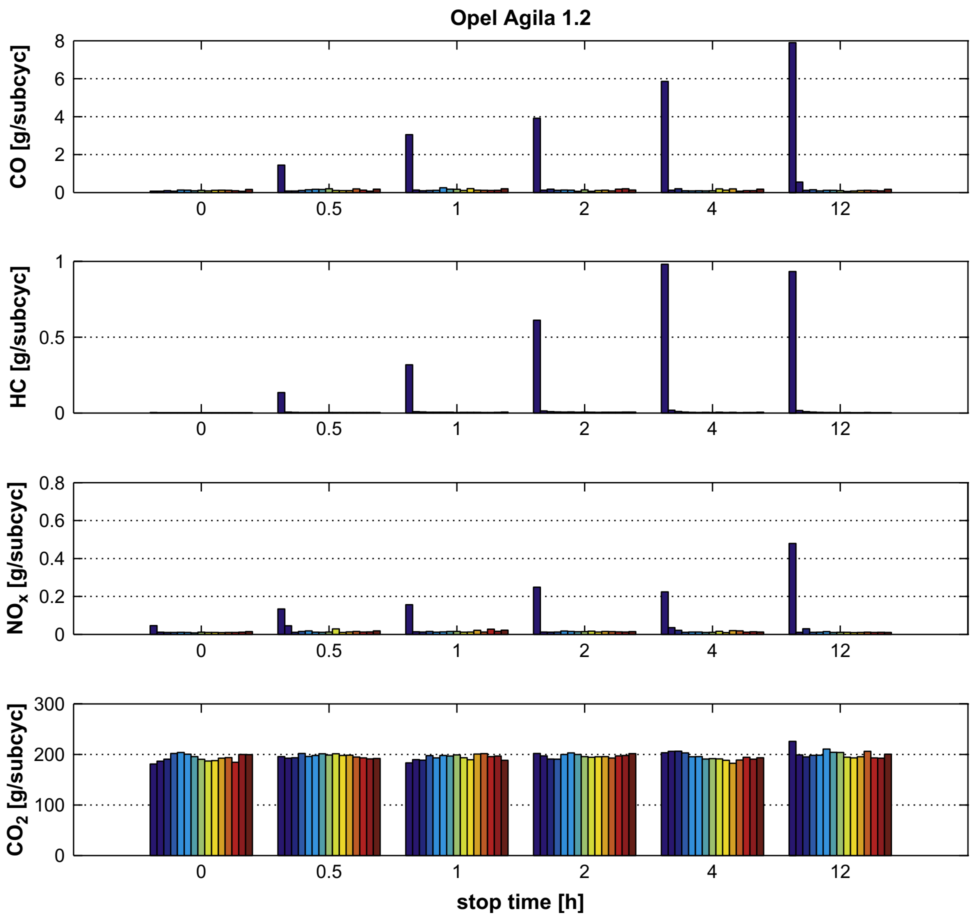

Fig. 6. Total subcycle emissions as a function of chronologically succeeding subcycles for each stop time for vehicle 1-4 (Opel Agila).

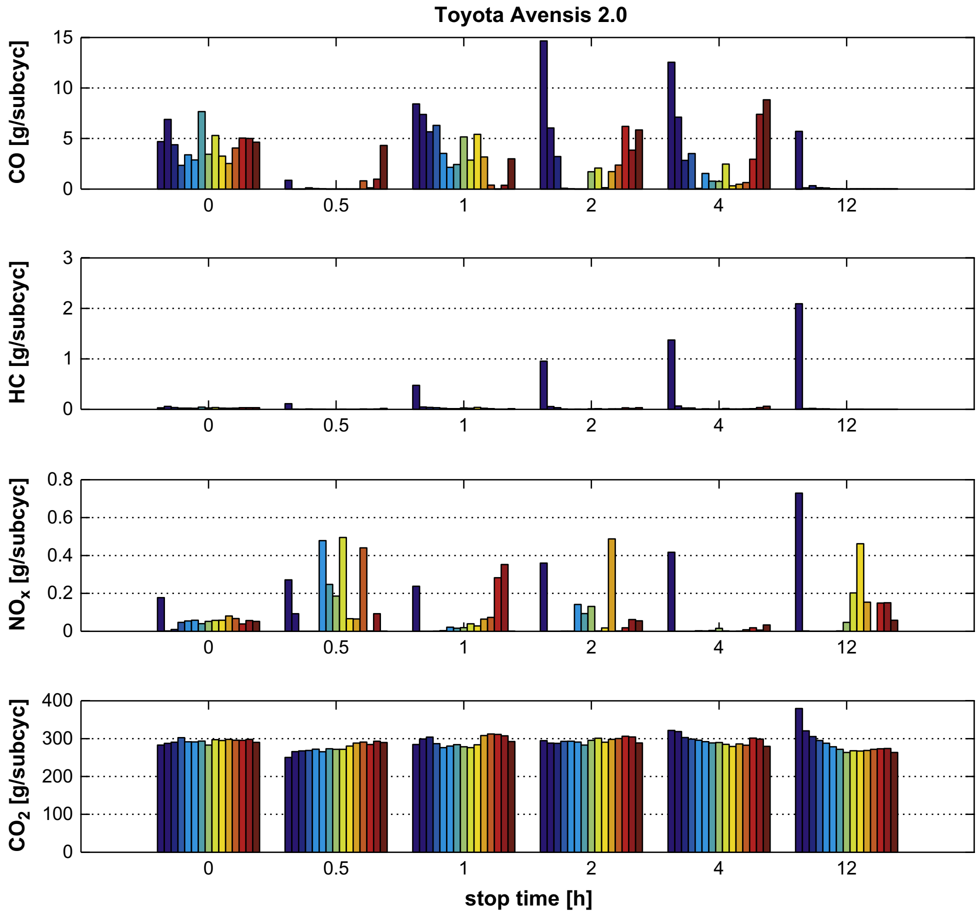

Fig. 7. Total subcycle emissions as a function of chronologically succeeding subcycles for each stop time for vehicle 4-4 (Toyota Avensis).

Similar considerations hold for the NO_x emissions. On the other hand, the hot phase emissions of HC show less variation (Fig. 4). Thus, the subcycles in the hot phase (used by the two subcycle methods), the third bag (used by the bag method) and the zero stop time cycle (used by the cycle method) have similar amounts of averaged emissions. This explains the fact that the 4 methods provide similar extra emissions estimations for HC (Fig. 3).

By analysing the six vehicles of the recent Euro-4 campaign we can distinguish between 3 different hot phase classes:

3.1. Homogeneous distributed hot phase emissions

For this class the hot phase emissions evolve almost constantly with only small variations. Thus, all 4 extra emission estimation methods provide meaningful results. Fig. 5 illustrates the results for the different estimation methods and Fig. 6 depicts the emissions as a function of the chronologically succeeding subcycles of vehicle 1–4 (Opel Agila). Vehicles 3-4 and 6-4 show similar subcycle emissions and thus belong to this class regarding the pollutants CO, HC and NO_x. In general, the HC pollutant for all vehicles also belongs to this class.

3.2. Heterogeneous distributed hot phase emissions

For this class the hot phase emissions oscillate and vary greatly. Thus, only the two subcycle analysis methods are sufficiently accurate. The CO and NO_x pollutants of vehicles 2-4 and 5-4 belong to this class. Fig. 3 illustrates the results for the different estimation methods and Fig. 4 depicts the emissions as a function of the chronologically succeeding subcycles of vehicle 5-4 (Ford Mondeo).

3.3. Non-determinable hot phase

The CO and NO_x pollutants of vehicle 4-4 (Toyota Avensis) show emission evolutions (Fig. 7) with the following characteristics: (i) extreme subcycle emission variations, (ii) huge variations in averaged hot phase emissions between cycles and (iii) for unusually many hot phase subcycles the emissions are larger than for cold phase subcycles.

Analysis of the air/fuel ratio of vehicle 4-4 reveals that different control strategies occur during the hot phases. Occasional air/fuel ratio drop peaks ($\Delta\lambda = -0.15\ldots-0.2$) and increase peaks ($\Delta\lambda = +0.01\ldots+0.03$) lead to a considerable augmentation of CO and NO_x emissions respectively. It has

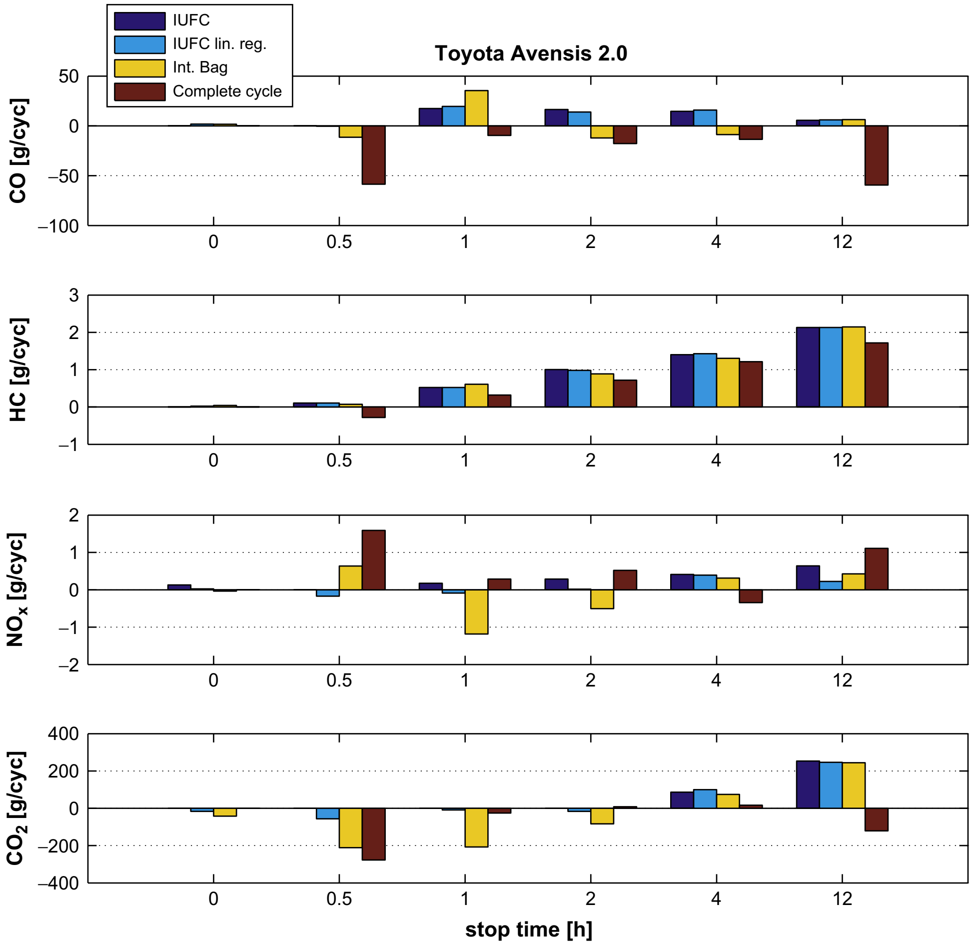

Fig. 8. Extra emission as a function of stop time estimated by 4 different methods for vehicle 4-4 (Toyota Avensis).

not yet been possible to establish the rule for these control strategies. Since the evolutions of the emissions show quasi-chaotic behaviour we conclude that for this type of vehicles a meaningful estimation derived from any proposed method cannot be expected. Fig. 8 illustrates the results for the different estimation methods for vehicle 4-4 (Toyota Avensis).

A possible explanation for hot phase emission variations can be found by inspecting the mode of operation of the three-way catalyst (TWC). The TWC requires the air/fuel

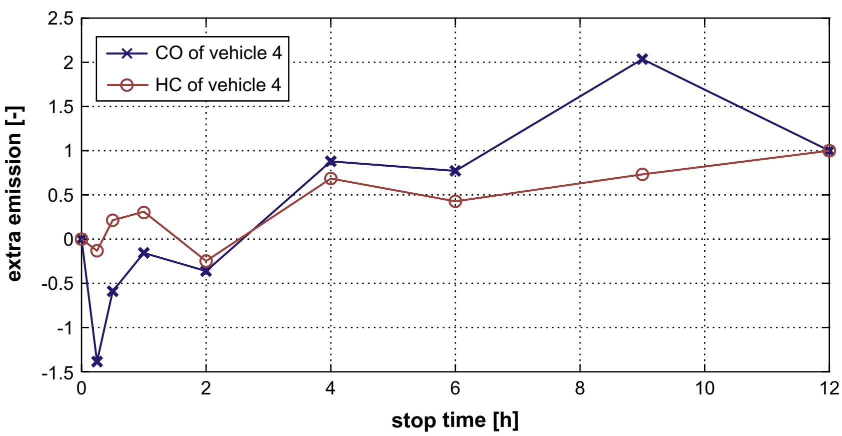

Fig. 9. Evolution of the normalised extra emission of the two Euro-1 samples excluded for the comparison.

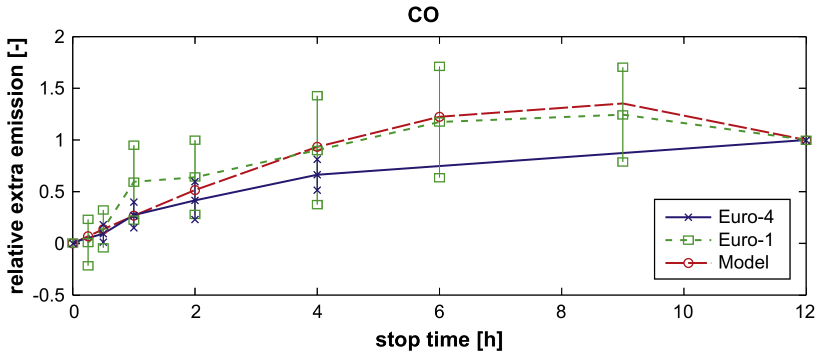

Fig. 10. CO extra emission comparison of the Euro-1 (average with standard deviation), Euro-4 (average with standard deviation) campaigns and the Inrets model.

ratio to be maintained at a value of one (stoichiometric level) in order to ensure optimal operating conditions. In practice, non-ideal components in the control loop, e.g. cross-sensitivity of the lambda probe, noise, crude or adaptive control laws and slight variations in driving behaviour lead to air/fuel ratio variations around the stoichiometric level which inevitably imply more or less pronounced emission variations.

4. Comparison of relative cold start extra emissions

According to the last section the estimated cold start extra emissions can be highly erroneous depending on the hot phase class and the estimation method applied. Thus, it first has to be determined which samples provide estimations that are too erroneous in order to exclude these data for the comparison. For the Euro-4 campaign we obviously use the subcycle analysis method since it provides the most accurate estimations. Thus, we only have to exclude the data of vehicle 4-4 since it belongs to the 'non-determinable hot phase' class. For the Euro-1 campaign only the cycle analysis method is applicable since cycle T50 is non-repetitive. The analysis of the normalised extra emission evolution as a function of stop time reveals that two samples, i.e. HC and CO of vehicle 4-1, have to be excluded. As illustrated in Fig. 9, these two samples oscillate with large amplitude variations and reach negative values for several stop times.

In general, as proposed in André and Joumard (2005), the cold start extra emission can be expressed as a function of ambient temperature T, averaged velocity V, travelled distance δ and the stop time t, i.e.

$$\mathrm{EE}(T,V,\delta,t) = E_0 f(T,V)h(\delta)g(t)$$

where E_0 is the reference extra emission at $T=20\,^\circ\mathrm{C}$, $V=20\,\mathrm{km\,h^{-1}}$, $\delta=d_c$ and $t=12\,\mathrm{h}$. Note that E_0 typically expresses the average cold start extra emission of the test sample. The function $f(T,V)$ expresses the influence of the temperature and averaged velocity, while $h(\delta)$ is the distance influence function and $g(t)$ is the stop time influence function. The extra emission function is normalised by dividing by the extra emission of the fully cold started cycle (stop time of $t=12\,\mathrm{h}$). Thus, since for the campaigns considered the temperature, velocity and travelled distance are constant and since $g(12)=1$, we obtain a relative extra emission function as a function of stop time which is equal to

$$\mathrm{EE_{rel}}(t) = \frac{\mathrm{EE}(T,V,\delta,t)}{\mathrm{EE}(T,V,\delta,12)} = \frac{E_0 f(T,V)h(\delta)g(t)}{E_0 f(T,V)h(\delta)g(12)} = g(t)$$

In the following we compare the relative extra emissions $\mathrm{EE_{rel}}(t)$ of both campaigns and the INRETS (André and

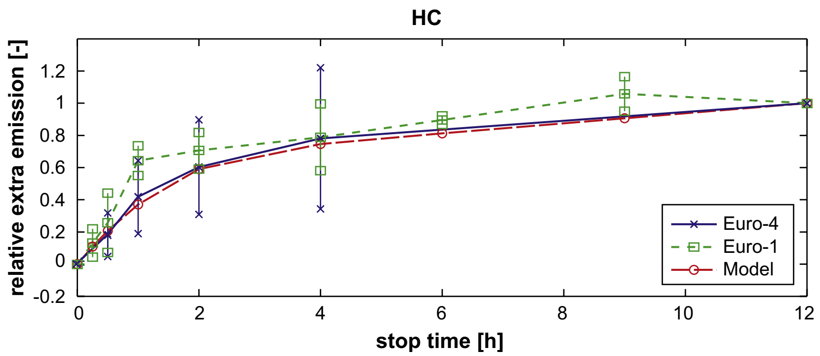

Fig. 11. HC extra emission comparison of the Euro-1 (average with standard deviation), Euro-4 (average with standard deviation) campaigns and the Inrets model.

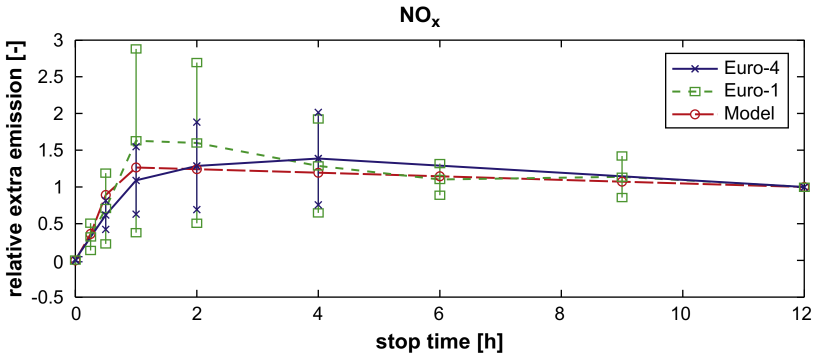

Fig. 12. NO_x extra emission comparison of the Euro-1 (average with standard deviation), Euro-4 (average with standard deviation) campaigns and the Inrets model.

Joumard, 2005) model against each other. Note that the INRETS model consists of polynomials as a function of stop time.

CO (Fig. 10): The standard deviations indicate that the CO mean variations of Euro-1 vehicles are much larger as for Euro-4 vehicles. The model fits the Euro-1 data well, except at t=1 h. This result is not surprising since the model is based on older vehicle data. For stop times longer than 1 h the relative extra emissions of the Euro-4 vehicles are well below the modelled and averaged Euro-1 extra emissions.

HC (Fig. 11): In contrast to CO, the HC mean variations are much larger for the Euro-4 vehicles. Surprisingly, the model fits the Euro-4 vehicles much better than the Euro-1 vehicles. The HC relative extra emissions of the Euro-4 vehicles are appreciably below the Euro-1 emissions in the stop time interval of 0.5–4 h.

NO_x (Fig. 12): In the stop time interval of 0.5–4 h the Euro-4 campaign fleet produce lower NO_x relative extra emissions than the Euro-1 fleet. But as the standard deviations are large for both campaigns this establishment should be viewed with caution. By taking into consideration the large standard deviations the model can be regarded as appropriate for representing both Euro-1 and Euro-4 vehicles.

Note that there is a similar tendency for CO, HC and NO_x that the Euro-1 campaign show higher relative cold start extra emissions than the model at stop times 1 and 2 h.

CO_2: With regard to the Euro-4 vehicles, potential relative extra emissions can only be detected for 12 h stop time cycles. Thus, no particular statements concerning the relative extra emissions for the relevant stop times ($\leqslant$4 h) can be deduced, apart the fact that they seem to be approximately zero. Similarly, no trends can be detected for the Euro-1 test fleet. This is remarkable, since other reports, e.g. Hammarström (2002) and André and Joumard (2005), claim to identify clear trends as a function of stop time for Euro-1 cars. The following two causes could explain this difference. Firstly, in this study only the cycle method could be applied for the Euro-1 test fleet. As mentioned above the cycle method is not as accurate as the subcycle methods. Secondly, we cannot average out several data sets since only one set of data per vehicle and stop time is available. Therefore, it is not possible to remove random emission variations in order to potentially establish stressed trends. Further investigations are required in order to identify the predominant factor for this discrepancy.

5. Discussion and conclusion

The comparison of the different extra emission estimation methods clearly indicates that the bag and cycle methods often fail when the hot phase emissions vary greatly. Thus, in general, one of the two distinctly more robust subcycle methods should be preferably applied in order to ensure meaningful estimation results. Nevertheless, there are vehicles for which the extra emissions cannot be estimated with any proposed methods. In such cases an improvement can probably only be achieved by considerably increasing the number of tests in order to obtain more accurate averaged hot phase emission estimations. Since the estimation methods may fail it is important to examine the resulting estimations in order to exclude non-meaningful data for interpretation and modelling purposes.

Currently we are not in the position to explain the wide emission variations during the hot phase. Therefore, we consider that the next steps should be the determination and characterisation of the causes of this phenomenon. Further analysis of emission variations during the hot phase are most important, especially if there are systematic changes as a function of time and distance when the identical cycle is repeated.

For the relative extra emission comparison it is difficult to state trends with great certainty since only a few vehicles are considered, i.e. three vehicles for Euro-1 and five for Euro-4. Nevertheless, we may claim with caution that for medium stop times of 0.5 to 4 h the averaged relative cold start extra emissions of recent vehicles (Euro-4) are well below the averaged extra emissions of 10-year-old vehicles. This new result may prove useful for expanding the INRETS and other models with stop time influences of Euro-4 vehicles.

In this paper we mentioned that the estimated cold distance of the six examined Euro-4 vehicles are about 1 km, while in André and Joumard (2005) the cold distances evaluated from data of 14 gasoline Euro-4 vehicles are given as follows: 5.2 km for CO, 6.6 km for HC, 3.9 km for NO_x and 1.9 km for CO_2. Thus, this large discrepancy has to be investigated in order to be able to provide a consistent model.

Acknowledgements

This work was done within the DACH+NL+S (German, Austrian, Swiss, Dutch and Swedish) cooperation on vehicle emission monitoring. The authors wish to thank FOEN, FEDRO, SFOE and all co-founders.

References

André, J-M., Joumard, R., 2005. Modelling of cold start excess emissions for passenger cars. INRETS Report, No. LTE 0509, Bron, France, 239pp.

André, M., Hammarström, U., Reynaud, I., 1999. Driving Statistics for the assessment of pollutant emissions from road transport. INRETS Report, No. LTE9906, Bron, France.

Council Directive 70/220/EEC 1970. On the approximation of the laws of the Member States relating to measures to be taken against air pollution by gases from positive-ignition engines of motor vehicles ⟨http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:31970L0220:EN:NOT⟩.

Hammarström, U., 2002. Betydelsen av korta motoravstängningar och körtid för avgasemissioner fran bensindrivna bilar med och utan katalysator (Exhaust emission variations for short engine stops and driving time for petrol cars with and without catalyst). VTI meddelande 931, Sweden.

Hausberger, S., 1997. Globale Modellbildung für Emissions- und Verbrauchsszenarien im Verkehrssektor (Global modelling of scenarios concerning emission and fuel consumption in the transport sector). Dissertation am Institut für Verbrennungskraftmaschinen und Thermodynamik der TU-Graz, Graz.

Sabate, S., 1996. Methodology for calculating and redefining cold and hot start emissions. CARB Report.

Schweizer, Th., Rytz, Ch., Heeb, N., Mattrel, P., 1997. Nachführung der Emissionsgrundlagen Strassenverkehr–Teilprojekt Emissionsfaktoren–Arbeiten 1996 (Tracing of emission bases-road traffic–subproject emission factors–work in 1996). EMPA Bericht-Nr. 161'150.

Weilenmann, M.F., 2001. Cold start and cold ambient emissions of Euro II cars. In: Proceedings of the 10th International Symposium on Transport and Air Pollution, Boulder, USA.