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An experimental evaluation of the toxic gas emission in case of vehicle fires

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ABSTRACT

Fire safety in tunnels enables to design safety measures to ensure a people safe evacuation in case of fire. Such an analysis considers the different impacts of fire on people as temperature, visibility but also toxicity. Most of standard curves are based on quite old fire tests without any toxic gas qualification. Very few fire tests were previously achieved in that way. Based on those few tests, some standard fire emission factors were proposed. The objective of this paper is to review those emission factors, not only regarding the nature of toxic compounds generated but also through a carbon monoxide equivalent factor.
To reach this objective, two series of tests were performed. The first concerns individual combustible compounds of a car as plastics, tyres and others. The second focusses on full car burning tests with smoke analysis. Those two series of tests lead to an analysis of the smoke toxicity and a comparison of emission factors with standard ones.

KEYWORD: smoke toxicity, car burning tests

INTRODUCTION

In case of fire in confined space as tunnels or car parks, while heat release is crucial for structure behaviour and aerodynamic, impact on people are mainly due to the smoke toxicity. However, while car fires were largely studied in the past regarding the heat release rate (HRR), few papers focussed on the toxic gases emissions [1]. From those papers, cars were concerned by large evolutions that have induced, as far as the topic of this paper is concerned, a major modification of the quantity of plastic but also some improvements regarding comfort or energy that could clearly impact the potential toxic load of cars.

To evaluate the impact of those evolutions, two major large scale experimental fires campaigns on real cars were achieved. Those tests are divided into several categories of cars. The first is a series of three different recent cars, with several sizes, from small "urban" to large "familial" cars. This first series of tests, compared with existing results in the literature, enables to evaluate the impact of embedded comfort on smoke toxicity. The second series of tests concerns the evolution of the energy carrier using the results from electric cars burning [3]. To enable a more detailed comparison, tests were also achieved on different components individually such as fuels, cables and plastics. Finally, toxicity of the produced smoke is compared based on Fractional Effective Concentration (FEC) and Fractional Effective Dose (FED), depending on the nature of the gases as detailed in [5]. This toxicity is evaluated considering all produced gases, to propose a new evaluation of emission rates to be considered regarding toxicity. Because carbon monoxide is not the only toxic product that is generated in case of fire in tunnels, emissions were, during these tests, characterized using an FTIR (Fourier Transform Infra-Red) spectrometer. Such a system enables to perform a detailed calibration including the concentration in carbon monoxide, but also in acid gases (hydrogen chlorine, hydrogen fluorine, …) or other compounds as carbonates for example. Not only the nature but also the quantity of the gases produced during fire are compared.

Regarding these new experimental calibrations of the smoke potential toxicity in case of car fire, a reflexion is proposed regarding the commonly used standard curves [4]. Of course, it is not relevant to take into account, in a safety study, the large variety of toxic compounds generated, according a simplified manner. To do this, CO equivalent production curves are proposed for tunnel safety evaluation, based on the toxic impact on people [5].

VEHICLE FIRE SOURCE TERMS AVAILABLE

The heat release curves

Considering that most of the emission factors for fire are given relatively to the HRR, it appears important to consider it. Furthermore, the smoke behaviour in confined or semi-confined infrastructure will highly depends on thermal gradient that governs smoke stratification. Several values are available regarding cars maximum HRR in the literature as detailed in [4] and [7]. Two examples or HRR curves are reproduced hereafter on Figure 1.

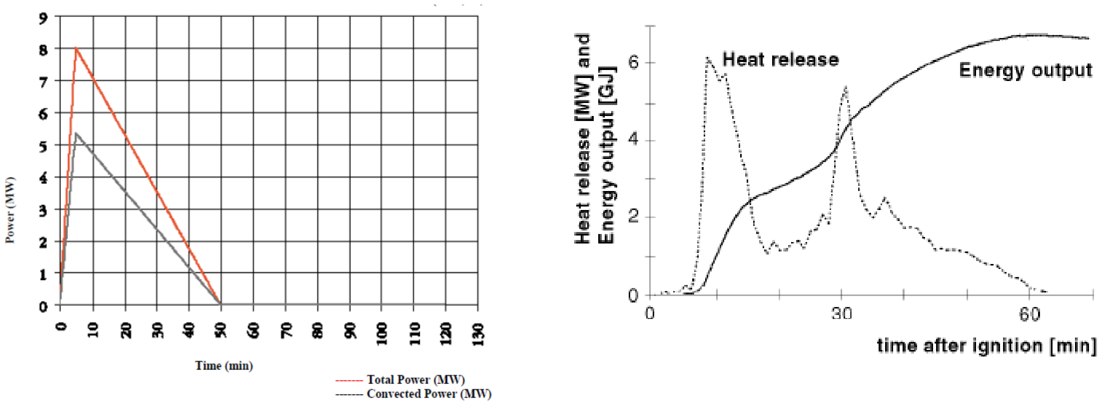

Figure 1: Two examples of HRR curves from French reference documentation [4] (left) and PIARC reference [7] (right).

The first, from [4] indicated a calorific load of 12 000 MJ for a large private car, the second, from [7], indicates a calorific load of 6 000 MJ for a private car, 7 000 MJ for a plastic one. It must be highlighted that the range of values is quite important, not only in terms of maximum HRR but also regarding the fire kinetic. The important issue regarding toxicity is then the relation between the HRR and the emission factor. For quite small cars, the plastic load is not so important but the nature of these plastics is not so different. It is then analysed, in the present paper, the relation between the calorific loading in the car and the emission factor.

The toxic gases emissions rates

While some data are available regarding the emission rate of carbon dioxide and carbon monoxide, very few data exists on other toxic compounds that can be found in smoke. One of the most detailed one is [2]. Those tests, achieved in 1999, concern vehicles that are quite old now. First of all, it is important for the following and for the estimation of the current model of smoke toxicity to compare the global emission rate in terms of CO equivalent production. This can be done using the FED and FEC relations detailed in [5] or based on a simpler approach as the one detailed in [17]. This is important to consider that not all gases can be considered in a safety study and that a global approach must be followed. This approach generally consists in modeling the CO transport in the tunnel. It is then obvious that the modeled gas must considered not only the effective CO but the effect of other toxic compounds.

It is then interesting to evaluate the impact of vehicle transformation between previous tests and nowadays in terms of nature of toxic compounds but also through the emission factor.

ANALYSIS OF RECENT FIRE TESTS PERFORMED AT INERIS

Brief description of experimental facilities

Experimental device that was used for the experimental campaign is the INERIS fire gallery. This fire gallery was described in some previous papers [13] but relevant details are given hereafter. This gallery is 50 m long with a 3 m width and 1.8 m height section, that corresponds to a two lanes tunnel at third scale. This fire gallery is equipped with a fan that can be control to manage the air flow in the tunnel. Photography of INERIS fire facilities is presented on Figure 2.

Figure 2 : INERIS fire gallery.

One of the main interests of this installation is the smoke treatment system instaled downstream. This system, design as for garbage furnace emissions treatement, enables to capture not only the toxic products as carbon oxides or acid gases but chronical toxic compounds, as dioxin or PAH (Polycycli Aromatic Hydrocarnons) too [15].

ELEMENTARY TESTS

Before going any further in the description of full scale fire tests on vehicle, it is quite important to analyse the emissions factors for different individuals components of the vehicle. Some data were previously published in the literature regarding this as in [8][9][10][11]. The data presented in these papers were recently published following dedicated fire tests achieved in INERIS [12]. During this experimental campaign, four individual car combustible compounds were burnt : gasoil, plastics, tires and electrical compounds. Those individual compounds were taken from a commercial car to be representative of the real materials used on vehicules. For those tests, plastics and tyres were previously crushed. Main results are summarized in Table 1. For each compound, the total duration of the tests was greather than 3 hours.

	Gasoil	Plastics	Tyres	electric cables
Mass of product burn [kg]	131	48	49	36
Emission factors [mg/g] or [g/kg]				
CO_2	2823	2034	1469	728
CO	31	20	42	9,1
HCl	-	2,2	0,2	2,1
HF	-	0,014	0,003	0,11
NOx	1,2	5,0	2,8	2,5

Table 1: Synthesis of individual combustible compounds fire tests.

Regarding the products that could generate acute toxicity, it is clear the carbon dioxide is clearly predominant. It represents more than 95% of acute toxic gases production.

FULL SCALE CAR BURNING

Measurements made during the tests are located on the scheme reproduced on Figure 3. It must be highlighted that, because of their importance, carbon oxides and oxygen measuremets were made on several points. The interest was not only in insuring the availability of the measurement but also to demonstrate the correct mixture was reached. Toxic products as acid gases were measured with both an online method, based on a FTIR spectrometer, and with integral method thanks to bubblers.

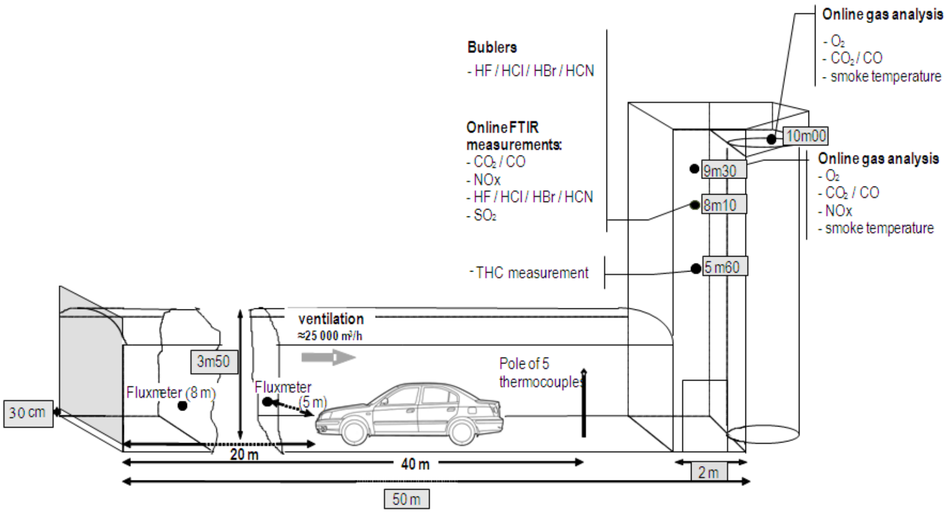

Figure 3: Probes location in the fire gallery.

Brief description of cars and calorimetric data

During the presently described experimental campaign, two series of cars where used. The main characteristics of those cars are described in Table 2. On top of the car characteristics, this table also provide the basic calorimetric data. In is important to note that some measurements can be influence because of the experimental set up characteristics. Then, while total amount of energy, of toxic gas are probably not significantly influenced bythe experimental set up, the HRR max value is probably overestimated compared to a free bruning because of the confinement. Another impact is the dilution of gas by the ventilation system. This aspect is discussed afterward.

	Car 1	Car 2	Car 3	Car 4
Total mass before ignition [kg]	936	1 404	1 564	1 501
Energy carrier	Fuel	Fuel	Fuel	Electricity
Cathegory	Urban car	Medium class familial car	Upper class familial car	Medium class familial car
Total mass loss [kg]	192	275	262	278,5
Mass loss fraction [%]	17	19,6	16,8	18,6
Peak HRR [kW]	4 900	5 900	7 800	4 500
Time between ignition and peak HRR [min]	15	18	15	30
Total energy [MJ]	6 890	10 600	10 000	8 540

Table 2: Main characteristics of burnt cars.

Those values have to be compared with the standard ones as those defined in the AIPCR reference document [6] or the CETU French guide [4] summarized in Table 3.

	PIARC guide [7]		CETU document [4]	
	Private car	Plastic car	urban car	familial car
Peak HRR [kW]	2 500	5 000	4 000	8 000
Time between ignition and HRR peak [min]	-	-	5	5
Total energy [MJ]	6 000	7 000	6 000	12 000

Table 3: Calorimeric standard values.

The first comparison shows that the standard values commonly used for car fires are relevant in terms of both HRR peak values and total energy released. While the delay between ignition and HRR peak value appears to be underestimated in the referenced document, it is important to remind the objectives of its. The above given values are used for safety studies where minimizing the delay for fire propagation leads to minimize the available escape time for people and consequently improving safety level. In that sense, it could be considered as relevant.

Gaseous emissions

Before going into the comparison between vehicles, each toxic compound proportion in gaseous products are summarized on Table 4 for the three common energy carriers.

	Car 1	Car 2	Car 3
Relative emission [% of total]			
Acid gases			
Hydrogen chlorine (HCl)	0.38%	0.29%	0.33%
Hydrogen fluorine (HF)	0.12%	0.11%	0.07%
Cyanhydric acid (HCN)	0.03%	0.02%	0.05%
carbon and nitrogen oxides			
Carbon dioxide (CO_2)	96.54%	96.95%	97.33%
Carbon monoxide (CO)	2.29%	2.11%	1.94%
Nitrogen oxide (NO)	0.13%	0.1%	0.15%
Nitrogen dioxide (NO_2)	0.06%	0.06%	
Sulfur dioxide (SO_2)	-	-	0.13%
unburnt			
Total hydrocarbons	0.45%	0.37%	-

Table 4: Gaseous emissions data.

First of all, as for individual coumpounds tests, it must be notice that the carbon dioxide proportion in smoke was higher than 95% for each tests. One of the most important issue when dealing with smoke is the CO/CO_2 ratio that depends on external conditions and mainly the fire ventilation. In the present fire tests, the total ventilation air flow, downstream the fire, is about 25 000 Nm^3/h, i.e. 8.97 kg/s of air and, consequently 1.88 kg/s of oxygen. Considering 1 kg of oxygen is required to produced 13.1 MJ, it means that the air flow can generate a 24.7 MW fire by consuming all provided oxygen. Not all the provided oxygen can however be consumed and, a concentration around 13% appears as a minimum. In that condition, the amount of oxygen that can be provided to the fire is about 0.7 kg/s, corresponding to a 9.4 MW fire. Fires were then ventilated enough to prevent under ventilation phenomena.
This is confirmed by oxygen concentration measurement downstream the fire, as plotted on Figure 4.

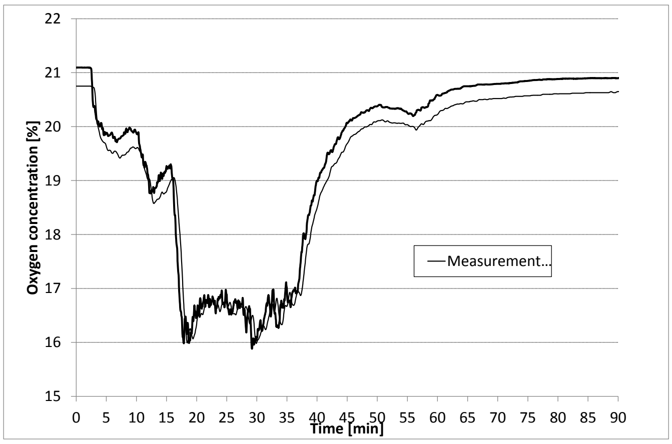

Figure 4: Evolution of oxygen concentration downstream the fire (car2).

This curve confirm that, when reaching the maximum HRR, the oxygen concentration is still above 13%. This curve also shows that the oxygen concentration is highly time dependant because of the HRR evolution. Consequently, the CO/CO_2 ratio is also time dependant, this is demonstrated on Figure 5.

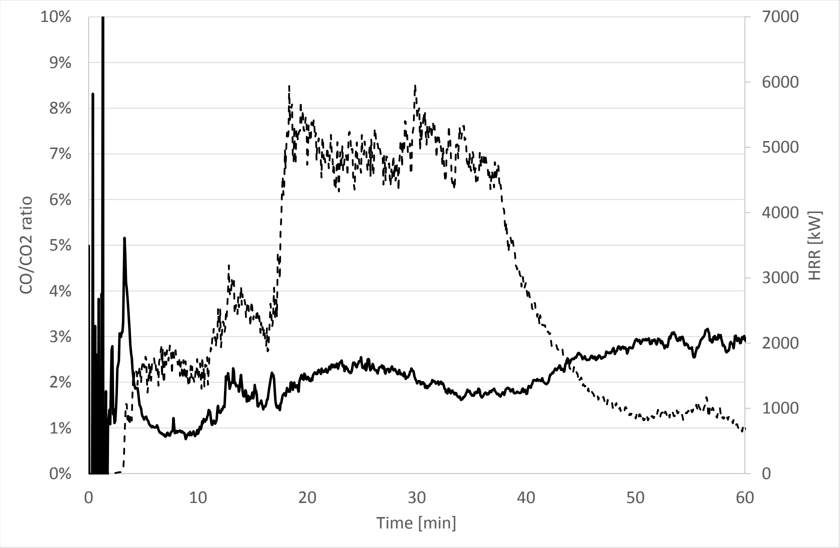

Figure 5: Evolution of CO/CO_2 ratio along time (car2).

This curve highlights that, even considering that the energy release is important compared to the air flow when reaching the maximum HRR, this does not slightly modify the CO/CO_2 ratio that stays under 5% all along the whole fire duration. This value is in accordance with observations made by Tewarson at laboratory scale for different series of well ventilated fires. Identical conclusions were made for the other fire tests.

The other interesting point that has to be discussed is the ratio between acid gases. For each cars, the hydrogen chlorine is the predominant one in terms of total amount released. The evolution of concentration in smoke for those gases along the tests however reveals that the emission dynamic are different in between, Figure 6.

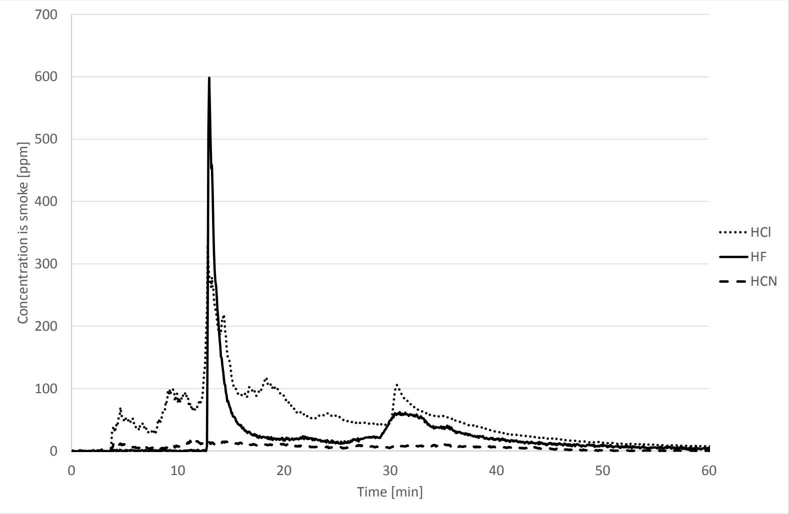

Figure 6: Acid gases concentration in smoke versus time.

This curve shows that while hydrogen chlorine is produced all along the fire, hydrogen fluorin is mainly produced during a short period. On top of that, regarding acid gases, the total quantity of cyanhydric acid is quite small even a lots of foam are present in the car. Once more, those conclusions are valid for all burnt cars.

It is then interesting here to compare emissions for these compounds with those measured by the past [2]. During tests managed by [2], that concerns 90's car, carbon monoxide was largely the main coumpound. During these tests, no HF nor HCN and Nox were measured into the smoke.

Impact of New Energy Carriers

Regarding the specific composition of their batteries, electric cars are commonly supposed to produce more toxic gases in case of fire. Data from electric cars burning were previously published [3]. Those tests were achieved in the same installation as the one described in the present paper and it is interesting to give some words about the specificities of those fires. All tests for electric cars published in [3] and mainly the one discussed in the present paper concerns Li-Ion batteries.

Main conclusions that are on interest here concern the heat release rate that is not modified by the battery and the toxic gases production that is also similar between fuel car and electric one. The proportion of toxic products for electric cars are indicated in Table 5.

	Car 4
Total amount of gas [g]	737 717
Acide gases	
Hydrogen chlorine (HCl)	0,30%
Hydrogen fluorine (HF)	0,23
Cyanhydric acid (HCN)	0,02
Carbon and nitrogen oxydes	
Carbon dioxide (CO_2)	96,98
Carbon monoxide (CO)	1,83
Nitrogen oxide (NO)	0,12
Nitrogen dioxide (NO_2)	0,05
Sulfur dioxide (SO_2)	-
Unburnt	
Total hydrocarbons	0,45

Table 5: Gaseous emissions data.

The main conclusion of this test is that toxic gases emissions are not affected by the battery.

A detailed analysis shows that the total quantity of HF is multiplied by a factor of about 1.8. However the emission curve of HF is, in the case of an electric car, not strongly different from a fuel one as plotted on Figure 7.

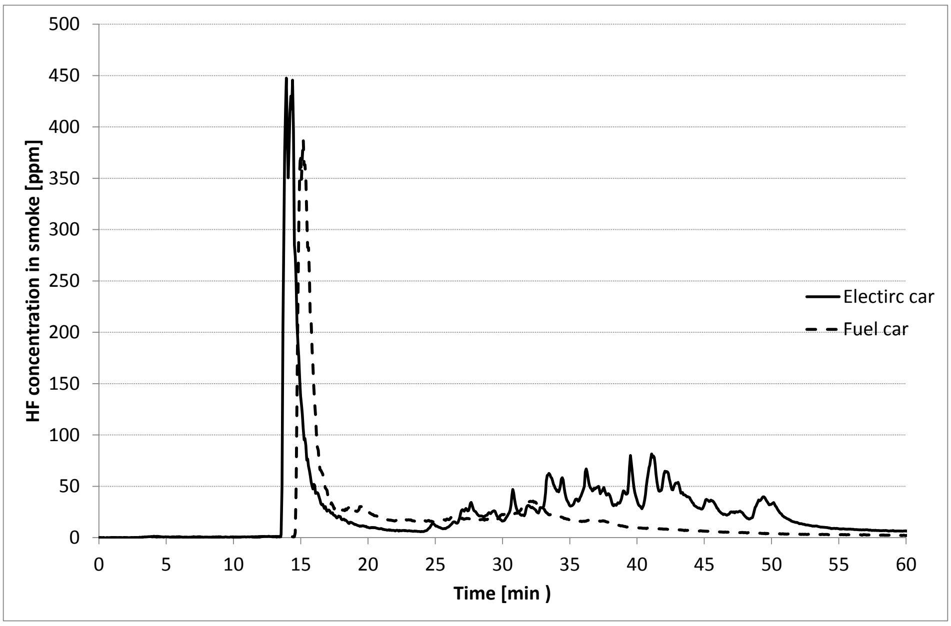

Figure 7: HF emission factor during the electric car burning.

This comparison clearly shows that, the first HF production is totally independent of battery. The contribution of this element appears on the second part of the fire, after 30 minutes burning. In such a condition, it is clear that this new energy carrier does not affect the smoke toxicicity for people during evacuation.

Equivalent toxicity

Because the smoke toxicity is a quite complex problem, mainly due to the relative toxicity of each products and interactions between gases regarding their impact on human beings, a criteria has to be defined for discussing about relative toxicity. Several methods exist to evaluate the relative impact of a toxic gases mixtures as the simple approach that consider all the toxicity as equivalent [17] or the one described in the ISO document 13571 [5] that defines the Fractional Efective Dose (FED) and Fractional Efective Concentration (FEC) and enable considering the difference between gaseous in terms of the nature of human being impact.

The first is based on a simpler approach call the equivalent thereshold method described in [17]. This approach consists in defining the equivalent impact, S_{eq}, on person without taking into accound the toxical nature of the different gases:

$$\frac{1}{S_{eq}} = \sum_{i=1}^{nb\_tox} \frac{[P_i]}{S_i}$$

In this relation, $[P_i]$ represents the concentration of product P_i in smoke and S_i the corresponding toxic threshold for that species. While this method is not as accurate as the FED/FEC approach regarding the evaluation of the toxic impact on the person, it enables to evaluate toxic impact during first stage of fire, that corresponds to the evacuation period, in fire safety studies for tunnels because it considers all toxicity, carbon monoxide, gaseous gases and other compounds.

Based on this and considering 10 minutes threshold on persons, it is then possible to build an equivalent CO emission factor. Of course, this factor cannot be constant and is time varying, as showed on Figure 8.

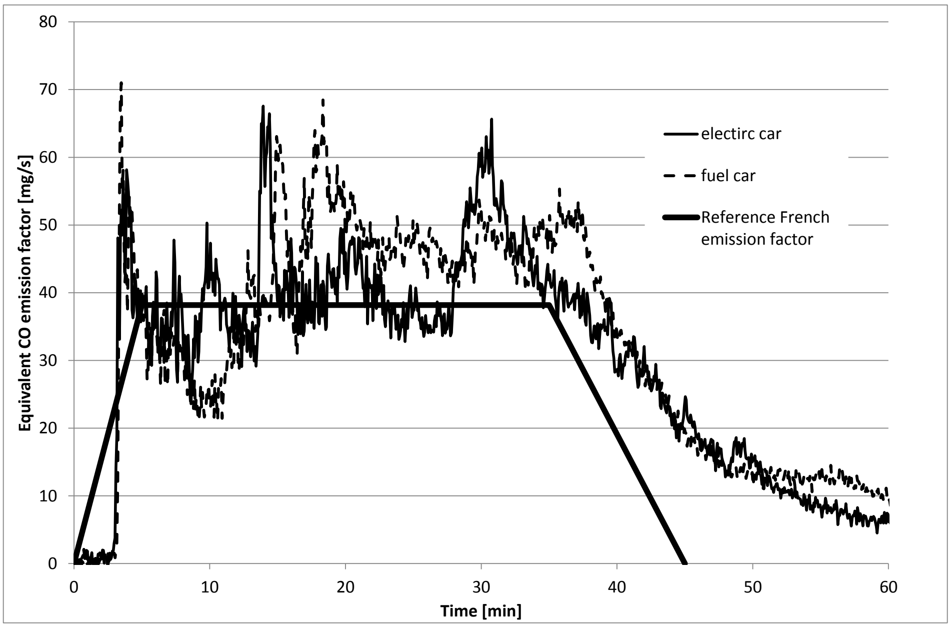

Figure 8: Evolution of CO equivalent emission rate along time, comparison of car 2 and 3, fuel and electric private cars.

This curve shows that, by comparison to existing references for equivalent CO emission factor [4], the actual emission factor can reach twice the standard value. On top of that, it can be produced during the first minutes of the fire, minutes that are crucial for people evacuation but, because the kinetic of the fire is linearized during the first minutes, the standard curve production could still be relevant. In some specific cases, when evacuation safety margin is not so important, some more detailed analysis should be achieved to take into account such specific emission factors.

While the previous method enable to propose an equivalent carbon monoxide source terme, it does not enable taking into account the different nature of gases in terms of toxicity. To achieve a toxic evaluation based on the ISO 13571 [5], the important data is the carbon monoxide emission factor, in mg by g of burnt materials, coupled with the ratio between the given species and carbon monoxide, along time. Based on this, a FED/FEC evaluation of toxicity became possible. The simplest way to deal with those quantities consists in using average values detailed in previous tables. It must be however kept in mind that those quantities are not stationary. The example of car 2 is used hereafter to give an illustration of this phenomena. For this car, the averaged heat of combustion is about 38 MJ/kg, this value is the only one considered as constant.

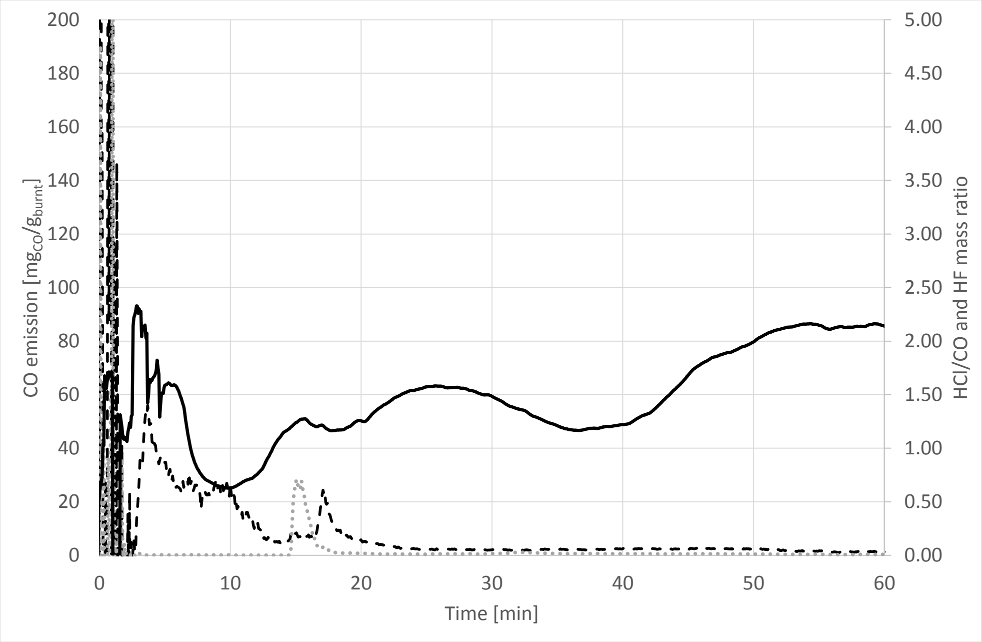

Figure 9 : Evolution of CO emission factor in mg of CO by g of material burnt (continuous line) and of the HCl/CO mass ratio (dashed line) and HF/CO mass ratio (grey dotted line).

This curve typically shows that, during the first minutes of the fire, the emission of hydrogen chlorine could be higher than the production rate of carbon monoxide. Then, after about 20 minutes, the production of hydrogen chlorine can be neglected. Such a comparison lets appear the details level requires to consider the separate impact if the toxic different compounds.

CONCLUSIONS

While a lots of data ara available in the literature regarding the HRR curve for different cars, most of the reference tests that's were used to built those curve were measured on 90's cars and few of them concerns the emission factor. Considering toxicity could be one a the key issues for tunnel fire safety during the ventilation design, this paper presents fire curves and toxic gases production rate for recent car in different categories.

The first important results that appears thanks to those tests is that, while both the total mass of car and plastic fraction were increasing, the maximum HRR value and total energy released given by the standard are still valid. It must be also highlighted that those curve consider a rapid fire growth in the very beginning, such a quick growth was not observed during those tests. This is clearly in favor of tunnel safety regarding the people evacuation.

Regarding toxic gases, carbon dioxide is still the major products that is generated. Other toxic compounds are produced in low proportion compared to that one. Some new gases, as HF, were mainly detected during the different tests, independently of the energy carrier used.

Finally, the emission rate of CO were compared with the standard, based on a equivalent toxicity approach. This comparison shows that, while the fire growth is overestimated in standard curves, the CO equivalent production rate could, in such a case, be higher than the commonly used curve. On top of that, while such an approach is usefull to built an equivalent toxic source term, it does not enable to consider the various effect of gases on human beings as the ISO 13571 FED/FEC approach. To enable such an approach, in case of requirement, a detail source term must be consider because of the time variation of the CO production rate but also regarding the variation of each toxic product vs carbon monoxide ratio along time.

To conclude, when toxicity is the design factor for a specific ventilation system, one must consider a more detailed approach based on a realistic source term instead of standard values than can be highly overestimated in the very beginning and underestimated just after when fire propagates to the whole car.

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