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Benjamin Truchot, Guillaume Leroy, Guy Marlair

CFD AND ENGINEERING METHOD COUPLING FOR EVALUATING THE FIRE RELATIVE TO BATTERY TRANSPORTATION

Benjamin TRUCHOT*, Guillaume LEROY and Guy Marlair
INERIS, Verneuil en Halatte, France

ABSTRACT

Using CFD fire modelling for underground infrastructure always face off the same problem that consists in defining the heat release rate and toxic gas source term. Based on a large series of experiments, standards were defined some decades ago and are currently used for safety design. The development of new energy carriers however let fire safety engineer to wonder about the applicability of those standards and the possibility to consider more realistic curves.
This paper proposes an innovative model to build the heat release rate and toxic gas emissions curve for trucks. It consists in splitting the vehicle in several interconnected elements that have their own curves. A relation can then be supposed for the propagation in order to obtain a global curve. After comparison to experimental available data, this model can be applied for designing source term including new energy carriers as batteries.
One of the main interest of such an approach consists in considering individual fire tests that could be easily managed and then considering real emission factors for the different individual component of the vehicle.

Finally, the fire and toxic gas emission curve produced by such an approach can be introduce in a CFD code, not for safety design because of the specificity of the curve but for giving a positioning regarding the applicability of standards compared to current real fires.

Keywords: electric car, HGV, CFD modelling

1 INTRODUCTION

New Energy Carrier (NEC) is nowadays in great expanding because of the well known impact of transport technologies on global warming. To ensure a mass development of those technologies, safety must be considered on the very beginning. Even several technologies exist, this paper focus on electro mobility. Some works were recently published focussed on the consequences of electric car fire in tunnel. One of the major issues for using such NEC should however be relative to transport. Consequences of fire have to be considered in case of Hazardous Goods Vehicle (HGV) that carries batteries, and compared with the commonly used standard curve for HGV.

This paper focuses on this case of fire on a HGV that carries batteries. Defining the fire curve is the first step. Data are available in the literature for a standalone battery fire, both in terms of heat release rate and in terms of toxic gas production, fire resistance of batteries were also communicating for some of them. This paper presents an engineering method that aims to compute the source terms that corresponds to fire propagation to the whole vehicle considering standalone fire curves and fire resistance available data. This model can also consider different ignition configurations, the case of a fire that stars on the lorry, brake failure for example, or the case of a fire that starts on one of the batteries. Of course, in such a case, the fire propagation to the battery loading is fully different and thus, fire consequences are also. This fire curve built with this model provides not only the heat release rate along time but also the distribution of toxic gases release rate.

Because the source term curve alone cannot be used for concluding regarding the human potential risk, the FDS fire code was used in order to predict detailed consequences on a given standard tunnel geometry on one chosen scenario using both standard and modelled fire curve. These consequences were evaluated both in terms of temperature, for the stratification process, and toxicity, for ensuring a safe evacuation.

2 BACKGROUND ON DATA USED FOR FIRE IN TUNNEL CONSEQUENCES MODELLING

The main focus of the present paper is the batteries loaded truck fire consequences in case of fire in tunnel. To provide a better understanding of the problematic, an overview of the current methods and standards used is required.

2.1 The difficult choice of the toxic properties of the design fire

As discussed in (1), different sources are available for defining the characteristics of the design fire. It is commonly admitted that a passenger car will generate less than 10 MW fire, even for a large passenger car, that a buses fire will generate around 20 MW fire and that heavy goods vehicles can lead to fire up to more than 100 MW. This heat release rate is of course directly linked, not only with the temperature curve in the vicinity of the fire, but with the smoke production too. A smoke production rate for design fire was proposed by different sources as (1) or (2). One of the main interests of those two references is to provide the quantity of carbon dioxide and monoxide and consequently an estimation of the ratio between those two values. Some values are reminded in Table 1.

Table 1: Example of design fire smoke production rate and CO/CO_2 ratio

Nature of the fire and source	Pic heat release rate [MW]	CO_2 production rate [kg/s]	CO production rate [kg/s]	CO_2/CO ratio
Plastic passenger car (1)	5	0.4 – 0.9	0.02 – 0.046	8 – 45
Large passenger car (2)	8	0.8	0.02 – 0.1	7.6 – 39
Lorry without dangerous goods (1)	20	1.5 – 2.5	0.077 - 0.128	12 - 32
Lorry without goods or heavy goods vehicle(2)	30	3	0.08 - 0.4	7.6 – 39
Heavy goods vehicle (1)	20 – 30	6 – 14	0.306 – 0.714	0.8 – 46
Heavy goods vehicle with combustible load (2)	100	10	0.25 – 1.3	7.6 - 39
Heavy goods vehicle with hazardous goods load (2)	200	20	0.5 - 2.6	7.6 – 39

It must be first added that, of course, CO is not the only toxic gases produced by a car fire but it gives a representation of the global toxicity (4) (5).

2.2 The impact of the load on the design fire

In the specific case of hazardous goods transport, the nature of the product in the loading could have a major influence on the smoke toxicity. This of course could change radically the conclusion of the safety study regarding the available time for people evacuation. Then, before going any further in analysing batteries impact on the toxic loaded of truck fire, the relation between toxic gases production rate, represented by the CO production, and the heat release rate has to be analysed for different categories of materials. Based on the available data for various products (9), the analysis could be achieved regarding the CO production rate, based on the CO_2/CO ratio. Common values for this ratio is typically given by (9)

3 BACK ON THE AVAILABLE EXPERIMENTAL DATA

3.1 Batteries fire

Batteries currently appear are a new king of hazardous goods that should need, in the future, a large amount of transport. Consequently, it is crucial to be able positioning batteries transportation truck fire relatively to the currently design fire.

Based on available date for batteries combustion (4), it is possible to build an equivalent CO production rate. Of course, batteries fires generate a large variety of toxic compounds as mainly hydrogen fluoride. Because of the high level of toxicity of such products, each compound has to be considered in building the toxic source term. To create an equivalent CO source term, the toxic cumulative effect from (11) is used.

3.2 Available data for other part of the truck

If batteries are a source of toxic gases in case of fire, other compounds in trucks also generate such products in case of fire. Data regarding toxic emission for cars and individual compounds were recently published (14). Those data indicate that, while carbone dioxide is the main product generated during a car fire, in terms of mass, acid gases as HCl or HF, while being produced in lower quantity, have a more important potential considering toxicity. Those gases are generated, at specific rate, by various compounds as foam in seats, plastics or also cooling system product.

3.3 Synthesys of available data

As an illustration of available data, emission factor for the different individual compounds are given in

Table **2**.

Table 2: Synthesis of toxic emission for some individual compounds.

	Gasoil	Plastics	Tyres	electric cables	Batteries
Mass of product burn [kg]	131	48	49	36	71
Emission factors [mg/g] or [g/kg]					
CO_2	2823	2034	1469	728	1 196
CO	31	20	42	9,1	5,4
HCl	-	2,2	0,2	2,1	1
HF	-	0,014	0,003	0,11	14,3
NOx	1,2	5,0	2,8	2,5	1,3

4 MODELLING FIRE PROPAGATION

4.1 Evaluation of the HRR curve

Regarding car fire, several tests were achieved (8) or more recently (4)(14) and lead to normalized fire curve for such vehicles (2). Such a curve does not however enable to predict real car fire considering these curve give just an estimation of the maximum power and duration linked with linear curve. Furthermore those curves are only provided for one “small vehicle” and one “large vehicle” while there is differences between vehicles. To make a better prediction of the heat release rate from a vehicle fire, a specific model was developed. The fire curve predicted using analytical model was then introduced in the FDS CFD fire code to evaluate the ability of this code to predict the fire consequences. Having validated the numerical approach, it was then used to model some other scenarios.

1.1. Mathematical modelling of a car fire

Considering total heat release rate for a vehicle is governed by the heat release of the different components, this tool enables to compute the fire curve by summing the individual heat release, considering also a propagation time. The car is split into 5 parts, namely: wheels, engine block, interior, trunk and fuel tank. The average combustion velocity and heat of combustion is then computed for each part considering the distribution between following materials.

Table 3: Used heat of combustion and combustion velocity for individual elements.

Material	□Hc (MJ/kg)	□ (g/m²/s)
Polymers	35	20
Elastomers	35	20
Oil	40	30
Battery	35	25
Tires	30	20
Fuel	42	55

Each component fire curve follows three phases: the fire growth, a steady state and a linear decrease phase. The contribution of each element is then summed. The non-combustible materials are considered as sink of energy.

4.2 Evaluation of batteries loading consequences

As detailled previouly in the present paper, consequences of the presence of batteries in the truck loading as to be considered not only in terms of HRR but in terms of toxic gases production too. The objective of the paragraph is to present the curve built with the model described hereunder for those two quantities. Hypotheses are described first.

4.2.1 Hypotheses

The considered truck was 38 tons one composed with tractor and trailer. The tractor includes about 5 tons of combustible products as tires, plastic and foams associated with the potential 600 kg of fuel. The trailer is assumed being composed mainly with non combustible materials excepted tires, around 1 000 kg, and loading, 25 000 kg. Considering that the mass of one battery can be taken equal to 250 kg, this means that about 100 of batteries can be present inside the trailer distributed as schemed on Figure 1.

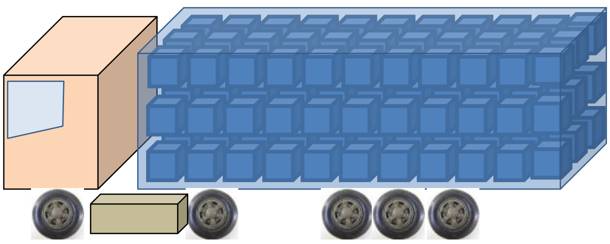

Figure 1: Schematic view of the modelled truck loaded with batteries

Even some data exist in the literature (1) (2) regarding truck fire that can be used for having a global HRR curve, propagation inside the batteries loading has to be modeled. Consequently, hypotheses are required regarding HRR for each and criteria for ignition. Based on available data in the literature concerning Li-Ion batteries, a design fire curve can be built for such a product, Figure 2.

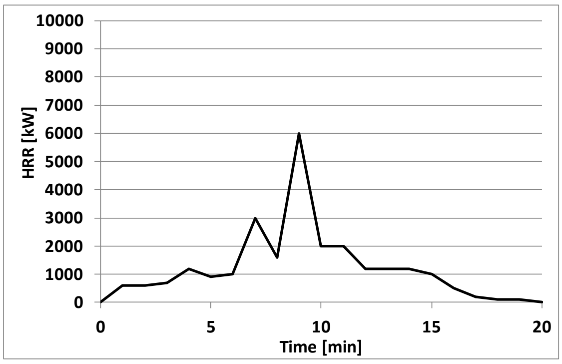

Figure 2: Design fire curve for a battery

Because defining the ignition temperature for a product as complex as a battery is quite complex, the criteria considered in the present paper is that the adjacent element fire starts when the one in fire reach 1 MW. Because of this can appear arbitrary, some parametric variations were made to evaluate its influence.

The last hypothesis is the ignition location. Two possibilities consequences were evaluated. The first case consists in a fire ignition due to a mechanical failure in the trailer, the second is a battery self ignition. Consequently, the fire propagation scheme is then highly different between those two cases.

4.2.2 HRR curve

The HRR curve obtained based on hypothesis described hereunder are given on Figure 3. Those curve are compared, on this graph, with the French standard one for truck loaded with highly flammable goods, without hazardous ones, and with the standard one for hazardous goods transportation truck (2).

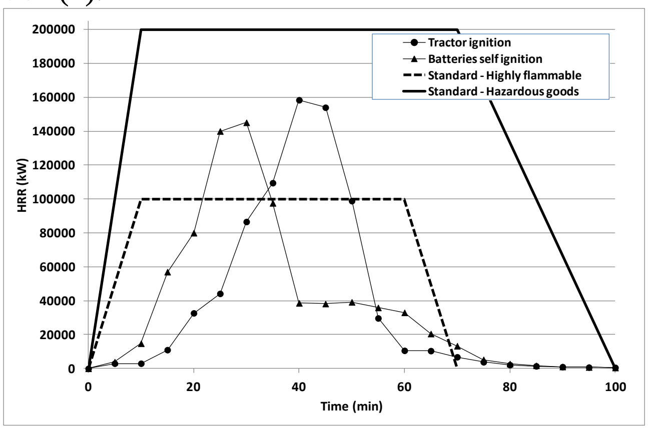

Figure 3: HRR curves for batteries loaded truck

The main conclusion of this first comparison is that the HRR for a batteries loaded truck stay under the hazardous goods one. This means that the fire design curve for hazardous goods still remain conservative.

The impact of the hypothesis regarding fire propagation was evaluated by forcing the propagation between the element after 2, 5 and 10 minutes. Results are plotted on Figure 4.

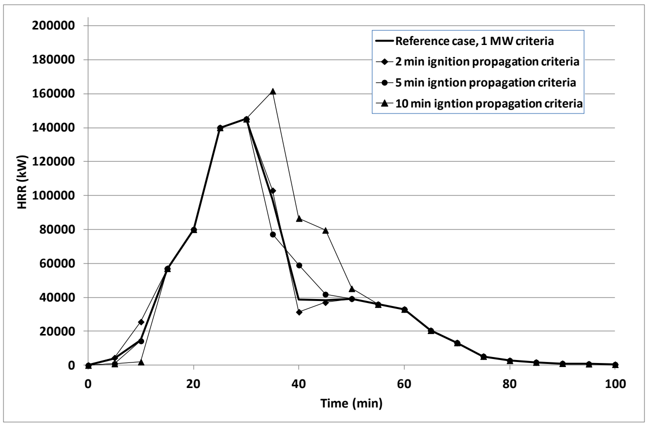

Figure 4: Parametric variation of the propagation criteria

This comparison shows that the hypothesis on the ignition criteria does not slightly influence the HRR curve. The 1 MW reference criteria is then considered in the following.

4.2.3 Toxic production rate curve

As mentioned previously, one of the key parameter for fire safety design is the toxic gases production rate. Because of the large amount of gases and their specific toxicity that are produced in case of battery fire, the equivalent rate of CO can reached around 50 (g/s)/MW considering the cumulative toxic effect as described in (11). This value is of course only valid for the battery, the emission rate to be considered for the other parts of the truck is the standard value for well ventilated fire, this means 2,56 (g/s)/MW. The emission curves for standard design fires and batteries loaded trucks are then given on Figure 5. The CO production curves for battery fires are given considering the experimental configuration, the standard curves are given for well ventilated and under ventilated fires for the purpose of comparison.

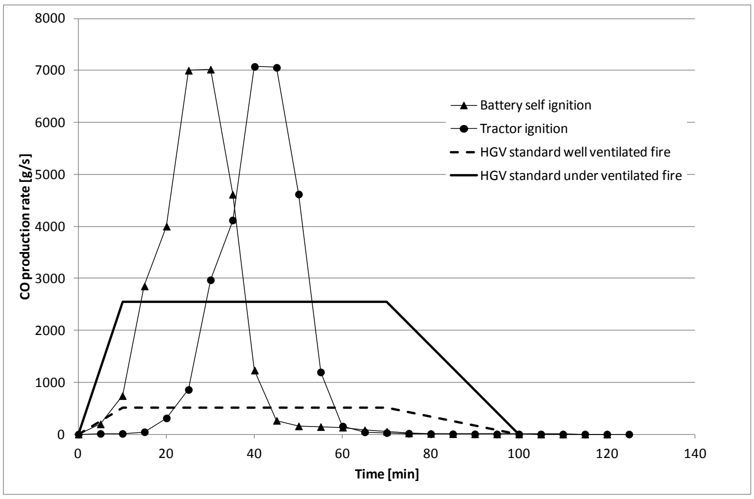

Figure 5: CO production curves for batteries loaded truck

These curves clearly indicate that, whatever the ignition source, the toxic gases production rates is clearly higher for a batteries loaded truck that for the standard case.

5 EVALUATION OF CONSEQUENCES IN CASE OF FIRE IN TUNNEL

As described in the previous paragraphs, while the HRR for a batteries transportation truck is lower than the HRR design fire curves, the toxic gases production rate is larger. An evaluation of the impact of this conclusion using a numerical modelling approach is proposed. This evaluation was managed using the Fire Dynamic Simulator (FDS) fire code developed by the

National Institute for Standard and technology (NIST). This code was previously evaluated by INERIS for tunnel configuration modelling based on experimental data (12). The objective of this paragraph is not achieving a detail analysis of consequences in case of tunnel fire but to give an illustration of consequences for a given scenario.

5.1 Geometry and numerical hypotheses

The data considered in the present study is a two lanes tunnel, 10 m width and 5.5 m height, a total length of 500 m was modelled. Because of their influence on the flow, vehicles inside the tunnel were considered based on a classical congested distribution. Because of the influence of vehicles blocked inside the tunnel on smoke distribution (13), a vehicle distribution inside the tunnel was considered. Considering the integral length scale is in the order of the half diameter of the tunnel, the cell size was set lower than the twentieth of the half width. The characteristic size of the cell was then 0.2 m in each direction. A picture of the geometry is given hereafter on Figure 6.

Figure 6: Picture of the numerical geometry

In such a configuration, the ventilation velocity has to be reduced to maintain the stratification during the evacuation phase. In the present simulation, a negative velocity at 1 m/s is supposed to be generated by pressure differences between tunnel portals. Then, he ventilation system is started after 1 minutes, after 2 minutes, the velocity reaches 0 and is then controlled at 1 m/s 3 minutes fire ignition.

5.2 Results representation

One of the main objectives of this simulation is to evaluate the impact of the fire of a truck that transports batteries in terms of temperature, visibility but also toxicity near the ground. As mentioned previously, a detail analysis should require numerous scenarios with different ventilation and traffic configuration. The one given in this paragraph only aims to give an illustration of how the above described experimental results can be introduced in a numerical simulation.

In such a situation, the first element to be checked is the stratification upstream and downstream the fire. Figure 7 shows the temperature distribution for both cases each minutes between the crucial 1 and 4 minutes after ignition.

Figure 7: Temperature distribution for standard fire (left) and batteries loaded truck fire (right)

This first result shows that stratification is maintained for both fire curve hypothesis and that, considering a real curve, with a lower HRR will led to a reduced temperature under ceiling and, consequently, a lower stratification criterion.

The important factor however is the toxicity near the ground during the evacuation process. To evaluate the impact in terms of toxicity, Figure 8 gives the equivalent CO toxicity 2 m above the g round 5 minutes after ignition.

Figure 8: CO mass fraction as equivalent toxic 2 m above ground during the evacuation process for the standard curve (top) and adapted one (bottom) after 4 minutes

This results shows that whether the fire development is slower using the real curve, the toxicity near the ground is more important. This phenomenon is clearly due to the relation between thermal stratification and toxic emission factor.

While this configuration is just an example for a given scenario, geometry, ventilation, cars distribution, … it indicates that, for hazardous goods that could generate a large amount of toxic, using the standard are not necessarily a safe way in a design process.

6 CONCLUSIONS AND PERSPECTIVES

While CFD models are nowadays commonly used for fire safety, mainly in the field of tunnel safety, one of the key issue consists in determining the source term. Over the past decades a lots of work were managed in the aim of defining such source terms for several types of vehicles in different conditions. Those works led to the publication of generic fire curves. While those curve are a fundamental background for fire safety, the development of new energy carriers generates imposes fire safety engineer to wonder about the applicability of the standards.

In order to be able defining specific consequences generated by an innovative configuration, this paper details a methodology for evaluating fire consequences from the vehicle fire development, including each component, to the smoke dispersion based on a CFD approach.

This paper shows, first that the HRR proposed by the standard curve are in good accordance with what can be evaluated thanks to this model. As an example, the HRR curve of a batteries loaded truck is still under the hazardous goods 200 MW fire curve, this means that structure design based on the HGV curve still prevent for an impact from such a transportation. On top of that, as many of other curves, this model shows a propagation not so fast as predicted by the standard.

Regarding people safety, the main interest is however consisting in defining a toxic equivalent source term based on the characteristics of each element. It can then be shown that, as for recent vehicles (14), emission factor is more important than the one proposed in the standard. To evaluate the impact of a modification on tunnel safety, a CFD model was run for a given

ventilation scenario. It shows, first, that considering the real HRR curve led to a limitation of under ceiling temperature in the first minutes of the fire with, as a consequence, a lower stratification phenomenon. On the opposite, because the fire development is not so fast, consequences on people are maintain in accordance with the evacuation process. This case show once more that being able evacuate rapidly the tunnel is a key issue for people safety because of the fast degradation of tenability after some minutes after ignition.
These conclusions still need to be extended to other scenarios and configuration. While the development of NEC is still a continuing process, it should be required, in the future years, to propose an evolution of the commonly used standard curves.

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