Modelling of fire spread in car parks

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Currently, design codes assume that in a car park fire at most 3-4 vehicles are on fire at the same time. Recent incidents in car parks have drawn international attention to such assumptions and have raised questions as to the fire spreading mechanism and the resulting fire load on the structure. E.g. a recent fire at Schiphol Airport showed a much faster fire spread and a larger number of vehicles on fire at the same time than was normally assumed. To understand and predict the fire spread in a car park a, for the time being deterministic, model is being developed based on the effects of the governing radiative heat transfer. With this model it will also be possible to quantify the effects of different relevant parameters.

Key words: Fire spread, car park, radiation

1 Introduction

In this research the focus is on fire spread in the case of a fire in a car park. The current, empirically founded, assumption is that during a fire in a car park at most 3-4 vehicles are on fire at the same time [3]. In a recent fire (10-2002) in a car park near Schiphol airport [1] however, around 30 cars were on fire at the same time. Also the fire spread was much faster than currently assumed. However, the fire occurred in a car park of a car rental company, which led to some specific circumstances that might have caused the more rapid fire spread than normally expected.

- All cars were parked on a small distance of each other, which can enhance fire spread from car to car.
- All cars were new and new cars contain more plastic parts than older cars. Plastics can be ignited more easily and produce more heat.
- All fuel tanks of the cars were completely filled, leading to a high fire load.
- The fuel tanks were made of plastic and started leaking fuel, creating pool fires which can also cause spreading of fire, by draining away under other cars.

Some of those specific conditions can however also apply in normal (public) car parks and the exact contributions of each of the effects are unknown. To quantify these effects, a deterministic model is being developed. The deterministic model is intended to be used together with a probabilistic approach, because a large number of input parameters is quite uncertain and occurs in a wide range. The choice of a probabilistic approach in combination with a deterministic model limits the possibilities for the deterministic model. CFD for example can give a detailed and accurate solution for a specific case with specific parameters, however it is too time consuming to be used in combination with a probabilistic approach. Furthermore the reliability of such a solution should not be overestimated, because large uncertainties are introduced by the uncertain parameters.

Figure 1. Picture after the fire in the car park near Schiphol airport (picture from [1])

The model focuses on fire spread by radiation, because this accounts approximately for the heat transfer of 30-40% of the heat released by the fire. Therefore, radiative heat transfer is expected to have the largest influence on fire spread. Furthermore radiative heat transfer does not require mass exchange or direct contact between the heat exchanging bodies and is described by well-known equations which can easily be solved. However, there is still the possibility to add the effects of the pool fires (due to the leakage of fuel from the fuel tanks) in the model, when the results based on radiative heat transfer turn out to be insufficient.

This study is to be seen as a first step to approach the trends which to a large degree undermine the current safety concepts: closer parking distances, large cars, more cars, application of more combustible materials, more electrical appliances (increasing the probability of short-circuits and self-ignition) and so fort. The probability and the consequences of large(r) fires seem to increase; this underscores the necessity to initiate the development of more fundamental research into fire spread in car parks.

2 Description of model

2.1 *Introduction*

Mainly two different types of fire spread can be distinguished: fire spread inside a car and fire spread from car to car. Currently the major interest is in the fire spread from car to car. Fire spread from car to car can occur in various ways, for example directly by flames or by means of convective or radiative heat transfer. This is illustrated in figure 2.

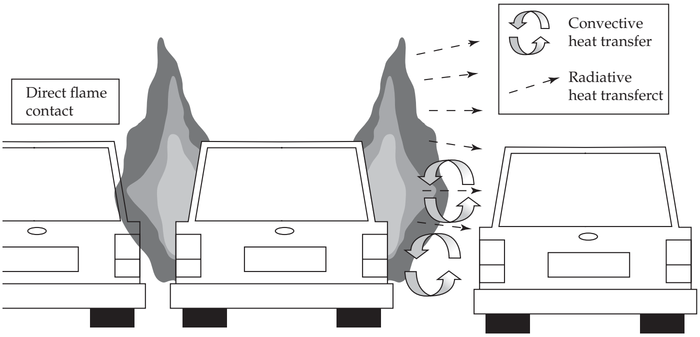


Figure 2. Different ways of fire spread; on the left direct fire spread by flame contact, on the right indirect fire spread by heating due to convection and radiation

When a car or other object is on fire, the flames emit a significant part of the total heat release by means of radiation. The radiation is transferred through the surrounding air towards other cars or objects. The parts of other cars absorb some of the incoming radiation, which causes heating of those parts. Because of the heating, the temperature will rise and when the ignition temperature is exceeded, those parts start burning too.
Three different processes can be distinguished: the emission of the radiation, the heat transfer through the air (transmission) and the absorption of the radiation. In the following sections those three processes are described in detail.

2.2 *The emission of radiation*

In the model, all objects are built of surfaces. Some of the surfaces are burning. A solid surface can burn, when inflammable gases evaporate out of the surface material (pyrolysis) and burn in flames after they have left the surface. The mass loss rate of gases evaporating out of the surface depends on the heat transfer towards the surface. When the gases burn, heat is released. A significant part of the total heat release is emitted by radiation.

The mass loss rate $\dot{m}''$ of a surface, caused by pyrolysed gases, is defined as [4]:

$$\dot{m}'' = \frac{\dot{q}''_e + \dot{q}''_{fr} + \dot{q}''_{fc} - \dot{q}''_{rr}}{\Delta H_g} \tag{1}$$

where $\dot{q}''_e$ is the external heat flux, $\dot{q}''_{fr}$ the radiative heat flux of the flame towards the surface, the convective heat flux of the flame towards the surface, $\dot{q}''_{rr}$ the outgoing radiation of the surface and ΔH_g the heat of gasification. The values of the heat flux from the flame towards the surface have been estimated using literature values for the maximum heat flux (unlimited oxygen available) from the flame towards the surface. Note that ignited surfaces without any external incidental radiation flux can still burn because of the heat flux of the flame towards the surface.

The calculated mass loss rate can be used to calculate the heat release rate, by multiplying the $\dot{q}''_{fc}$ mass loss rate with the heat of combustion and a parameter to take into account the incomplete combustion. About 30-40% of this heat release rate is emitted as radiation. The rest is used to heat up the burning products and the entrained air.

The part of the total heat release rate which can be regarded as radiation is emitted by the flames. This is described by the equation:

$$\dot{Q} = \varepsilon A \sigma T^4 \tag{2}$$

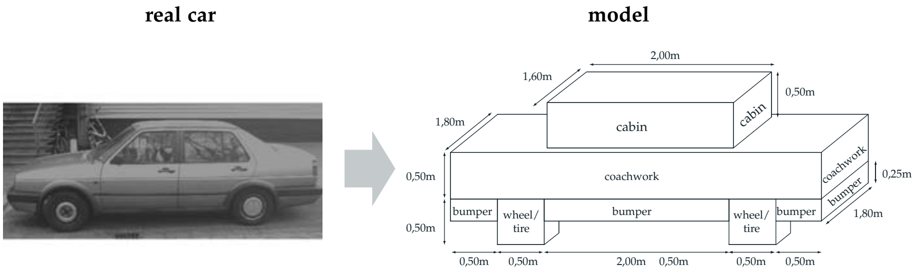
where $\dot{Q}$ is the emitted amount of energy, e the emission coefficient of the flame, A the area of the flame, s the Stefan-Boltzmann constant and T the absolute temperature of the flame. The flame will have a different size (and shape) than the burning surface.

In the model the mass loss rate of a surface is calculated, as stated before, as a function of the radiative heat flux on the surface. In the model the temperature of the flame and the emission coefficient are simply fixed. For a given radiative heat flux, the area of the flame can be calculated using equation (2).

2.3 *Heat transfer by radiation*

The radiative heat transfer between two surfaces of a certain temperature depends on the thermal and geometrical properties of the surfaces. The important thermal properties are the temperatures, emission and absorption coefficients. The geometrical properties are the shape, the orientation and the position of the two surfaces.

The radiative heat transfer between two surfaces can be described by analytical expressions. The expressions are quite simple for rectangular surfaces orientated perpendicular or parallel to each other. Furthermore in a car park the surfaces of most objects are orientated that way and most shapes can be approximated using rectangles. So in this model, it is assumed that all objects are built of rectangular surfaces orientated perpendicular or parallel to each other, which makes the calculations much more efficient.



real car **model**

Figure 3. Example of a car built of rectangular surfaces orientated perpendicular or parallel to each other

The model is chosen such that the main parts that contribute to the fire development can be treated separately and, if desired, in relative great detail.

This means the cars in the car park are built of rectangular surfaces orientated perpendicular or parallel to each other. The surfaces have different properties, depending on the material used. In figure 3 is shown how a car can be built of this kind of surfaces. The exact size and location of the parts in a car can be chosen which results in a different type of car. The car can also be 'refined' by building it of more, smaller rectangles resulting in a more detailed model. The cars can now be placed in the car park, but again all surfaces have to be orientated perpendicular or parallel to each other, which results in four possible orientations for a car with respect to another car.

The radiation flux on a surface is the result of a number of visible (hot) surfaces close to it. Those surfaces have a constant temperature. Let's now consider the radiative heat transfer between two surfaces. The discussed procedure can easily be extended if there are more hot surfaces (which are not located 'behind' each other) by taking the sum of all fluxes as the total radiation flux on a surface, which is also done in the model.

The radiation flux on a surface is calculated in a few points (infinitesimal small surfaces) on the surface in so-called sensor points and depends on the thermal properties of both surfaces and the position and orientation of the surfaces. The position and orientation of the surfaces can be combined in one coefficient: the view factor or configuration factor, which resembles the part of the total solid angle covered by the other surface. This leads to the following equation for the incoming radiative flux in a sensor point A_{d1} (on a surface A_1) caused by a (hot) surface A_2:

$$Q''_{2\to d1} = a\varepsilon\sigma A_2 T_2^4 F_{d1\to 2} \qquad (3)$$

where $Q''_{2\to d1}$ is the radiation flux per unit area at the location of the sensor point (d1) on surface A_1 caused by surface A_2, a the absorption coefficient of surface A_1, ε the emission coefficient of the emitting surface A_2, σ the Stefan-Boltzmann constant (5.67x10^{-8} $Wm^{-2}K^{-4}$), A_2 the area of surface A_2, T_2 the temperature of surface A_2 in Kelvin and $F_{d1\to 2}$ the view factor from the infinitesimal small surface A_{d1} to surface A_2. Note that the fixed values for the flame temperature and emission coefficient, introduced after equation (2) , do not necessarily change the results. Because equation (3) can be seen as the absorption coefficient times the amount of radiation from a flame reaching the receiving surface, which is actually the product of the radiation heat release by the flame (equation (2)) and a geometrical factor. The geometrical view factor takes into account the part of the radiation from the flame reaching the receiving surface and within certain limits this factor would not change much for different flame heights. As mentioned before the view factor depends on the geometrical properties of the two surfaces relative to each other. In Appendix A some simple view factors are described for the interested reader.

2.4 ***Absorption of radiation, heating and ignition***

The incoming radiation flux $Q''_{2\to d1}$ resembles the amount of energy entering a infinitesimal small area on surface A_1. There is also energy leaving the surface by radiation and convection. The energy flux leaving the surface by radiation $Q''_{rad.loss}$ can simply be found to be:

$$Q''_{rad.loss} = \varepsilon\sigma T_1^4 \tag{4}$$

where ε is again the emission coefficient of the emitting surface, σ the Stefan-Boltzmann constant and T_1 the temperature of the emitting surface in Kelvin. The energy flux leaving the surface due to convection $Q''_{conv,loss}$ is:

$$Q''_{conv,loss} = \alpha\left(T_1 - T_0\right) \tag{5}$$

where a is the convective heat transfer coefficient, T_1 the temperature of the surface and T_0- the ambient temperature.

The difference between the energy entering and the energy leaving the surface causes heating or cooling of the surface. The temperature at the next time step can be calculated with a simple energy balance. When the calculated temperature exceeds the ignition temperature the surface will start burning the next time step.

In figure 4 the time to ignition is shown for different plastics as a function of the radiative heat flux on the surface (data from [5]). In the figure the large spreading can be seen between the different materials.

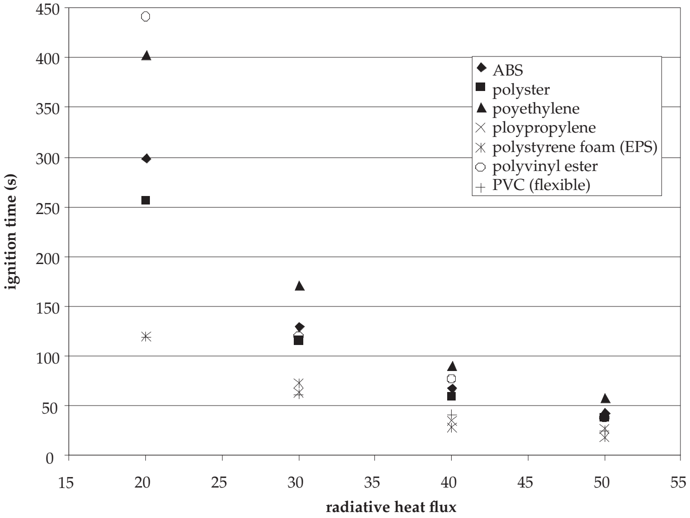


Figure 4. The time to ignition as a function of the radiative heat flux on the surface for different plastics

3 Results

The development of this model is in an early stage and the model is not validated yet. Nevertheless the first results show realistic ways of fire spread and realistic temperature predictions. A few qualitative pictures are presented here to show how the results of the model can look like. Note that in the current model each part of a car is built of surfaces, but the surfaces have to be the faces of a block. So a complete bumper is made of three faces on a block. The blocks are used to model fire spread within a car, for example from one side of the bumper to another side of the bumper. Currently the fire spread within a block is not really modelled, because a whole block will be in fire when one of the surfaces starts burning. This will significantly increase the fire spread, but this will be changed in a later version.

A fire starts with a burning car in a car park, which can ignite other cars. In figure 5 an example of a car park with 6 cars is showed after some time. The dark surfaces in the figure are on fire and the second car from the left was initially on fire. In the figure, it can be seen that at the current time the compartment of the car in the front is on fire too. In the figure the *surfaces* are showed. Note that the burning surfaces have a different height than in the initial (non-burning) situation. This represents the flame height, which depends on the mass loss rate, which on its turn depends on the incoming radiation flux.

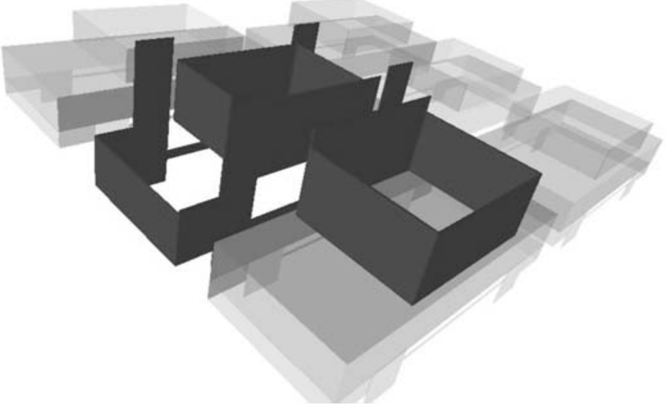


Figure 5. The surfaces on fire after a certain time. The dark surfaces are on fire, note that the height of a burning surface represents the flame height and is based on the heat release rate

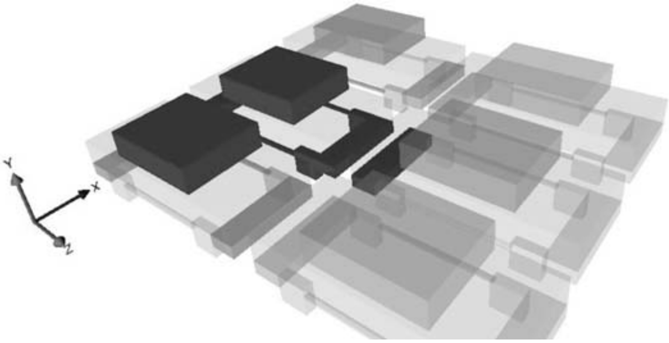


Figure 6. Parts on fire in the car park after a certain time. The dark parts are on fire, the lighter parts are non-burning. This only indicates whether or not a part is burning

In figure 6 the same car park with 6 cars is showed, only from a different point of view. In this figure all blocks (resembling car parts) are showed. The dark blocks now represent car parts that are on fire. In this figure it is much easier to see which parts are burning. Now can be seen that even the bumper of the car parked behind the initially burning car is on fire.
Normally the showed figures are in colour, where the colour is a measure for the temperature and state (not yet burning, burning, finished burning) of the block or surface.

4 Conclusions and recommendations

4.1 ***Conclusions***

Driven by the uncertainty in the development of fire experienced in real fires in parking garages, a fire spread model was developed that is capable of predicting the fire spread between cars in parking lots in an arbitrary configuration. The model predicts fire spread on the basis of radiative heat transfer which is considered the dominant fire spread mechanism. Although the model is still in the development phase and needs further validation and improvement, some very promising features already became clear:

- The model is very fast and robust because of the explicit calculation procedure.
- The model is very flexible, due to the modular structure. The position of the cars as well as their shape and composition can be varied easily.
- Thanks to the flexibility, speed and robustness of the model, it can be combined with a probabilistic approach. In that way the effects can be quantified of different parameters like the distance between cars, the influence of material properties (e.g. different types of plastics) and car dimensions.
- The model forms a suitable basis for the predicting of other fire spread problems such as fire spread between objects in storage buildings.

4.2 ***Recommendations***

It is expected that more and larger fires will occur in the near future. With a view to better understand the phenomena involved and hence the possible (combination) of countermeasures, the model will be further developed.

Variations in the results are currently caused by both uncertainties in the combustion characteristics and the simplicity of the used models. So, improvements will be concentrated on the probabilistic approach taking into account these material uncertainties and on the reduction of the model uncertainties. The reduction of the model uncertainties is planned by the following improvements:

- Fire spread within a surface: A more realistic representation of fire spread within a surface is needed. Currently a complete surface starts burning when at one of the sensor points the ignition temperature is reached, which can lead to a too fast fire spread. Using a simple quadratic growth model the fire spread on one surface of a car part can be described in more detail. Data of the research project on fire spread in cars by MVFRI and NHTSA [2] can be very useful here to obtain a more realistic description of the fire spread on a surface

- Fire spread within a car: A more realistic representation of fire spread within a car is needed. Currently a complete car part starts burning when one of the faces start burning, which leads to a too fast fire spread. It is more realistic to let a (non-ignited) face of a car part start burning after some time, maybe when the initially ignited face is completely on fire (as described before). Again data of the research project on fire spread in cars by MVFRI and NHTSA [2] can be very useful here to obtain a more realistic description of the fire spread in a car.
- Shadow effect: The shadow effect, the effect that a surface behind another surface is not (completely) visible, should be taken into account. Not taking it into account can lead in extreme cases to a too fast fire spread. There are algorithms available to take this effect into account
- Smoke layer: A hot smoke layer above the parked cars can enhance fire spread by radiation towards the cars from above. Currently no smoke layer is taken into account, which leads to a slower calculated fire spread. A smoke layer can grow and parts of cars can become surrendered by hot smoke, which can lead to heating of not yet ignited parts. On the other side a smoke layer, which surrenders car parts, can shield those car parts from radiation. A smoke layer can possibly be introduced by solving simple mass and energy balances, as done in the current zone models.

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