Fire safety assessment in semi-open car parks

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FIRE SAFETY ASSESSMENT OF SEMI-OPEN CAR PARKS

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ABSTRACT

Guidelines for the safe design of semi-open car parks require a minimum amount of open façade in order to ensure an effective removal of heat and smoke during a car fire. In this study the fire safety level is assessed by the use of validated Computational Fluid Dynamics (CFD) simulations of different design variants. The fire safety is assessed using temperature and sight length criteria for safe deployment of the fire department. Results show that 3 out of 7 studied variants did not meet these criteria. It is therefore concluded that it is possible to design semi-open car parks which comply with current Dutch guidelines, yet when assessed with criteria for safe deployment of the fire brigade have an insufficient fire safety level.

INTRODUCTION

U.S. vehicle research on fire trends and patterns in 2002 (Ahrens 2004) showed that there were about 329,500 vehicle fires that year, causing 17% of the total civilian fire deaths, 10% of the total civilian fire injuries and roughly 1.4 B$ in direct property damage. It appeared that more people died as a result of vehicle fires than was the case for apartment fires. At the same time it is clear from statistics in the Netherlands (CBS 2010) that the number of motorized vehicles has grown with 11% in the last six years, increasing the demand for additional car park area. This growing demand for car park area combined with unavailable usable land in major cities leads to the construction of car parks (Zhang et al. 2007) which are mainly constructed at the basements of commercial and residential buildings (Chow 1998). However, as illustrated above, car fires and thereby car park fires involve a significant risk.

Several studies on car fires and car park fires have been performed. The heat release of car fires is studied in several researches, e.g. Cheng and John 2002, Joyeux et al. 2001, Mangs and Keski-Rahkonen 1994 and by Shipp and Spearpoint et al. 1995 who concluded that a burning car can reach its maximum heat release in as short as 10 min after ignition, with a peak heat release of at least 7.5MW (Shipp and Spearpoint 1995). In a study presented by Chow 1998 it is found that during a 5MW car fire in a 3,125m^3 car park, the average temperature will be higher than 191°C in one third of the car park. This indicates that a smoke control system should be provided to ensure an adequate fire safety level (Chow 1998). The fire spread and smoke movement in an underground car park is studied by Zhang et al. 2007 using Computational Fluid Dynamics (CFD) for a car park fire consisting of three burning cars. It is stated in the paper that detailed studies on fire spread and smoke movement are required in order to ensure a sufficient fire safety level in large underground car parks (Zhang et al. 2007). By Mangs and Keski-Rahkonen 1994 it is demonstrated that a car fire in an open car park is different from a fire in an ordinary room, because the fire is most likely to be located near the burning car or at most be spread to one or two adjoining cars. This local car fire should therefore be taken into account in the assessment of the fire safety level for the design of open car parks (Mangs and Keski-Rahkonen 1994). However, based on a semi-open car park fire at Schiphol Airport it is questioned by Noordijk and Lemaire 2005 if an assumed spread to two or three cars is valid. The number of simultaneous burning cars during the Schiphol fire was namely between 10 and 30 (Miedema et al. 2002).

Naturally ventilated (semi-open) car parks are different from mechanically ventilated (closed) car parks, since they are affected by the influences of wind. The effects of wind on a fire for high-rise buildings is presented in (Chen et al. 2009). The paper shows that wind affects the smoke temperature in a fire compartment in a complex manner. By Meroney 2010 the effect of wind on atrium fires is investigated. It is concluded that thermal and smoke columns above a fire are distorted by the influence of wind (Meroney 2010). This is supported by (Poreh and Trebukov 2000) where it is stated that the probability of significant wind effects is not small. That wind therefore is an important contributory factor in the fire safety level of buildings is also concluded in (Kandola 1986).

As shown above researches on e.g. car fires, car park fires and wind-effects on fire have been performed. Ideally the results of these studies would be implemented in the regulation for the design of car parks, the Dutch regulation will be addressed in the proceedings of this chapter.

In the Dutch building decree two sets of guidelines are addressed for designing car parks with a proper fire safety level. These guidelines can either focus on closed (mechanically ventilated) car parks, or on semi-open (naturally ventilated) car parks. In the latter case, there is a correlation between the amount of open façade area and the fire safety level. Most car parks have fire compartments with an area larger than 1000m^2, and thus don't meet the prescriptive requirement, for maximum fire compartment size, in the Dutch building decree. The decree allows for this deviation as long as it can be shown that an equal level of fire safety is obtained in terms of the decree (De Jong 2003). This is where the guidelines for naturally ventilated car parks are applicable, for which the norm NEN2443 (NEN 2000) is mostly used in practice. This guideline basically consists of three requirements. First, at least two opposing façades must have an opening. Second, these openings must have a combined area of 1/3 of the total facade. Third, the openings should not be located more than 54 meters from each other. However, if these requirements result in a sufficient fire safety level for safe deployment of the fire brigade, has never been systematically investigated.

The objective of this study was to indentify whether the requirements in the NEN2443 will ensure proper fire safety levels. In order to examine the safety level, validated Computational Fluid Dynamics (CFD) simulations were performed. By the use of these simulations, fire safety assessments were made of seven different cases, which all comply with NEN2443. Two out of the seven variants included wind effects. The performance criteria used in the assessment are based on safety criteria for safe deployment of the fire brigade as obtained from (Ingason 2008) and (NEN 2010). This is why, the temperature of the smoke layer and the temperature at head height were monitored as well as the sight length (towards a car fire) at 1.5m. The results showed that three out of seven studied variants did not meet these safety criteria.

METHODOLOGY

In order to examine the Dutch guidelines for the design of semi-open car parks, an inventory of typical semi-open car parks dimensions in the Netherlands was made (section on typical semi-open car park dimensions). These dimensions were used in validated Computational Fluid Dynamics (CFD) simulations to examine seven different variants (section on simulation variants). The variants represent worst case designs of semi-open car parks which still comply with the requirements in the guidelines. For the validation of the CFD simulations a case study was used which consisted of a 88m long corridor in which a diesel pool fire was ignited. (section on case study for CFD validation). The assessment of fire safety of the different variants was based on the temperature and sight length safety criteria for safe deployment of the fire brigade which were:

- A maximum temperature at 1.8m height of 100°C.
- A maximum temperature at 2.3m height of 270°C.
- A minimal sight length of 30m towards the car fire at 1.5m height.

Based on the results of the assessment, an analysis was made on the possibility that unsafe designs of semi-open car parks are made which comply with the guidelines.

Typical semi-open car park dimensions

The dimensions of 75 existing semi-open car parks in the Netherlands have been examined using size determination tools based on satellite maps. As shown in Fig. 1. the most commonly found length of a semi-open car park was between 55 and 65 meters. Fig. 2 shows that roughly 50% of the examined car parks had a width between 30 and 35 meters. This can be explained by the car park design commonly found in the Netherlands, which consists of four rows of parkingplaces divided by two driving lanes. The car park dimensions used in the CFD simulations were based on these results, which is why a 65 x 35m (l x w) floor plan was used. For the height a standard height of 2.4m was used.

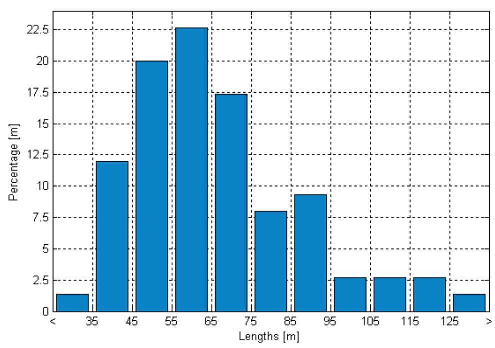


Figure 1. Distribution of lengths of 75 semi-open car parks in the Netherlands (van der Heijden 2010)

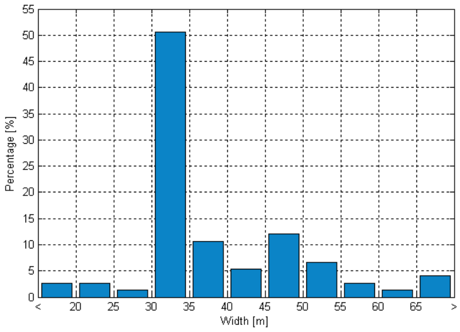


Figure 2. Distribution of width of 75 semi-open car parks in the Netherlands (van der Heijden 2010)

Validation of CFD simulation

The validation of the CFD simulations was obtained by the use of a case study as described in (Hu et al. 2005). The case study consisted of a corridor with dimensions 88 x 8 x 2.65 m (l x w x h) of which one end was closed. The sidewalls of the corridor were made of concrete and the ceiling was made of gypsum. At the closed end a diesel pool fire was ignited with a maximum heat release of 1.5 MW. The temperature underneath the ceiling was measured using a total of 49 thermocouples and 8 thermal resistors along the length of the corridor. CFD simulations were performed under the same conditions as was the case during the experiments, subsequently the results were compared (Fig. 4). Out of the comparison it was concluded that for this situation in which the smoke spread is mainly in one direction, CFD-simulations provide reliable results. The boundary conditions used for the simulation are visible in Table 1.

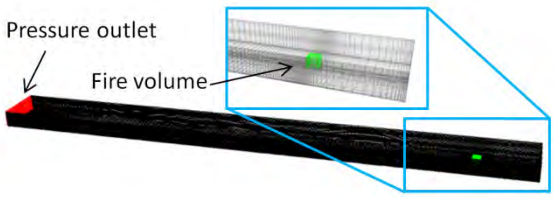


Figure 3. Visualization of mesh used in CFD. The fire is displayed in green, the pressure outlet in red. (98,154 nodes)

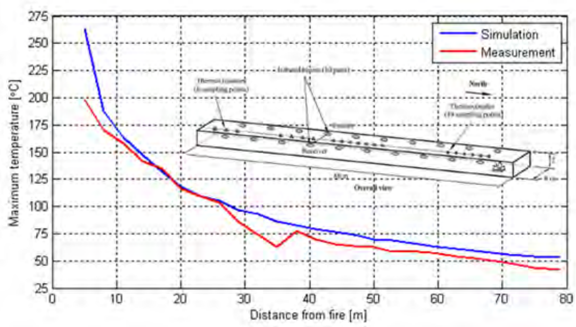


Figure 4. Maximum temperatures underneath the ceiling of the corridor over the time span of the fire. Experimental results are obtained from (Hu et al. 2005), the simulation results from this study.

Table 1. Used boundary conditions for CFD simulation of case study

Object	Used Condition
Grid	Three dimensional, Structured grid, minimal cell size 10cm with maximum grow rate of 1.05. Total 98,154 nodes.
Unsteady solver	time 350s / Δt=1s
Convergence criteria	Velocities: 10^{-4} | Energy: 10^{-5} | κ: 10^{-3} | ε: 10^{-3} | DO: 10^{-4}
Turbulence model	Standard K-ε
Wall treatment	Standard wall functions
Radiation model	Discrete Ordinates
Walls	1D heat transfer T(t=0) = 27°C, thickness 5mm, in which the thermal capacity of concrete (CEN 2001) and gypsum (Sultan 1996) are used, including temperature dependency of material properties.
Outlet	Pressure outlet, ΔP=0Pa. Temperature of entering air is 27°C.
Heat release rate of fire	Maximum 1.5 MW, for the fire curve a linear increase is assumed.
Volume fire	Dimensions determined by regression rate of liquid pool fires (Dinenno et al. 2002) which resulted in a fixed fire volume of 1m^3
Emissivity and absorption	Weighted Sum of Gray Gases Model (WSGGM)

The discussed validation case has a free flooding ceiling jet which was comparable to a ceiling jet in a semi-open car park. However where the validation case describes a case in which the flow is mainly in one direction the case of a semi-open car park will be omnidirectional. This is why a transition case was used in which the same fire was created as in the corridor case study, yet with a geometry comparable to a car park. The results of the transition case are compared to the Alpert's correlation (Alpert 1972, Dinenno et al. 2002) which are adressed for car fires in (Mangs and Keski-Rahkonen 1994) as well. The Alpert's correlation used for the temperature distribution is defined as:

$$T = 5.38 \cdot \frac{\dot{Q}^{2/3} / H^{5/3}}{(r/H)^{2/3}} + T_\infty \qquad (1)$$

Where:

T	=	Temperature [°C]
$\dot{Q}$	=	Heat release [kW]
r	=	Distance from fire [m]
H	=	Ceiling Height [m]
T_∞	=	Starting temperature [°C]

The dimensions of the car-park model for this transition case were obtained from the inventory of typical semi-open car parks, which were 35 x 65 x 2.4 m (w x l x h). The fire created inside the car park is similar to the pool-fire used in the case study and is placed in the middle of the car park, moreover the created grid has the same characteristics as was the case for the corridor case. The walls are completely open (pressure outlets) which makes the comparison with the Alpert's correlation possible. This correlation is valid for a complete omnidirectional free ceiling jet smoke layer which was created in

CFD by elimination of the walls. The applied mesh can be seen in Fig. 5. where the pressure outlets are displayed in red and the fire volume in green.

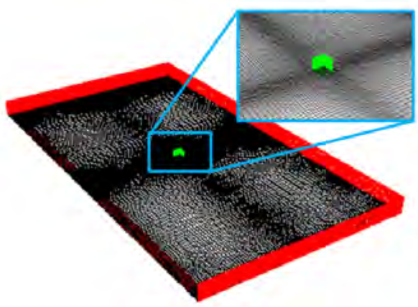


Figure 5. Mesh for transition case (652,533 nodes)

For the comparison the smoke layer temperature 0.15m underneath the ceiling was monitored in longitudinal- and perpendicular direction. The results of this comparison are displayed in Fig. 6 and Fig. 7, where is shown that there was a good agreement between the temperature prediction and the correlation. It was therefore assumed that there was an accurate CFD prediction in case of an omnidirectional free ceiling in a car park. As a result of this it was concluded that the CFD model will predict the airflow pattern inside a car park in a adequate way to allow comparison of results of different car park variants.

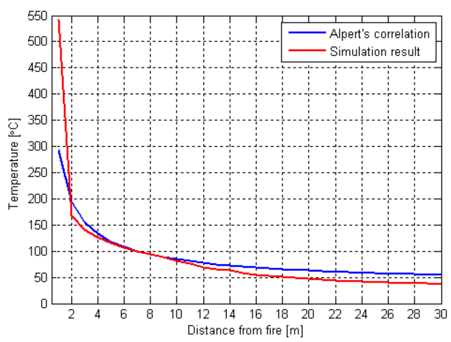


Figure 6. Temperature in perpendicular direction

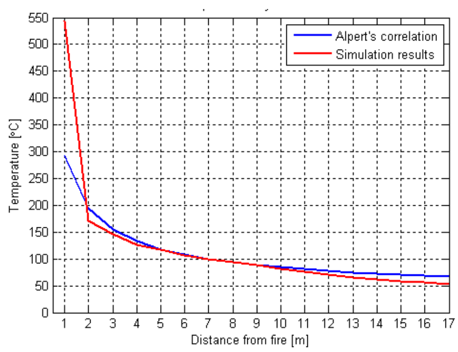


Figure 7. Temperature in longitudinal direction

Simulation variants

It is unlikely that there are more than three cars on fire during a fire in a car park. Therefore a maximum of three different heat sources are used for the implementation of these fires into the CFD-model. For the fire development it is assumed that the second car will burn 10 minutes after the ignition of the first car and the third car will start burning 5 minutes after the second car starts burning. This is in line with the fire curve used in the guideline for mechanically ventilated car parks, which is currently in development (NEN 2010). The fire curve of one burning car is based on (Oerle et al. 1999). Moreover it is assumed that it takes 5 minutes from the start of the fire before it is detected, after which the fire brigade will need 10 minutes to reach the location of the car park and 5 more minutes to prepare their equipment on location and to reach the fire. Meaning that 20 minutes after the start of the fire, the firemen can have water on the fire as long as they can reach the fire in a safe manner. Meaning that the CFD-simulations will be done till this point in time to assess the situation on its safety using the criteria as mentioned above. The fire curve of three combined car fires results in a total heat release of roughly 9MW, 20 minutes after ignition of the first car.

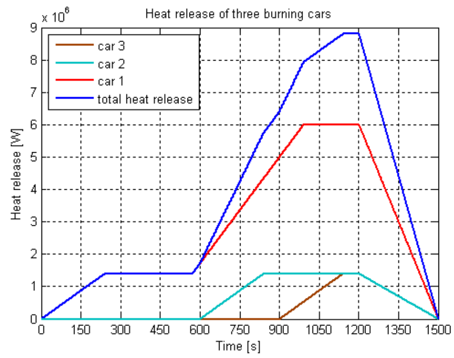


Figure 8. Fire curve with three burning cars

For the smoke a production a smoke potential of $400m^2kg^{-2}$ burned fuel is assumed with a heat of combustion of the burning car material of $25MJ^1kg^{-1}$. The cars are simulated by a solid block of 1.0 x 4.2 x 1.7m (h x l x w) above which a volume is created with the same size where the heat is released. The distance between the cars is based on the minimal width that a parking place must have on basis of the requirements in NEN2443 (NEN 2000). Therefore based on a 1.7m width of the car the distance between the cars is set to 0.65m (minimal parking place width is 2.35m).

The dimensions used for the car park variants were obtained from the inventory of general car park dimensions. In the simulations of the car park variants the cars were placed on one end of the car park, which is visible in Fig. 9.

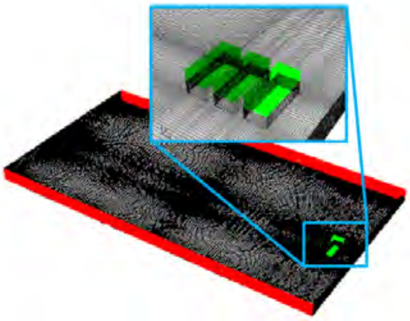
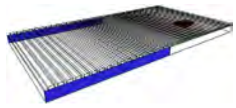


Figure 9. Example of used mesh for simulation variants (open walls on long sides; closed walls on short sides; no structural bearings; cars are displayed in green; variants 1 to 6 contain 930,147 nodes; variant 7 contains 1,941,417 nodes)

In order to assess the NEN2443 (NEN 2000) three variants will be tested which just meet the requirements as stated in the guideline. These will represent worst case situations. On the other hand to determine the effect of wind induced ventilation on a car fire inside a semi-open car park, an approach is chosen in which the open area of the facade of the car park is maximized to provide a situation in which wind can play a significant role. This is implemented with one pressure inlet and one pressure outlet. Sketches of the variants which are analyzed are displayed in Table 2. For the outside temperature 9.8°C is used, since this the average outside temperature over a year in the Netherlands (KNMI 2010) .

In order to assess the influence of wind on a car park fire, the variants three and four take wind into account. Therefore, different wind pressures where created on the open facade of the car park. This was done by determining the dynamic pressures belonging to 1.5m/s and 5m/s wind induced ventilation throughout the car park. To determine the turbulence intensities which are likely to belong to the specified wind pressures it was necessary to take the landscape description and observed height into account. For the landscape description the aerodynamic roughness length of 1.0 ("closed") out of the revised davenport roughness classification (Wieringa 1992) was used. It is considered that a higher turbulence intensity will result in a higher mixing factor of the incoming fresh air with the air inside a car park. As a result of the high smoke potential of a car fire the higher mixing will result in a larger surface area where the sight length will be minimal. The turbulence intensity is inversely proportional to the height (Stathopoulos and Storms 1986). Therefore, to create a worst-case scenario the pedestrian height is taken into account. This height combined with an aerodynamic roughness length of 1.0 ("closed") will result in a turbulent intensity of roughly 40% (van Hooff and Blocken 2010). Using this intensity, the turbulent dissipation velocity and turbulent kinetic energy at a certain wind pressure was calculated and implemented in the CFD simulations.

Table 2. Description of different simulation variants, open facade is displayed in blue and the cars on fire are coloured red

Variant 1  No wind	**Variant 2**  No wind
Variant 3  1.5m/s wind	**Variant 4**  5m/s wind
Variant 5  No wind	**Variant 6**  No wind
Variant	**Variant 7**  No wind
1	Walls over the length of the car park are open. The short sides are closed. Wind effects aren't taken into account.
2	Openings over the length of the car park are reduced so they match the 1/3 requirement of the NEN2443 exactly.
3	Walls over the length of the car park are open. The short sides are closed. On the boundary a wind pressure is set which will result in a wind velocity of approximately 1.5m/s.
4	Walls over the length of the car park are open. The short sides are closed. On the boundary a wind pressure is set which will result in a wind velocity of approximately 5 m/s.
5	Openings over the length of the car park are reduced so they match the 1/3 requirement of the NEN2443 exactly. The location of the openings is translated.
6	Walls over the length of the car park are open with exception of a 1m high balustrade. The short sides are closed. Wind effects aren't taken into account.
7	Openings over the length of the car park are reduced so they match the 1/3 requirement of the NEN2443 exactly. Structural bearings are taken into account.

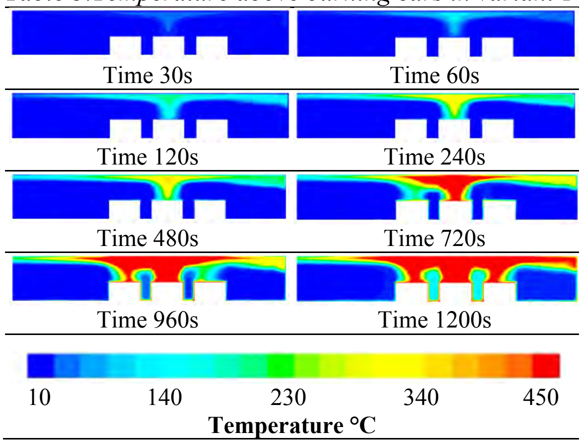
RESULTS

The CFD simulations provide results on the safety criteria (as discussed in the session on the Methodology). This is why the temperature of the smoke layer is monitored as well as the temperature on head height (1.8m), finally the local visibility at 1.5m height is tracked over the time span of the car fire. In this paragraph first an indication of the temperatures near the burning cars will be provided after which the results on the safety criteria are shown. Finally, an assessment of the safety criteria is provided.

Temperature near burning cars

Considering the heat generation near the cars, it is shown in Table 3 how the temperature above the cars increases as a result of the heat generation by the car fires. In the table close-ups of the cars are provided which are displayed with a doubling time interval up to 480 seconds, after which snap shots are displayed with an interval of 240s. The cars start burning at different times, which is a result of the fire curve for three burning cars (as discussed in section on simulation variants). Moreover, the stratification of the smoke layer is visible.

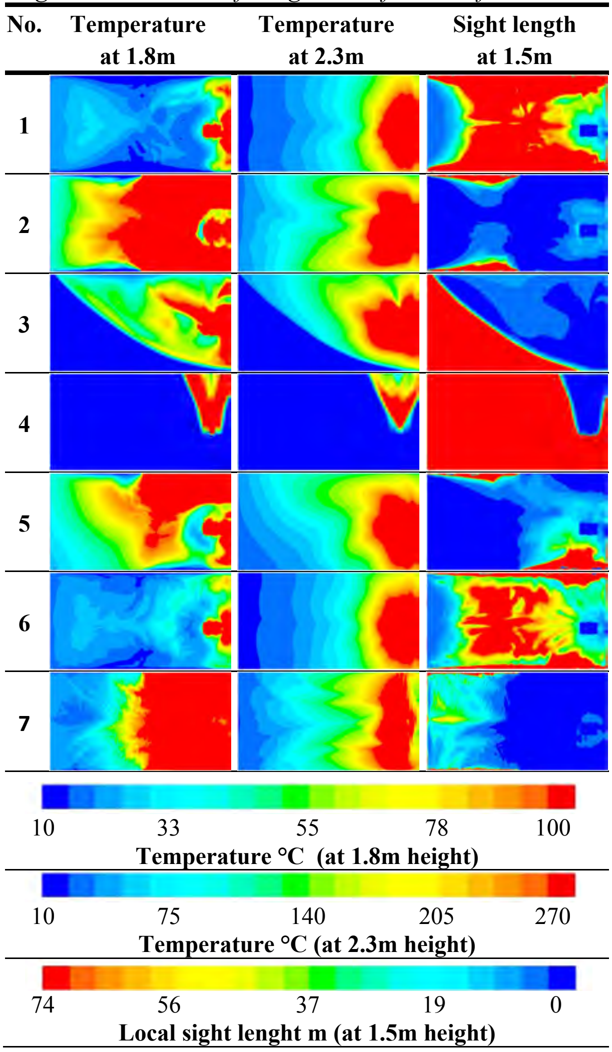
Table 3.Temperature above burning cars in variant 1



Safety criteria applied to the seven variants

In the assessment of the fire safety of the seven variants, the safety criteria for safe deployment of the fire brigade were used. In table 4 the three parameters as mentioned in the safety criteria are displayed. The results show the temperature at horizontal cross-sections at 1.8m and 2.3m height, and the local sight length at 1.5m height. These results were created 20 minutes after the ignition of the fire. The results are displayed with a legend limited to the maximum value for each safety criteria.

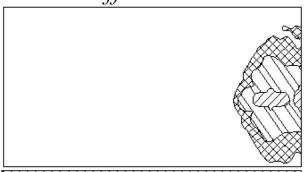
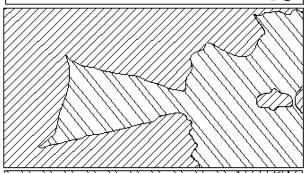
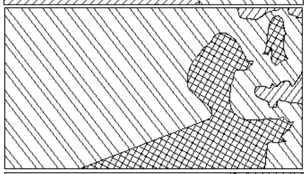
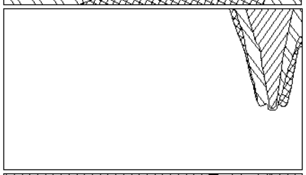
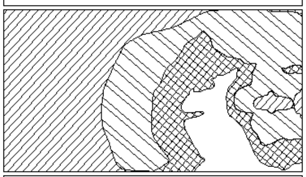
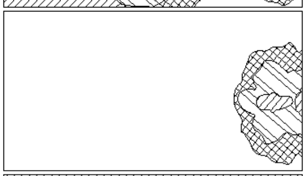
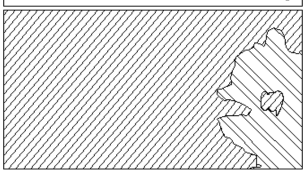
Table 4. Safety criteria for safe deployment of the fire brigade, 20 minutes after ignition of the car fire.

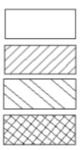


Safety criteria assessment

As an extension of the obtained results, the results of the temperature and sight length criteria are combined into one figure. This is shown in Table 5 where different hatched areas are presented. These areas represent the unsafe areas for firemen which are displayed in a 5 minute interval starting 10 minutes after ignition of the fire. The white areas will be relatively safe for firemen over the total time span of the fire. The hatched area will be unapproachable after a certain time interval because the temperature will be too high or visibility towards the fire is too low (based on the safety criteria). This analysis shows that there are significant differences between the seven variants. The approachable area for firemen ranges from an entire approachable car park to an unapproachable area that covers the complete car park after 10 minutes. For variants 1, 4 and 6 the unapproachable area is limited to the location close to the fire. Based on these results is was therefore concluded that firemen will be able to extinguish the fire in a relatively safe manner. For the variants 2, 3 and 7 there is no area available which allows for a safe approach of the fire after 20 minutes. Meaning that these variants provide an insufficient fire safety level. Moreover, for variant 2 and 7 this is the case after 15 minutes. Comparing variant 2 and 7 it is visible that in variant 7 the unapproachable area after 10 minutes is larger than for variant 2, meaning that the performance of variant 7 is worse than variant 2. Variant 5 indicates that there exists an area which is approachable for firemen, however this area is surrounded by surfaces in which the temperature will exceed the safety criteria. It is therefore questionable if it is really safe for firemen to enter this area.

Table 5. Unsafe areas for seven different variants

Variant 1 Adequate fire safety level	
Variant 2 Inadequate fire safety level	
Variant 3 Inadequate fire safety level	
Variant 4 Adequate fire safety level	
Variant 5 Questionable fire safety level	
Variant 6 Adequate fire safety level	
Variant 7 Inadequate fire safety level	



CONCLUSION

The objective of this study was to identify whether the requirements in the Dutch guideline for the design of semi-open car parks will ensure adequate fire safety levels. Based on the assessment of seven different variants which all comply with the guideline it was found that, three out of seven did not meet the safety criteria for safe deployment of the fire brigade. For one variant the obtained fire safety level was questionable. The results indicate that the guideline does not account for effects of wind, structural beams and distribution of façade openings.

It is therefore concluded that designing semi-open car parks based on the requirements as stated in the current Dutch guideline, can result in semi-open car parks with an inadequate fire safety level.

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