Multiparametric CFD to analyze the key variables in car park smoke control

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ABSTRACT

Computational Fluid Dynamics (CFD) modelling has become an industry standard for assessment of the safety in car parks. However, despite its abundant use in engineering, multiparametric studies to research the principles of car park smoke dynamics are seldom. In this paper, we present preliminary results of such an investigation, in which over 480 different car park CFD simulations were performed for various combinations of car park architecture (height), design fires and systems. We try to identify which design parameter has the most significant impact on the consequences of fire, and if shortcomings in one area (e.g. low height) can be mitigated by the increase in another (e.g. exhaust capacity). We have found that the car park height is the most critical variable in the process, with no favourable simulation outcomes found in car parks with a height of 2.40 m. With increasing height, the system performance was better, and the higher the car park, the more significant the differences were between systems. Finally, we have found that in the event of rapidly growing fire (i.e. linear growth from 0 to maximum HRR within 30 s), if the maximum HRR is 750 kW the results of the analysis are similar to the results obtained with popular design fire scenarios (TNO), while for larger rapidly growing fires, the results were unfavourable. This finding should be considered if the car park is designed with parking EV's in mind.

INTRODUCTION

Car park fire safety is an interesting topic from a global point of view. Despite car parks being similar in construction and use over the world, a variety of local requirements exists, that lead to significant differences in the 'safety' of such premises. Although the car parks do not come to mind as places of extreme fire risk, we have faced some catastrophic car park fires in last years that made to the headlines (eg. 2017 – Moscow, Liverpool, 2019 – Cork, 2020 – Stavanger). It is unlikely that the existence of smoke control alone could have changed the outcome of these events. However, smoke control may have had changed the course of them, allowing for more efficient firefighting operations. For myself, this is the prime aim of the use of smoke control system in a car park – to change smoke and fire dynamics by removing heat and smoke from the building, and changing the flow field within the building to one, that allows for safe and efficient rescue operations. Additionally, in the first phase of the fire, the smoke control system should allow for the safe evacuation of the occupants, by providing sufficiently free of smoke access to escape routes. Most importantly, the smoke control should prevent situations, in which rapid development of the smoke layer cuts off the only route of the escape of occupants, creating a potentially deadly trap. I believe these principles of smoke control in the car parks can be considered as universal, whatever numbers are placed for tenability criteria by the local law systems or whatever minimum performance characteristics are defined in the design guidelines.

This research programme aims to identify what design parameters and variables influence the outcome of a fire in a car park equipped with a smoke control system. We try to answer simple questions, such as: how much does height of a car park impact the 'safety' ? Can you place a system with higher exhaust rate to mitigate shortcomings in other features of the car park? What will happen if a fire develops quicker than the assumed design fire? Furthermore, we aim in identifying the differences of performance between various types of systems and solutions, to aid designers and lawmakers in making informed choices in the early stage of the design, when the smoke control strategy is born. In this paper, we present an overview of the project assumptions and a brief summary of the most important findings.

This project also complements our earlier multiparametric research on car park fire safety, which can be found in (Suchy and Węgrzyński 2018) and (Węgrzyński 2018). The principles of car park smoke control and smoke management, as well as the description of various smoke control systems used in car parks, were given (in Polish) in (Węgrzyński and Krajewski 2015, 2017a, 2017b). The design fire, described in this work as the 'TNO' fire originates from the research (van Oerle, Lemaire, and van de Leur 1999) and is introduced by NEN 6098 standard (NEN 6098:2010 2010). Some valuable knowledge related to the design of smoke control systems in car parks may also be found in (BSI 2003; CEN 2005).

PROJECT SUMMARY

To better understand the smoke dynamics in ventilated car parks, we have performed a multiparametric study, that includes 480 individual CFD analyses. An array of variables was chosen as input for the simulations, which will be further described in more details. All of the simulations were performed on the same numerical model of a car park, with a length of 60 m and width of 40 m. For duct based smoke control system, this car park was connected on two sides (shorter walls) with parts of neighbouring compartments, separated by a smoke curtain with a bottom at 2.00 m above the floor. The parts of the compartments next to the ventilated compartment were open, to allow for uniform, low-velocity air supply. In case of the jet-fan systems, the compartment with smoke control was connected to a neighbouring compartment from one side (as in the ducted system), and the other wall was closed, with a single large exhaust point located in the middle. The examples of car park models used in the study are shown on Fig. 1.

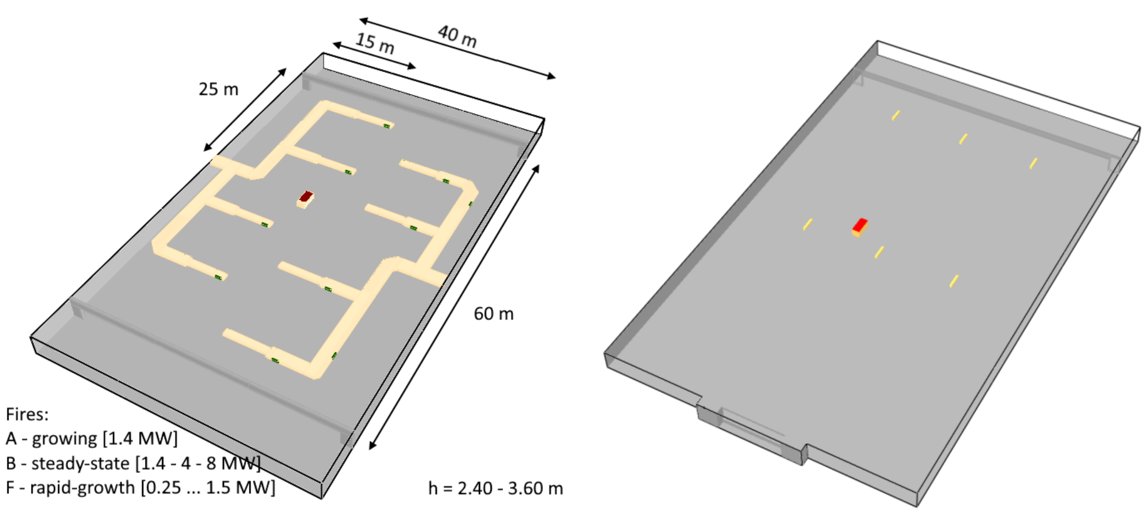

Figure 1: Car park model used in the analysis. Left picture – duct smoke control system, right picture – ductless jet fan system

Before analysis, we have identified variables that may affect the performance of the smoke control system in the car park. The key variables that are investigated in this multiparametric study are given in bold.

Architectural variables

Although car parks are similar in their general image, the architectural details such as the location of inlet/outlet points, location of walls, ramps, columns, stairwells etc., make each car park unique. These architectural details have a significant impact on the flow field within the car park, leading to varied outcomes of analyses of similar fires under equivalent safety systems. Due to the complexity of parametrization of architecture for a multiparametric study, and the research approach employed (analysis of all of the combinations of input parameters) an effort to include this in the current study would lead to a disproportionate number of scenarios to be investigated. Such analysis will be in focus of future work, where the impact of particular architectural features will be studied with probabilistic approaches, such as one presented in (Van Weyenberge et al. 2017, 2018).

Following architecture related variables were identified:

- **car park height;**
- car park dimensions, area;
- the shape of the car park;
- are vehicles in the car park modelled? (previously investigated in (Suchy and Węgrzyński 2018));
- location of inles, outlets, ramps and obstructions.

Smoke control system variables

Smoke control design is a unique solution for every car park. Thus a variety of smoke control systems mirrors the variety of architecture. It is not possible to fully parametrize the smoke control system into an array of variables, as the final product – system design, will always be an outcome of the creative, engineering process. Based on our practical engineering experience we have made an attempt to list the most critical variables, that may be used to distinguish systems from each other, and are a product of the MEP engineers choice, rather than a direct outcome of the architectural design. These variables are different for 'duct based' and 'ductless jet-fan' systems.

For 'duct based' systems, the identified variables are:

- **total exhaust capacity**;
- number of exhaust points (exhaust capacity of each point, maximum exhaust velocity);
- non-uniform performance of individual exhaust points;
- location of exhaust points;
- size of ducts;
- air-supply strategy.

For 'ductless jet-fan' systems, the identified variables are:

- **use of exhaust point or venting through an open façade;**
- **total exhaust capacity**;
- number of jet-fans and their location (previously investigated in (Węgrzyński 2018));
- the thrust of jet-fans (previously investigated in (Węgrzyński 2018));
- air-supply strategy.

Design fires

When investigating the outcomes of a fire in a car park, the fire itself is arguably the biggest unknown. Thankfully, as CFD becomes a more routine approach to car park smoke control engineering, there are some emerging design fires, that can be considered as an industry. One of such fires is so-called 'TNO' fire, originating from (van Oerle, Lemaire, and van de Leur 1999), introduced by (NEN 6098:2010 2010) and the 'go-to' design fire in (Węgrzyński and Krajewski 2015). This design fire was also used as the reference design fire for this research project.

By using a prescribed design fire we have made a conscious decision to not try to identify the impact smoke control has on fire dynamics. For such an analysis one would be better using a probabilistic approach such as (Tohir, Spearpoint, and Fleischmann 2018; Zahirasri et al. 2020). However, similar to the problems created by the variety of the architecture, such an approach would introduce overwhelming complexity to this study, making a direct comparison between systems more difficult.

As the design fire scenario, Fig. 2, is transient (i.e. developing in time), some modifications were introduced for this research project. The different parts of our analysis were focused on user and firefighter safety separately. In consequence, the design fires for these parts were chosen accordingly. For the occupant safety (series A), the first 450 s of the 'TNO' fire were used as a benchmark, and compared with an 'αt^2' *fast* fire and a quickly developing fire, with the same peak HRR value. The time at which the result assessment was performed (RSET) was estimated between 180 s and 300 s. For the firefighter safety (series B), transient fire development was replaced with long steady-state fires, with the assessment performed after 450 s.

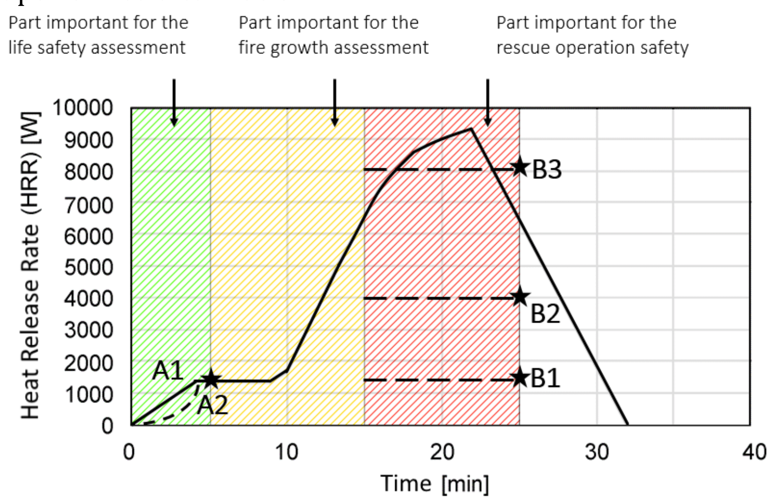

Figure 2: Design fires (A1, A2, B1, B2, B3) used in the analysis overlayed on the 'TNO' design fire curve as given in (Węgrzyński and Krajewski 2015)

To account for new challenges in car park fire safety, a range of 'rapidly growing' design fire scenarios was introduced. The aim of these scenarios is to represent almost instantaneous fire development, observed in some Li-Ion batteries and EV vehicle fires. Despite multiple ongoing research projects (Sun et al. 2020) we do not have a 'go-to' design fire for EV, and we are unable to determine what is the heat flux of such a fire in its early stage. Despite this shortcoming, we were interested in a comparison between outcomes of rapidly growing fires and common design fires. Six different fire growth scenarios (series F) were prepared. The peak HRR in these fires was chosen arbitraly, and varied between 250 kW to 1600 kW (Fig. 3). These fires **are not a representation** of an EV fire, **and should not be used for design.** The only purpose of their introduction is to investigate the differences in system performance between traditional design fire scenarios and rapidly growing fires. It is also worth to mention that the current research did not include jet-fire like the behavior of EV fires, nor did differentiate ICE and EV fire toxicity or smoke production. The only comparison was made for the development and peak value of the HRR.

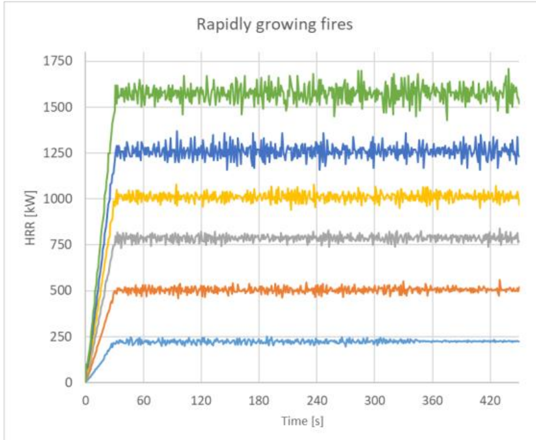

Figure 3: Rapidly growing design fires (F1 – F6) used in the analysis

Other parameters describing combustion were not changed between simulations to decrease the complexity of the study. The chosen value of HRRPUA was 500 kW/m^2, and the soot yield was given a conservative value of 0.1 kg/kg (Węgrzyński and Vigne 2017).

Summary of assumptions

The architectural, smoke control and fire-related variables and other assumptions for the project are summarized in Table 1. The total number of simulations that cover all of the variables was 480.

Table 1: Summary of the variables in the simulations

Variable	Values
Car park height	2.40 m, 2.70 m, 3.00 m, 3.30 m, 3.60 m
Smoke control type	- no ventilation - mechanical smoke and heat exhaust ventilation (with ducts) - mechanical smoke and heat exhaust ventilation (ductless, with jet fans)
Duct system exhaust rate	17 m^3/s, 34 m^3/s, 50 m^3/s
Jet-fan system exhaust rate	44 m^3/s, 66 m^3/s, 88 m^3/s and a system with an open wall (smoke pushed through the façade, no prescribed exhaust rate)
Fires (series A)	Fires to investigate outcomes in the early phase of fire (evacuation phase): - A1: 'TNO' design fire with 1.40 MW peak; - A2: αt^2 'fast' fire with 1.40 MW peak; - A3: linear growth to 1.40 MW in 30 s;
Fires (series B)	Fires to investigation of the environmental conditions on the onset of rescue operations / extinguishing: - B1: 1.40 MW (steady state); - B2: 4.00 MW (steady state); - B3: 8.00 MW (steady state).
Fires (series F)	Fires to investigate the development of smoke layer and conditions in evacuation phase in a rapid growth scenarios: - F1: linear growth to 0.25 MW in 30 s; - F2: linear growth to 0.50 MW in 30 s; - F3: linear growth to 0.75 MW in 30 s; - F4: linear growth to 1.00 MW in 30 s; - F5: linear growth to 1.25 MW in 30 s; - F6: linear growth to 1.60 MW in 30 s;

MAIN FINDINGS

Car park height and duct systems

The preliminary result analysis has shown, that the height of the car park may be the single, most important variable that determines the 'safety' of a car park in the event of a fire. The reason for this outcome is related to the method of assessment. The 'safety' is commonly assessed as a measure of tenability criteria at a certain height (i.e. in our case 1.80 m above floor) in a function of time (ie. at the end of the Required Safe Evacuation Time, RSET). In such a case, increasing the height of the car park and moving the smoke layer upwards above this plane of measurement must improve the outcome. However, if one does analyze the analytical models presented in (BSI 2003; CEN 2005; Węgrzyński and Krajewski 2015) such effect of the increase of height is not so evident. In the analytical models based on axisymmetric plume theory (Vigne et al. 2019) the rise of compartment height must be followed by an increase of the smoke extraction rate. If the extraction rate is not increased, then the height of the smoke layer interface should remain at the same height (i.e. it is assumed that smoke layer increases depth, rather than move upwards). This means that the same system installed in two car parks of different height would have the same efficiency, which is opposite of what was found in this study, Fig. 4. For five different heights of the car park equipped with same 17 m^3/s duct systems, the results (shown a space-time plot through the fire in the y-axis) differ significantly. From a car park filled with smoke in the first 3 minutes for 2.40 m, to car park virtually free of smoke (at the 1.80 plane) for 3.30 m and higher. A comparison between the outcome of simulations for all of the investigated systems, with a changing height is shown at Fig. 5. The figure shows the mean value of visibility in smoke at the 1.80 m plane in the 450th second of analysis (for steady-state fires B1 and B3).

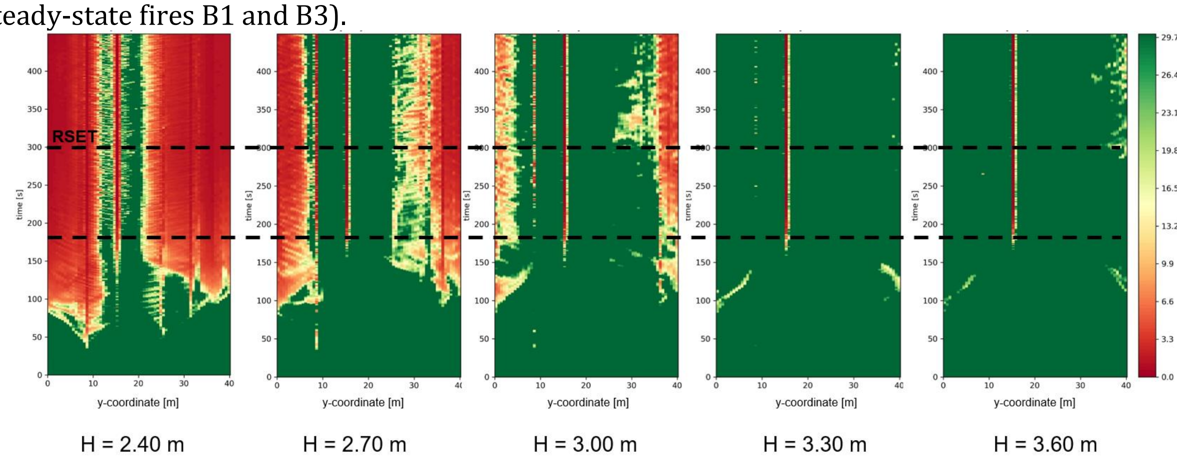

Figure 4. Space-time (for x = 25 m, z = 1.80 m, along axis y) plots for the TNO fire growth, and duct system with capacity of 17 m^3/s, for different heights of the car-park. The dashed lines mark the range of RSET time for car-parks of this size.

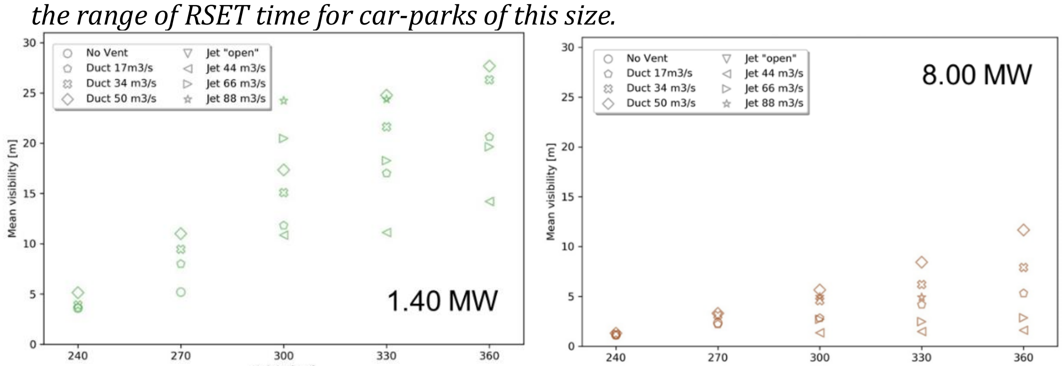

Figure 5. Mean visibility in smoke at the height of 1.80 m after 450 seconds of analysis for fires B1 (1.40 MW) and B3 (8.00 MW) for all tested systems and heights

Figure 6 presents results of qualitative analysis – investigation of the % of cells at the height of 1.80 m in which the visibility tenability criterion (visibility less than 10 m) was passed. What is particularly interesting from this analysis, is that there is no significant difference in results between simulations of different systems for heights of 2.40 m and 2.70 m. This means that a higher exhaust rate does not lead to a better outcome if the height of the car park is insufficient. Furthermore, an increase of the car park height from 2.70 m to 3.00 m caused a decrease in the number of smoked cells similar to the effects of a three-time increase of system capacity (from 17 m^3/s to 50 m^3/s). Finally, if one compares low- and high-capacity systems, a difference in the transient development of smoke layer is observed. This difference in smoke filling time may be important if life safety aspect of the system performance is investigated (Vigne et al. 2019).

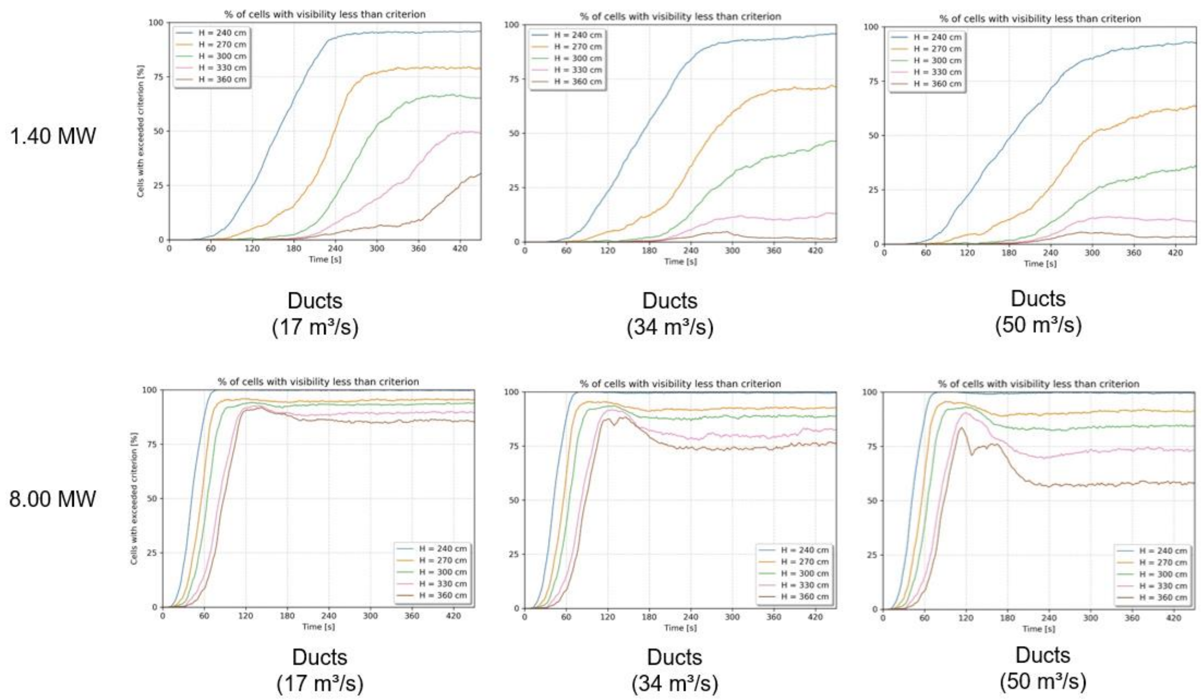

Figure 6. Comparison of the % of cells in which 10m visibility criterion was met in the function of the time, at the height of 1.80 m, for different duct smoke control systems and different car park heights. Fires B1 and B3.

Car park height and jet fan systems

Jet-fan systems are usually triggered after a delay for evacuation (in our case 270 s into the simulation) to not cause premature smoke mixing and loss of stratification of the smoke. For jet-fan systems it is expected, that increasing the height of the car park will improve the outcomes in the evacuation phase. Thus, until the 270 s mark the 'safety' is provided by the car-park architecture, and afterwards by the smoke control system. As observed in Fig. 7, in the evacuation phase large quantities of smoke were observed at 1.80 m height (the plane of assessment) for 2.40 m and 2.70 m car parks. This means that depending on the RSET value, these car parks may be not tenable. However, for higher car parks, the smoke reservoir is large enough to contain the smoke produced in the fire, and until the start of the jet-fans, the conditions in the car park are acceptable. What was unexpected is that for higher car parks, the system performance after the jet-fans start is improved. We have expected a slight drop in system efficiency, as with the increased car park height the mean longitudinal airflow velocity in the car park decreases. However, other effects (eg. lower temperature of the smoke, lower ceiling jet velocity) were more significant, and in the end the system performance improved with the increase of height.

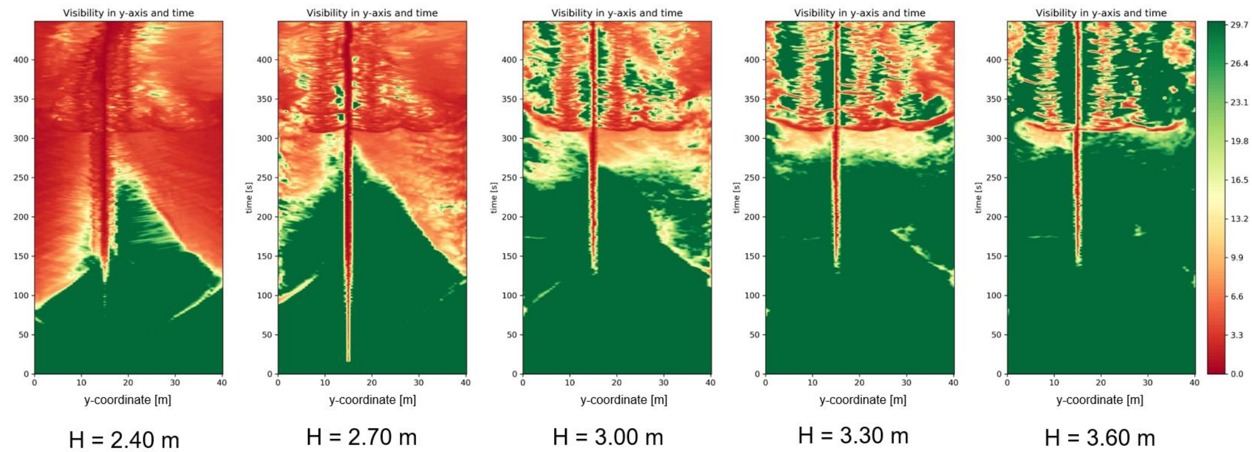

Figure 7. Space-time (for x = 25 m, z = 1.80 m, along axis y) plots for the TNO fire growth, and ductless jet-fan system with a capacity of 44 m^3/s, for different heights of the car-park

Comparing the number of cells for which the visibility criterion (less than 10m) was exceeded at a height of 1.80 m, for a 3.00 m car park, it is noticeable how the increased system capacity improves the outcomes, Fig. 8. For 44 m^3/s system, approx. 70% of the car park was filled with smoke, while for 66 m^3/s and 88 m^3/s this was 32% and 19% respectively. For a large fire (B3), none of the investigated systems has achieved state, in which half of the car-park (windward side) would be free of smoke, although individual assessment of the results of the simulations has revealed, that in some scenarios a smoke-free path was present between the entrance to the car park and the fire. In near future an automated qualititve assessment tool will be used to perform such analysis for all of the simulations, which should improve the qualitative conclusions related to the jet-fan system performance.

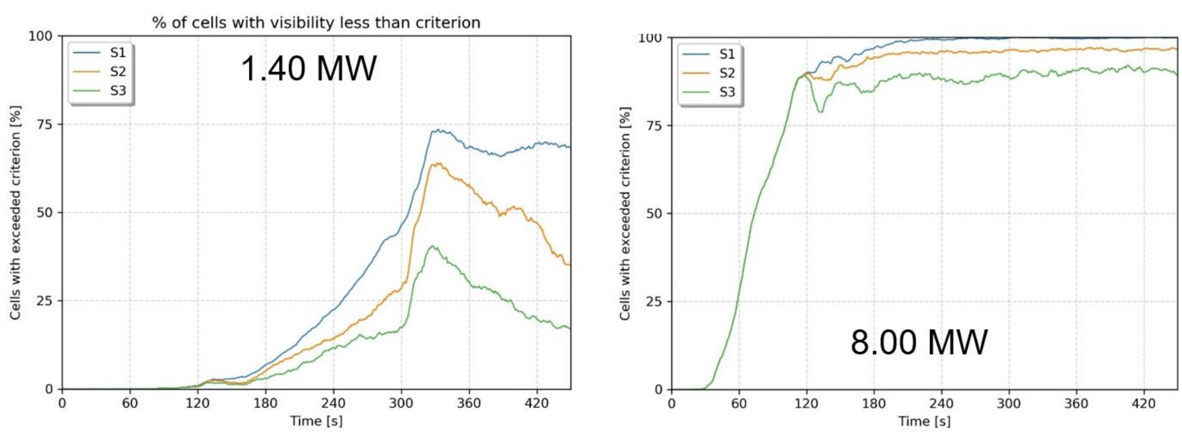

Figure 8. Comparison of the % of cells in which 10m visibility criterion was met in the function of the time, at the height of 1.80 m, for different jet-fan smoke control systems and fires B1 and B3.

<u>The outcome of rapidly developing fire scenarios</u>

In case of rapidly developing fire scenarios and no-ventilation (empty) car-park it was observed, that fires with size 500 kW and larger lead to quickly declining smoke layer, and eventually to untenable conditions within expected RSET, Fig. 9. This is obviously connected with the height of the car park, with lower car parks having worse outcomes, Fig. 10. Higher car parks take longer to fill with smoke, and at the end of the simulation have the lowest number of cells, in which the visibility criterion was exceeded.

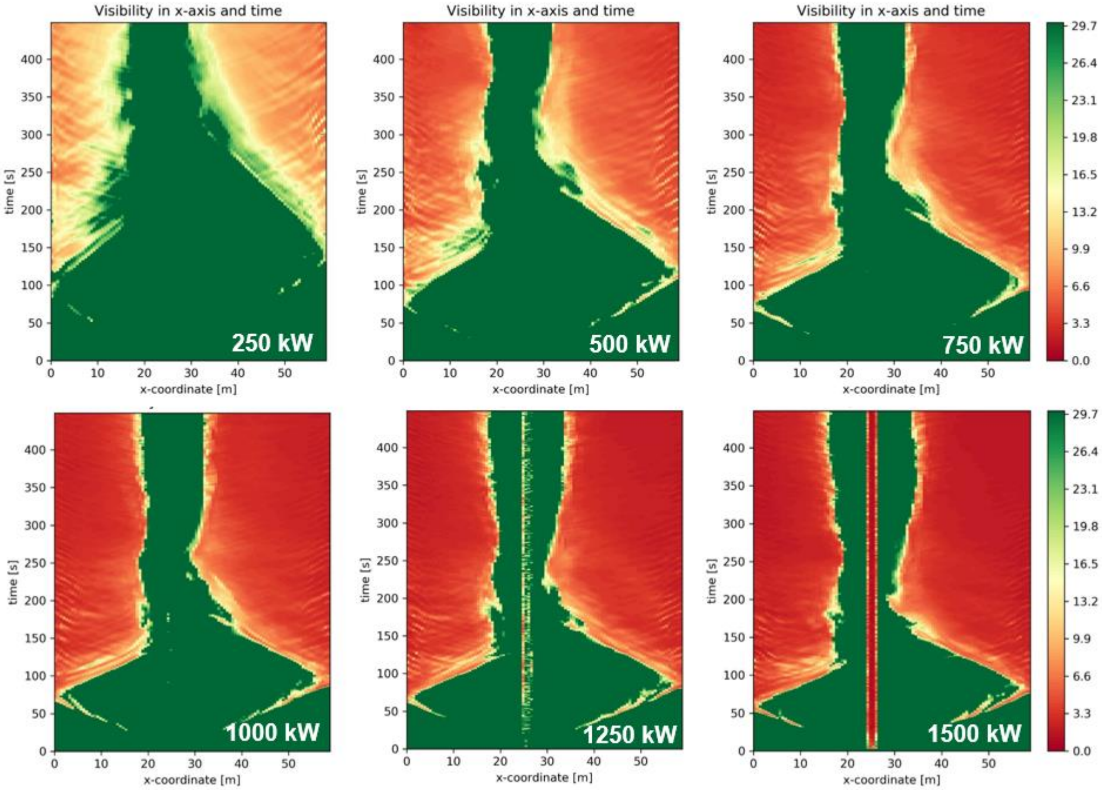

Figure 9. Space-time (for x = 25 m, z = 1.80 m, along axis y) plots for the F1-F6 fires, 2.70 m height of the car park and no-ventilation case

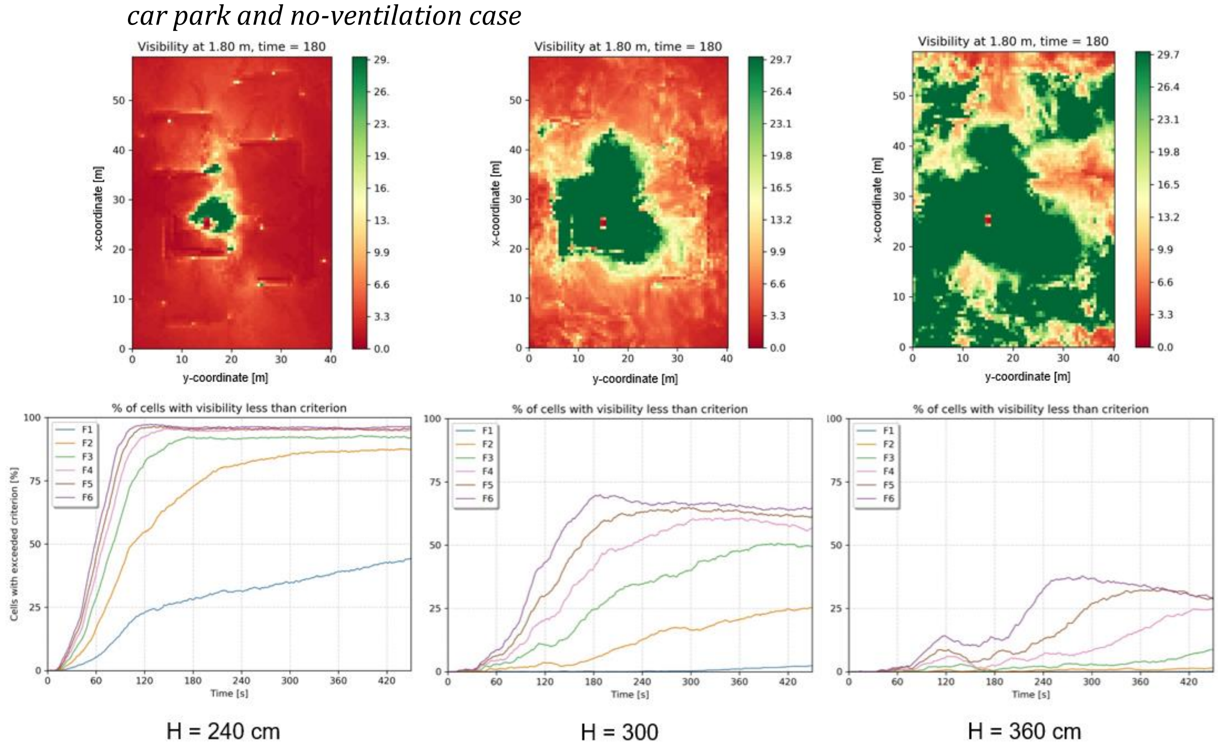

Figure 10. Upper part presents the visibility at the height of 1.80 m at the 180th s of the simulation for fire F4. Lower part presents comparison of the % of cells in which 10m visibility criterion was met in function of the time, at a height of 1.80 m, for no-ventilation case and fires F1 – F6

A comparison of the results for rapidly developing fires in all tested car-parks and for all ventilation systems is given in Fig. 11. The mean visibility in the car park at the 180th s of the analysis decreases with the increase of the size of the fire, and with the decrease of the car park height. The larger the size of the fire, the larger the differences between different types of systems. At the height of 3.30 m and higher the differences in systems are small, because the smoke layer is maintained above the assessment plane (thus the analysis is not sensitive for any further improvements). This will also be investigated with an automated qualitative assessment tool, to quantify the differences between systems, to which the current approach is insensitive.

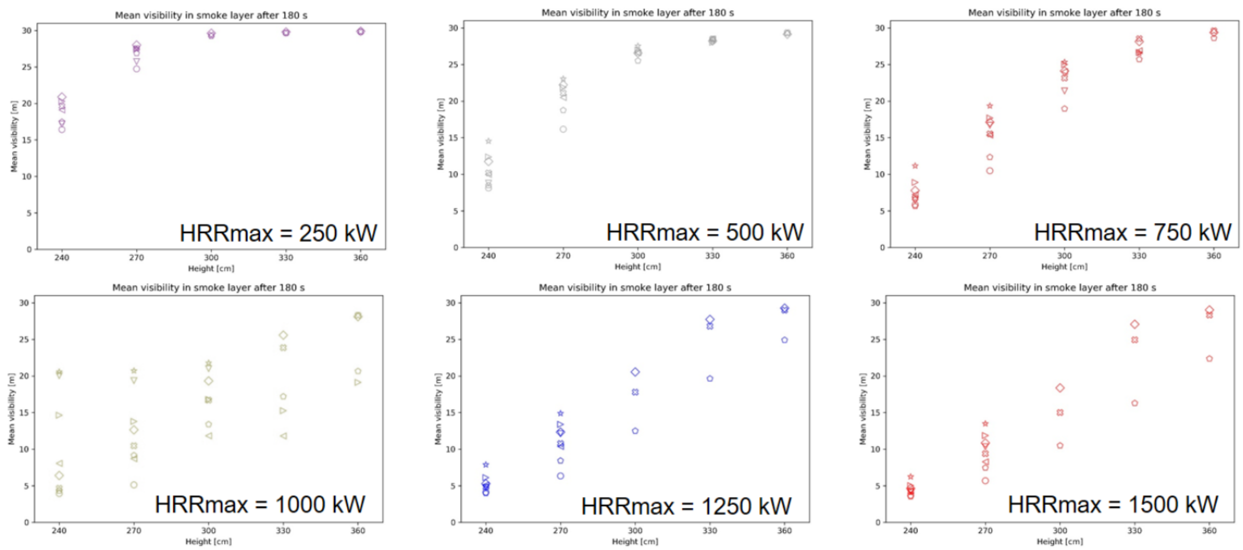

Figure 11. Mean visibility in smoke at the height of 1.80 m after 180 seconds of analysis for fires B1 (1.40 MW) and B3 (8.00 MW) for all tested systems and heights

Finally, a comparison was made between the outcomes of rapidly growing fire scenarios and the outcomes of a standard 'TNO' design fire, Fig. 12. Rapidly growing fires were generally more onerous than the 'TNO' scenario. In preliminary analysis results for non-ventilated car-parks, the F3 (750 kW) scenario were found closest to the outcomes of the 'TNO' design fire cases. This means that if one considers a rapidly growing fire with peak HRR larger than 750 kW, as a rule of thumb, worse outcome may be expected than for a standard design fire (TNO). This is a preliminary result and must be confirmed through a more detailed statistical analysis of the simulation results for different car park heights and different systems.

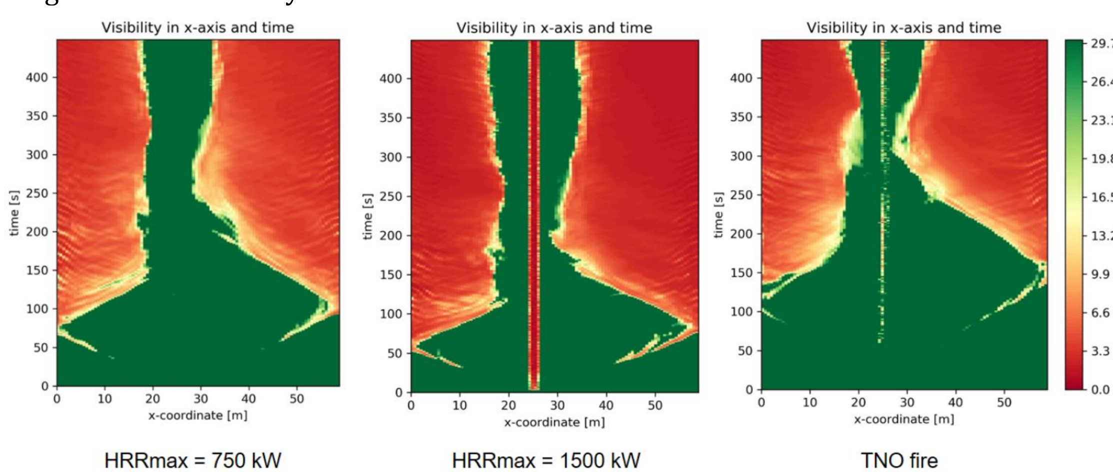

Figure 12. Space-time (for x = 25 m, z = 1.80 m, along axis y) plots for the F3, F6 and TNO fire growth, no-ventilation case, 2.70 m high car park

CONCLUSIONS

The results of this multiparametric study are interesting, and in some aspects contradictory to common design practice. It was found that the height of the car park has the most profound impact on the car park safety, and furthermore – a certain height is required to benefit from the smoke control systems. The higher the car park, the more visible were the differences between different tyes and parameters of the investigated smoke control systems. In a comparison of simulation results between fast-growing and traditional design fires, it was found, that rapidly developing fires (if their size is 750 kW or larger) pose a more serious threat to the car-park occupants, than the current state-of-the-art design fires. This means that an outcome of a rapidly growing fire may be worse than expected, and the performance of car park safety systems may be unsatisfactory in such a scenario. There is a need to research this aspect further and define new design fire scenarios that better represent the hazards imposed by modern vehicles.

REFERENCES

BSI. 2003. "BS 7974 Part 4: Components for Smoke and Heat Control Systems. Functional Recommendations and Calculation Methods for Smoke and Heat Exhaust Ventilation Systems, Employing Steady-State Design Fires. Code of Practice."

CEN. 2005. *CEN/TR 12101-5:2005 Smoke and Heat Control Systems. Guidelines on Functional Recommendations and Calculation Methods for Smoke and Heat Exhaust Ventilation Systems*.

NEN 6098:2010. 2010. "Ontw. Nl Rookbeheersingssystemen Voor Mechanisch Geventileerde Parkeergarages."

Oerle, N. van, A. Lemaire, and P. van de Leur. 1999. "Effectiveness of Forced Ventilation in Closed Car Parks." In *TNO Report No. 1999-CVB-RR1442*.

Suchy, Przemysław, and Wojciech Węgrzyński. 2018. "The Influence of the Arrangement of Passenger Cars in Indoor Car Parks on CFD Calculations." *BEZPIECZEŃSTWO I TECHNIKA POŻARNICZA* 52 (4): 118–39. https://doi.org/10.12845/bitp.52.4.2018.8.

Sun, Peiyi, Roeland Bisschop, Huichang Niu, and Xinyan Huang. 2020. *A Review of Battery Fires in Electric Vehicles*. *Fire Technology*. Springer US. https://doi.org/10.1007/s10694-019-00944-3.

Tohir, Mohd Zahirasri Mohd, Michael Spearpoint, and Charles Fleischmann. 2018. "Prediction of Time to Ignition in Multiple Vehicle Fire Spread Experiments." *Fire and Materials* 42 (1): 69–80. https://doi.org/10.1002/fam.2458.

Vigne, Gabriele, Cándido Gutierrez-Montes, Alexis Cantizano, Wojciech Węgrzyński, and Guillermo Rein. 2019. "Review and Validation of the Current Smoke Plume Entrainment Models for Large-Volume Buildings." *Fire Technology* 55 (3): 789–816. https://doi.org/10.1007/s10694-018-0801-4.

Węgrzyński, Wojciech. 2018. "JET-FAN SYSTEMS IN CAR PARKS DESIGN METHODS: AN OVERVIEW AND ASSESSMENT OF PERFORMANCE." *SFPE Europe*, no. 9.

Węgrzyński, Wojciech, and Grzegorz Krajewski. 2015. *Systemy Wentylacji Pożarowej Garaży. Projektowanie, Ocena, Odbiór*. *Instrukcja ITB Nr 493/2015*. 493/2015. Instytut Techniki Budowlanej.

———. 2017a. "Wentylacja Pożarowa Garaży – Dobór Systemu i Projektowanie Wg ITB 493/2015." *Rynek Instalacyjny* 3: 31–36.

———. 2017b. "Wentylacja Pożarowa Garaży – Symulacje Numeryczne (CFD) Wg ITB 493/2015." *Rynek Instalacyjny*, no. 5.

Węgrzyński, Wojciech, and Gabriele Vigne. 2017. "Experimental and Numerical Evaluation of the Influence of the Soot Yield on the Visibility in Smoke in CFD Analysis." *Fire Safety Journal* 91 (SI): 389–98. https://doi.org/10.1016/j.firesaf.2017.03.053.

Weyenberge, Bart Van, Pieterjan Criel, Xavier Deckers, Robby Caspeele, and Bart Merci. 2017. “Response Surface Modelling in Quantitative Risk Analysis for Life Safety in Case of Fire.” *Fire Safety Journal* 91 (July): 1007–15. https://doi.org/10.1016/j.firesaf.2017.03.020.

Weyenberge, Bart Van, Xavier Deckers, Robby Caspeele, and Bart Merci. 2018. “Development of an Integrated Risk Assessment Method to Quantify the Life Safety Risk in Buildings in Case of Fire.” *Fire Technology*, August. https://doi.org/10.1007/s10694-018-0763-6.

Zahirasri, Mohd, Mohd Tohir, Michael Spearpoint, and Charles Fleischmann. 2020. “Probabilistic Design Fires for Passenger Vehicle Scenarios.” *Fire Safety Journal*, 103039. https://doi.org/10.1016/j.firesaf.2020.103039.