INFLUENCE OF PARKED CARS ON SMOKE PROPAGATION DURING CAR PARK FIRE

Weisenpacher, P. [(a)], Halada, L. [(b)], Glasa, J. [(c)], Astalos, J. [(d)]

[(a)] Institute of Informatics, Slovak Academy of Sciences, Dubravska cesta 9, 84507 Bratislava, Slovakia
[(b)] Institute of Informatics, Slovak Academy of Sciences, Dubravska cesta 9, 84507 Bratislava, Slovakia
[(c)] Institute of Informatics, Slovak Academy of Sciences, Dubravska cesta 9, 84507 Bratislava, Slovakia
[(d)] Institute of Informatics, Slovak Academy of Sciences, Dubravska cesta 9, 84507 Bratislava, Slovakia

[(a)] Peter.Weisenpacher@savba.sk, [(b)] Ladislav.Halada@savba.sk, [(c)]Jan.Glasa@savba.sk, [(d)] Jan.Astalos@savba.sk

ABSTRACT

In this paper, the influence of number and shape of cars parked in underground car park on smoke propagation during the car park fire is examined. A series of high performance parallel computer simulations of fire scenarios is performed on cluster of computers using the NIST FDS system, version 5.5.3. Special emphasis is on evaluation of tenability conditions in the car park under different circumstances. Variable circumstances include different number and size of parked cars, ventilation configuration as well as fire source. Visibility at head level determined by simulation shows a significant impact of the cars number and shape on smoke propagation. The effect is more significant if cars are high enough to disrupt hot layer like vans and less significant for passenger cars. Air flow patterns differences of selected fire scenarios are analysed as well.

Keywords: fire dynamics, fire simulation, smoke propagation

1. INTRODUCTION

Computational Fluid Dynamics (CFD) is a powerful tool, which has been recently used for both theoretical research of fire and smoke movement and also in practice for design of fire safety measures. Smoke movement simulation in large, complex compartments with non-trivial geometry like underground car parks is especially important CFD application, in particular if there is a significant threat of fire with probable severe impact on people and property. Because of non-linear nature of fire, proper design of mechanical ventilation in car parks requires careful evaluation of its possible unintended effects. Temperature under ceiling, smoke back-layering and non-trivial flow patterns in case of car park fire is studied in (Deckers, Haga, Sette, and Merci 2013) by full-scale experiments and by CFD simulations in (Deckers, Haga, Tilley, and Merci 2013). Several fire parameters were varied in simulations including presence or non-presence of beam. The impact of parked cars on smoke propagation in the case of tunnel fire is dealt in (Glasa, and Valasek 2014). However, due to complexity in flow and smoke patterns there is a difference between car parks and tunnels.

In this paper, the influence of parked cars on ventilation efficiency is evaluated and quantified. In order to increase the reliability of the simulation, relatively fine resolution of 6 cm is used, which requires significant computing resources. Therefore, parallel computation on cluster is used. The modelling of fire source is very realistic and based on experimental observation. Two passenger cars with very detailed representation are used in simulation as a fire source. Their representation includes interior equipment geometry and material properties, whose reliability is based on full scale experiments in open air including a fire in automobile interior and its spread onto a near standing vehicle (Polednak 2010; Svetlik 2010). During this experiment, temperatures inside and outside passenger compartment were measured to be used for the calibration of computer simulation. Subsequent simulations confirm credibility of this model (Weisenpacher, Glasa, and Halada 2012; Weisenpacher, Halada, Glasa, and Slizik, 2013) and the values of heat release rate (HRR) obtained by simulation are also in agreement with car fire experiments (Okamoto, Watenabe, Hagimoto, Chigira, Masano, Miura, Ochiai, Satoh, Tamura, Hayano, Maeda, and Suzuki 2009). The model enables to take into account mutual interaction between fire and car park ventilation as well as specific geometry of particular scenario, given by number and size of parked cars. Similar approach to car modelling for simulation purposes is used in (Partanen, and Heinisuo 2013).

2. FDS OVERVIEW

The Fire Dynamics Simulator (FDS) is CFD simulation system of fire-driven fluid flow, developed at National Institute of Standards and Technology (NIST), USA (McGratten, Baum, Rehm, Mell, McDermott, Hostikka, and Floyd 2010). FDS solves numerically a form of the Navier-Stokes equations appropriate for the low-speed, thermally-driven flow with an emphasis on the smoke and heat transport from fires. It includes also modules for physical and chemical processes like thermal radiation, pyrolysis, combustion of the pyrolysis products, conductive heat transfer and fire suppression by sprinklers.

The basic set of equations includes conservation equations for conservation of mass, species, momentum and energy and equation of the state. These equations must be simplified in order to filter out sound waves, which are much faster than the typical flow speed. The final numerical scheme is an explicit predictor-corrector finite difference scheme, which is second order accurate in space and time. The flow variables are updated in time using an explicit second-order Runge-Kutta scheme. This part of the algorithm is highly suitable for parallel computation. Momentum equation is simplified and transformed into Poisson equation, which is solved in every time step.

All input data for a simulation are required in the form of a text file in the prescribed format, which describes the coordinate system, geometry of the domain and its location in the given coordinates, mesh resolution, obstacles, boundary conditions, material properties and different simulations parameters. Important limitations of the program is that the domain and all obstructions representing real objects, which can burn, heat up, conduct heat etc., should be rectangular, conforming with the underlying grid. Boundary conditions are prescribed on the walls and vents.

The strategy of parallel computation consists in decomposition of the computational domain into multiple meshes and computation of the flow in each mesh separately. Each computation is usually performed as an individual MPI process assigned to one CPU core. Values at mesh boundaries must be averaged in every time step in order to maintain solution stability. Therefore, the way of domain decomposition influence the precision of simulation results.

3. CAR PARK FIRE SIMULATION

Model of an underground single storey car park with dimensions 23.04 x 38.88 x 3.0 m (the total area of 895.8 m^2) with parking places for 24 cars is used in simulation. Its geometry includes two concrete beams and eight columns, tube system under the ceiling, car park entrance, lift shaft and other alcoves. Two different metal ductwork systems for mechanical extraction of smoke (D1 and D2) or none ventilation are considered. The first scenario (D1, see Fig. 1) uses 9 inlet fans located in the proximity of the elevator and corridor entrance and 9 outlet fans, more or less regularly distributed within the ductwork system. Both inlet and outlet fans are represented by 96 x 48 cm surfaces with given normal air velocity. The second scenario (D2, see Fig. 2) uses 9 inlet fans (three of them with different location than in D1) and 12 outlet fans. Fans velocities are piecewise-linear functions of time given by Tab. 1.

Two burning cars are located in the middle part of the car park. Two types of cars are considered: passenger cars with maximal dimensions 421 x 180 x 150 cm and vans with maximal dimensions 534 x 192 x 210 cm. Seven scenarios are evaluated: scenario with empty car park (only 2 burning cars are included), scenarios with half-full car park (10 additional cars are included, of which 0, 4 and 8 are vans) and scenarios with full car park (22 additional cars are included, of which 0, 4 and 8 are vans). As a main quantity influencing tenability conditions, visibility in head level is evaluated. Visibility averaged over the whole car park area is a good, though simplified aggregate measure of untenability evolution. Taking into account a simple shape of this quantity curves, their time averaged value is even simpler scalar quantity illustrating the rate of untenability rise in the car park.

Table 1: Inlet and outlet ventilation velocities [ms^{-1}]

Conf.	$v_{180s,}$ inlet	$v_{180s,}$ outlet	$v_{360s,}$ inlet	$v_{360s,}$ outlet	$v_{600s,}$ inlet	$v_{600s,}$ outlet
D1	1.5	2.0	1.5	3.0	2.0	4.0
D2	1.5	2.0	1.5	2.0	2.5	3.0

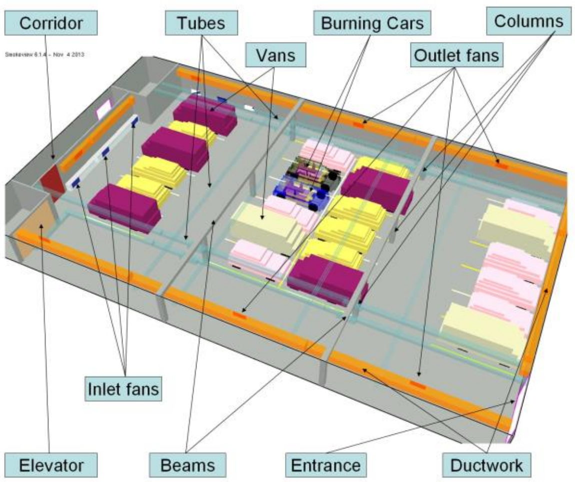

Figure 1: Scheme of car park with full number of parked cars including eight vans.

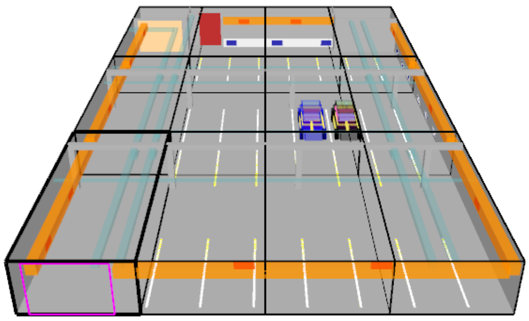

Figure 2: D2 ventilation configuration and the way of decomposition 12M (4-3-1).

In order to use parallel computation, FDS requires dividing the whole computational domain into particular computational meshes, each assigned to one CPU core. For all simulation scenarios, 12 meshes are used (12M, the way of decomposition 4-3-1, see Fig. 2), while in some cases also 6M (2-3-1), 36M (4-9-1) and 144M (8-9-2) simulations are performed to test reliability of parallel computation. The simulation includes 384 x 648 x 50 cells (the total cells number is 12,441,600) with 6 cm resolution. 600 s of fire is simulated on SIVVP cluster at the Institute of Informatics SAS, Bratislava, Slovakia. It is an IBM dx360 M3 cluster with 54 computational nodes (2x Intel E5645 @ 2.4 GHz CPU, 48 GB RAM). The number of cores is 648. The total computational time is about nine days for 12M simulations.

4. SIMULATION RESULTS

Time averaged values of visibility at head level (see Tab. 1 and Figures 3-9) show significant impact of car number on smoke propagation.

Table 2: Time averaged visibility for particular fire and ventilation scenarios and 12M

	$S_{no\ vent}$[m]	S_{D1}[m]	S_{D2}[m]
Empty	10.76	18.26	19.94
Half-full-0van	10.69	18.36	20.75
Half-full-4van	-	18.46	20.63
Half-full-8van	-	17.47	20.41
Full-0van	10.66	18.02	19.89
Full-4van	-	17.64	20.12
Full-8van	10.35	16.38	19.43

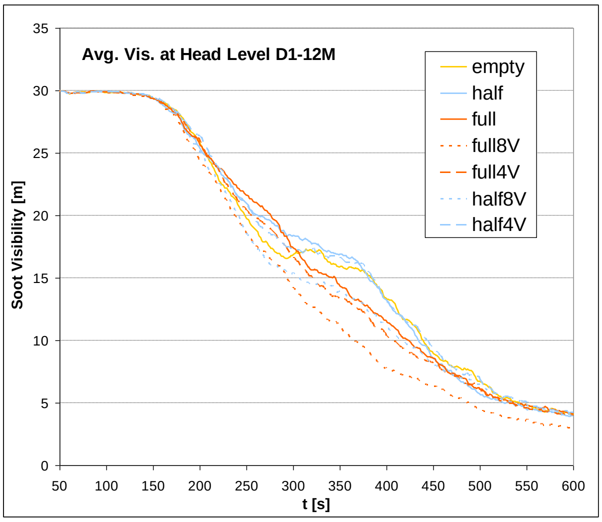

Figure 3: Averaged visibility for particular fire scenarios with D1 ductwork and 12 meshes

.

In D1 scenarios including only passengers cars, the impact of their number on average visibility decrease is small (maximal difference is 34 cm). Up to 300th s, "full" scenario provides slightly more efficient ventilation, probably due to dissipative effect of parked cars on inlet air flows (seee Fig. 6), while in "empty" scenario fast inlet flow disrupt hot layer slightly. After 300th s, the low hot layer is disrupted by car bodyworks in "full" scenario (see smoke fluctuations in Fig. 5) and "empty" scenario increases its relative performance. "Half" scenario is the most efficient, as it combines advantages of other two scenarios. Some differences between smoke patterns can be also observed (see Fig. 5). In "empty" scenario there are two large compact smoke-free areas in the car park, whereas in "full" scenario visibility fluctuates significantly within almost all car park area after smoke layer is torn.

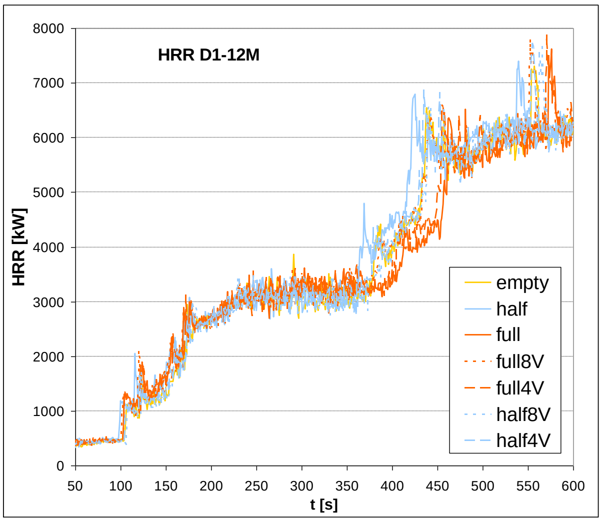

Figure 4: Heat Release Rate for particular fire scenarios with D1 ductwork and 12 meshes.

Inlet fans produce horizontal air flow in the car park slice, which is diverted towards the top of the slice slightly after it interacts with fire in the central part of the car park. Dissipated inlet flow in "half" scenario are diverted more considerably, which increases heat transfer towards the second car, accelerates its ignition (see Fig. 4) and increases smoke production in this scenario. Despite this fact this scenario is more efficient than other two. Its efficiency is even more clearly demonstrated if pool fires with the same HRR are used in all three scenarios and visibility difference of 0.71 m between "half" and "empty scenario is then achieved. Note that efficiency is not surprising, as the fans velocities are optimised for half-full car park. Optimisation for other scenarios would lead to slightly different fans velocities, nevertheless, typical phenomena causing the differences between particular scenarios are still the same.

A different kind of behaviour can be observed in D2 configurations, as the phenomena observed in D1 are strengthen by specific configuration of D2 (see Figures 7-9). Again, "empty" scenario provides worse results than "full" in the first half of the fire and better results in the second half, though the difference is small. Scenario "half-full-0van" leads to significantly higher averaged visibility value than "empty" scenario. In the former one specific character of air flows created by the presence of the cars enhance the efficiency of the ventilation. In "empty" scenario there is a considerable flow leading from the left part of the car park slice to the central bottom part (see Fig. 9). It disrupt smoke layer and cumulates smoke on the left bottom part of the slice and after interaction with air flow leading from the portal also in the right part of the slice. In the "half" scenario, this flow is hindered and dissipated by cars and directed more horizontally to the central part of the slice, where it enhance the rotation of air mass and thus also ventilation efficiency. Ignition of the second car occurs more or less at the same time in these two scenarios, however, in "full" scenario it occurs sooner, which exacerbate ventilation performance.

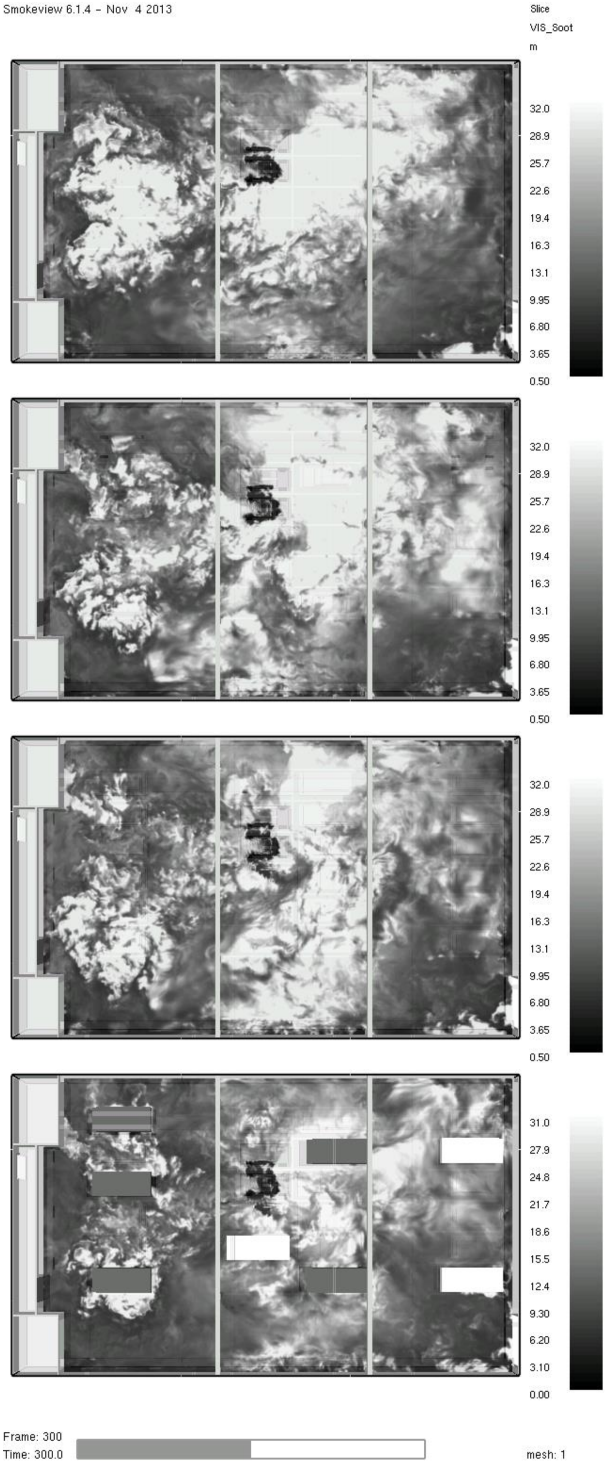

Figure 5: Visibility slices at human head level after 300 s for the fire scenarios "empty", "half", "full" and "full-8van" and D1 configuration.

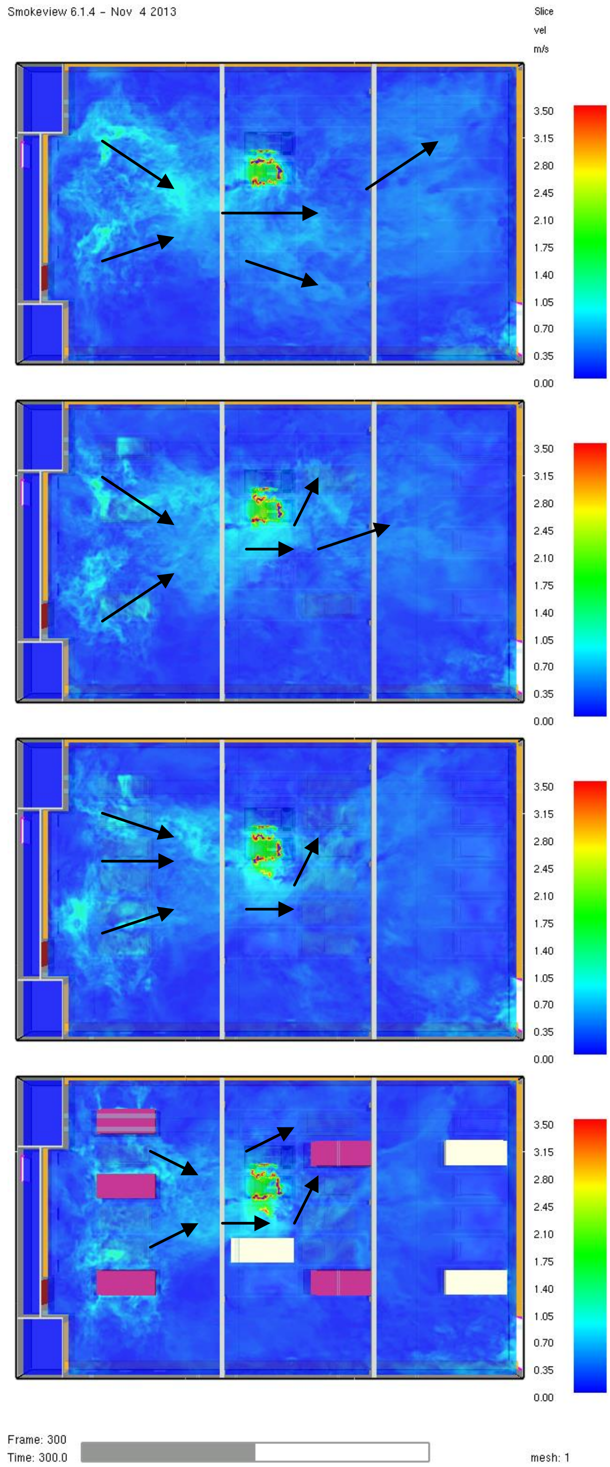

Figure 6: Velocity slices at head level after 300 s for the scenarios "empty", "half", "full" and "full-8van" and D1 configuration.

In scenarios without ventilation the difference between empty and full car park scenario is almost negligible (10 cm for 12M simulations) because of small air velocities. Smoke patterns are very similar as well.

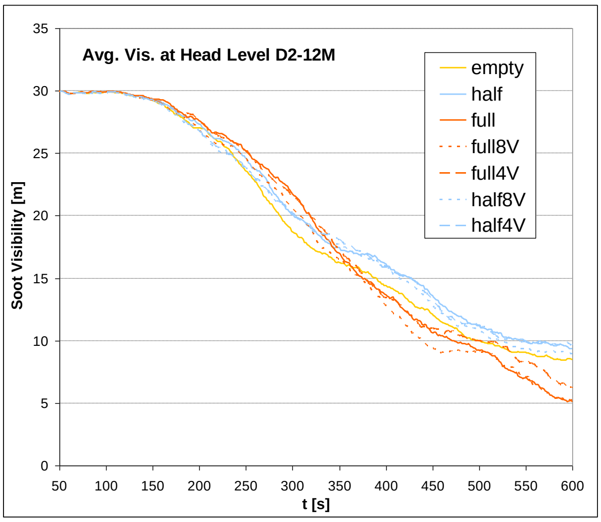

Figure 7: Averaged visibility for particular fire scenarios with D2 ductwork and 12 meshes.

In configurations including also vans, the hot layer is disrupted, smoke descend to head level sooner and the average visibility decreases with increasing cars number. This effect is stronger in D1 than in D2 configuration. Visibility at transversal slice of the rear part of the car park is shown in Fig. 10.

In D1, the difference between "empty" and "full-8van" configuration is about 1.88 m. Average untenable conditions occur about 67 s sooner in latter scenario. The biggest differences between configurations occur between 300th and 400th s. At t = 367 s "full-8van" conditions become untenable, while "half-0van" visibility is more than 6 m better.

In D2, the difference between "empty" and "full-8van" configuration is smaller, about 0.51 m. Untenable conditions occur about 60 s sooner, although visibility decreases very slowly in both cases in this phase of fire. In scenario "half-full-0van" untenable conditions occur even 50 s later than in "empty" scenario and visibility drops only slightly below 10 m. In general, the differences between scenarios behaviour are relatively small. As the fans velocities are not optimal for "full" scenarios, it is not surprising that the presence of vans can decrease them to more optimal values and thus enhance ventilation efficiency, which moderates general tendency of full scenarios to decrease visibility. In the case of "full-4van" scenario this tendency is even overcome and the averaged visibility is better than in "full-0van" (air flow pattern is similar as in scenario "full-8van", see Fig. 9). The impact of vans on air flow pattern is more significant in D2 scenario, in which vans limits the size of rotating whirl, while in D1 air flows mostly in horizontal direction between vans.

Note that better visibility in D2 scenarios is achieved because of specific configurations of burning cars. Air flows created by D2 avert flames from the second car and thus decrease the fire HRR. In general, D2 is not more efficient than D1.

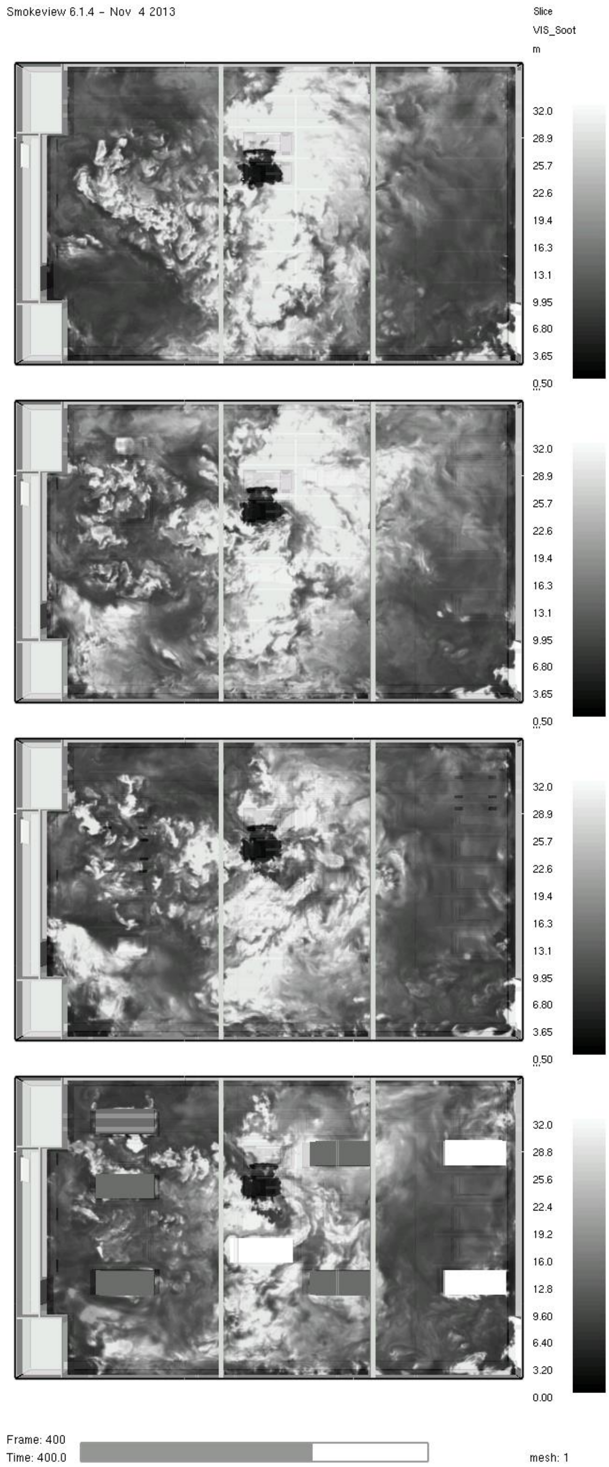

Figure 8: Visibility slices at human head level after 400 s for the fire scenarios "empty", "half", "full" and "full-8van" and D2 configuration.

Averaged visibility does not reflect the local character of smoke concentration. In the early phase of the fire in scenarios including vans, smoke cumulates not only on the same locations as in "empty" scenarios, but also in the proximity of vans (see Fig. 11). However, the general pattern of smoke cumulation is very similar in all cases, although in "vans" scenarios smoke cumulation is accelerated. The largest difference in D1 occurs at about 300th s, when in "empty" scenario a large smoke free area is created in the central part of the car park, while in "vans" scenario the area is filled with smoke (see Fig. 4). Similar tendencies, although less considerable can be observed also in D2 configuration (see Fig. 8).

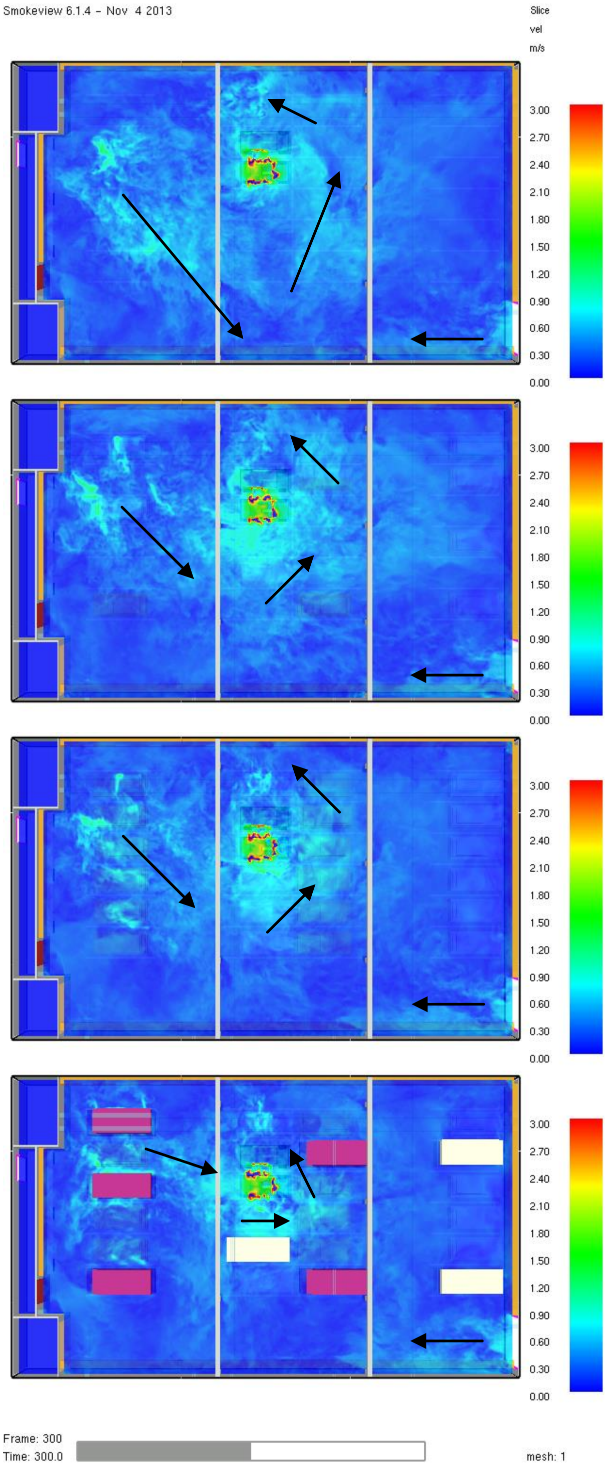

Figure 9: Velocity slices at head level after 300 s for the scenarios "empty", "half", "full-8van" and D2 configuration.

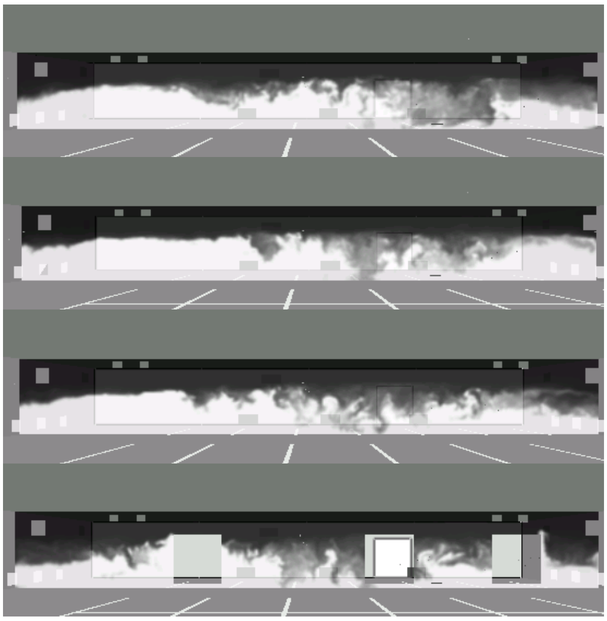

Figure 10: Visibility at transversal slices of the rear part of the car park after 350 s for the fire scenarios "empty", "half", "full" and "full-8van" and D1 configuration.

Figure 11: Fire scenarios "full" and "full-8van" and D1 configuration. Creation of smoke clusters in vans proximity at t = 140s.

5. PARALLEL COMPUTATION

Simulations 144M tend to overestimate averaged visibility values as well as differences between empty and full scenarios (see Tables 3 and 4). Fewer mesh number results in better precision as well as smaller differences between particular scenarios results. However, even simulations 144M provide good visibility estimates which are precise enough to conclude visibility decrease in "full" scenarios correctly. Typical difference between 6M and 12M simulations is only several centimeters for scenarios without ventilation (small air flows, see Table 3) and up to 50 centimeters for D1 scenarios (faster air flows, see Table 4). In Fig. 12 can be seen that the differences between simulations 6M, 12M and 144M increase after 350th s of fire with increasing fans velocity. It suggests that faster flows result in worse simulation precision, if higher number of meshes is used. Typical duration of 12M simulations is about 9 days, up to 1.5 days for 144M simulations and more than 11 days for 6M simulations.

Table 3: Time averaged visibility for particular fire scenarios and mesh decomposition without ventilation.

	6M	12M	36M	144M
Empty	10.73*	10.76	10.92	11.34
Half-full	10.66*	10.69	11.04	10.78
Full	10.71*	10.66	10.90	10.77
Full-8van	10.49	10.35	10.84	10.84

Table 4: Time averaged visibility for particular fire scenarios and mesh decomposition and D1 ventilation. * - Windows PC computation.

	6M	12M	144M
Empty	18.70	18.26	19.07
Half-full-0van	18.81	18.36	19.51
Half-full-4van	-	18.46	18.67
Half-full-8van	17.52	17.47	17.81
Full-0van	18.39	18.02	18.62
Full-4van	-	17.64	18.47
Full-8van	16.80	16.38	17.25

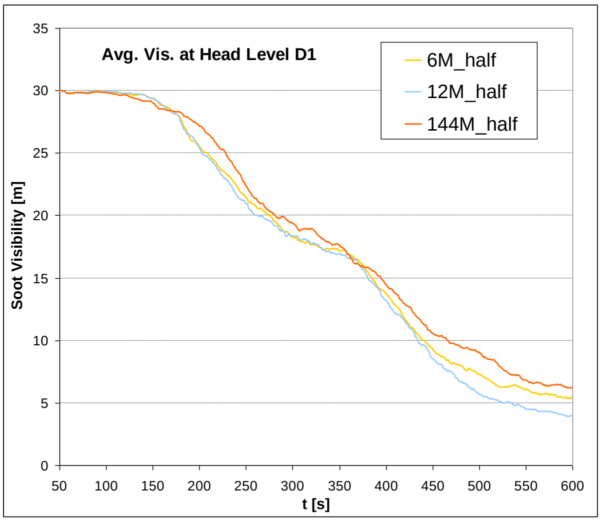

Figure 11: Averaged visibility for "Half-full-0van" scenario with D1 ductwork and 6M, 12M and 144M mesh decomposition .

CONCLUSION

Series of simulations of car park fire have been performed for two ventilation configurations and seven scenarios with different number and size of parked cars. Simulations have confirmed and quantified significant impact of parked vans on smoke visibility decrease, which can accelerate the rise of untenability by about 60 s for some specific scenarios (averaged visibility differences of up to 2 m) due to smoke layer disruption. If only passenger cars with lower bodyworks are included, differences about dozens of seconds can be expected for scenarios with different car number (averaged visibility differences of up to 1 m). The number and locations of cars influence inlet air flows, which can be hindered, dissipated, strengthened or redirected. Such differences influence the ventilation efficiency, fast flows can even disrupt smoke layer when it is low enough. Tops of car bodyworks tear smoke layer after it descend at that level in later phase of the fire, which results in more significant visibility decrease in "full" scenarios.

ACKNOWLEDGMENTS

The authors would like to thank to P. Smardz for fruitful discussions, to P. Polednak, J. Svetlik, M. Simonova and J. Flachbart for the organization of automobile fire experiments and to M. Dobrucky and V. Sipkova for technical support during FDS simulations. This paper was supported by VEGA (project VEGA 2/0184/14).

REFERENCES

Deckers, X., Haga, S., Sette, B., Merci, B., “Smoke control in case of fire in a large car park: Full-scale experiments”, Fire Safety Journal 57: 11–21 (2013)

Deckers, X., Haga, S., Tilley, N., Merci, B., “Smoke control in case of fire in a large car park: CFD simulations of full-scale configurations”, Fire Safety Journal 57: 22–34 (2013)

Glasa, J. and Valasek, L., "Study of Applicability of FDS+Evac for Evacuation Modeling in Case of Road Tunnel Fire", Research Journal of Applied Sciences, Engineering and Technology 7(17): 3603-3615 (2014).

McGratten, K., Baum, H., Rehm, R., Mell, W., McDermott, R., Hostikka, S. and Floyd, J.: Fire Dynamics Simulator (Version 5), Technical Reference Guide, NIST Special Publication 1018-5, NIST, Gaithersburg, Maryland, USA, 2010.

Okamoto, K., Watenabe, N., Hagimoto, Y., Chigira, T., Masano, R., Miura, H., Ochiai, S., Satoh, H., Tamura, Y., Hayano, K., Maeda, Y. and Suzuki, J., “Burning Behaviour of Sedan Passenger Cars”, Fire Safety Journal 44:301-310 (2009)

Partanen, M. and Heinisuo, M., 2013. Car fires with sprinklers: A study on the eurocode for sprinklers. *Proc International Conference Applications of Structural Fire Engineering*, pp. 23-28. April 19-20, Prague, Czech Republic.

Polednak, P., 2010. Experimental Verification of Automobile Fires (in Slovak). *Proceedings of the 4th International Conference on Fire Safety and Rescue Services.* June 2-3, Zilina, Slovakia.

Svetlik, J., 2010. Fire in the passenger car engine compartment (in Slovak). *Proceedings of the 4th International Conference on Fire Safety and Rescue Services.* June 2-3, Zilina, Slovakia.

Weisenpacher, P., Glasa, J. and Halada, L., 2012. Parallel simulation of automobile interior fire and its spread onto other vehicles. *Proceedings of Fire Computer Modeling: International Congress,* pp. 329-338. October 19, Santander, Spain.

Weisenpacher, P., Halada, L., Glasa, J. and Slizik, P., 2013. Smoke Propagation In Car Park Fire: A Parallel Study. *Proceedings of Eight Mediterranean Combustion Symposium*. September 8-13, Cesme, Izmir, Turkey.

AUTHORS BIOGRAPHY

Peter Weisenpacher studied theoretical physics at Comenius University, Faculty of Mathematics and Physics, Department of Theoretical Physics, Bratislava, Slovakia and received PhD. in 2003. He works as research scientists at Slovak Academy of Sciences, Institute of Informatics, Department of Numerical Methods and Algorithms. His current research interests include computational fluid dynamics, fire computer simulation and parallel computing. He participates in various research projects on fire simulation.

Ladislav Halada graduated in mathematics in 1971, received the RNDr. degree in mathematics and physics from the Faculty of Mathematics and Physics of Comenius University in Bratislava, and the C. Sc. degree (equivalent to Ph.D.) in mathematics in 1982 also from this university. He is Associate Professor from 1991. During 1972-2001 he worked on different scientific institutions and universities in Slovak Republic and also abroad. He is co-author of scientific books and numerous scientific papers.

Jan Glasa graduated in numerical mathematics in 1986, received the RNDr. degree in numerical mathematics and optimization methods and algorithms in 1986 at the Faculty of Mathematics and Physics of Comenius University in Bratislava. He has received the C. Sc. degree (equivalent to Ph.D.) in computer science at the Slovak Academy of Sciences. He is with the Institute of Informatics of Slovak Academy of Sciences in Bratislava as senior scientist. He serves as head of scientific council of the institute. His current research interests include mathematical modelling and computer simulation of fires, theory of curves, efficient algorithms, and parallel computing. Currently he is the leader of computer fire simulation project at the Institute of Informatics of Slovak Academy of Sciences.

Jan Astalos studied informatics at Slovak University of Technology, Faculty of Electrical Engineering and Information Technology, Bratislava, Slovakia. He works as research scientists at Slovak Academy of Sciences, Institute of Informatics, Department of Parallel and Distributed Information Processing. He focuses on high-performance computing systems and distributed computing infrastructures.