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# PROBABILITY OF FIRE BRIGADE SUPPRESSION SUCCESS IN AN UNDERGROUND CAR PARK FIRE

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*SUMMARY: Underground car park fires are among the riskiest firefighting operations. The main reasons for high risks are underground location, large spaces, possible high fire load, lack of installed fire protection systems, etc. When accounting for an underground car park fire scenario we must know the fire load, i.e. car characteristics, number of cars in underground car park, underground car park design features and possible ignition sources. Based on this framework we can predict the fire development. Additional help can be provided by using deterministic and probabilistic methods. In general, fire spread will be highly dependable on the initial fuel – the first vehicle, which was ignited and the spread of fire to adjacent vehicles. The success of fire brigade intervention depends on fire development stage at the time of its arrival at the fire scene.*

*In this paper heat fluxes during car fires were analyzed. Experimental data were recalculated by computational fluid dynamics code (CFD) where some significant consistency was found. In addition to this, real underground car park fire (the fire that was used as an example happened in Ljubljana in 2007) and fire brigade response times were analyzed by probabilistic method. Car burning properties and realistic fire data were compared to probabilistic values. The expected performance of these features has often been predicted using rules-of thumb or expert judgment. These approaches often lack the convincing technical bases that exist when addressing fire safety measures and fire brigade responses. This paper presents science-based approaches to analyze fire brigade response and fire spread in underground car parks.*

**Key words:** *fire, underground car parks, computational fluid dynamics, probabilistic methods*

## INTRODUCTION

Construction requirements for newly built underground garages originate from Slovene national codes and standards. During the fire safety design procedures fire safety designers can use national and international fire safety codes. Since the Rules on fire safety in buildings act that was published in 2004, fire safety designers can use performance-based design to plan and design fire safety measures in underground car parks.

Nowadays, it is not a common practice in Slovenia to use a performance-based design but in some cases computer codes such are Computational fluid dynamics models (CFD) are used.

It can be said with some confidence that newly built underground car parks are more or less safe. The problem occurs when the assessment of fire safety measures in older underground car parks is a subject of analysis. At this point two important factors influence the evaluation of fire safety in underground car parks:

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- Year of construction,
- Maintenance level and fire safety awareness of the owner.

To assess the real condition and to analyze these factors, 30 larger objects in Slovenia2 were analyzed. For the analysis five underground car parks were examined in details. During the time of analysis only one underground car park was equipped with fire suppression system. All studied underground car parks had automatic fire detectors installed, fire hydrants and sufficient number of fire extinguishers. Only two among all five underground car parks were separated into fire sectors with 60 or 90 minutes rated fire barriers.

Detailed risk analysis showed that fire safety systems in existing buildings are generally unmaintained. It is very difficult to predict how they will behave in case of fire and how safe are actually underground car park users and firefighters.

## ORGANIZATION OF FIRE SERVICE IN LJUBLJANA

The average number (from 2005 to 2010) of fires that occur in Ljubljana per year is approximately 1,700. From the total number of fires per year, approximately 47% or 800 fires occur in buildings. Underground car park fires happen approximately five times a year.

The maximum response time of Fire brigade Ljubljana is defined in Slovene national regulations (Regulation on the Organization, Equipment and Training of Protection, Rescue and Aid Forces) and it is one minute after the fire brigade has been notified about the fire. The aim of short fire response time is to attain a quick initial attack by first fire truck and sufficient number (at least five) firefighters. With approximately 98% of all fires Fire brigade Ljubljana responds within one minute. With 43% of all fire events their response and travel time is from one to five minutes (Fig. 1), and in 44% cases from six to 10 minutes and in 12% from 11 to 15 minutes. Annually, there are only few events, when the response time is longer than 15 minutes.

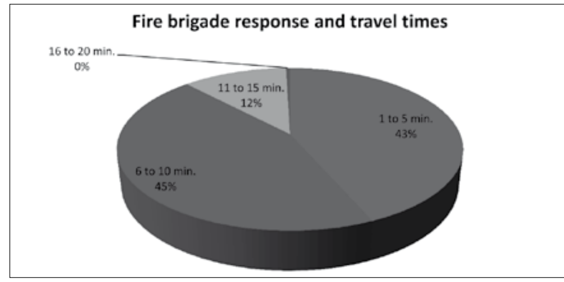


*Figure 1. Fire brigade response and travel times*

*Slika 1. Vrijeme odziva i vrijeme putovanja vatrogasne postrojbe*

The arrival of the first fire truck to the fire scene does not necessarily mean that the fire brigade will begin to suppress the fire and start with rescue operations.

The period between arriving to the fire scene and fire suppression activities depends on the conditions of access roads and fire brigade areas, familiarity with the building, first information about the fire, and water availability.

Based on the information and available fire troops, fire chief will decide where and how the fire will be attacked. Pre-operation time that usually elapses between the arrival of firefighters at the fire scene and start of intervention is from one to five minutes.

## CAR FIRES

Car burning fire curve and combustion profile is quite well known today. An average car is composed of about 10,000 parts and 40 different materials.

The average passenger car produced in 1960 contained 82% of iron and nonferrous materials (2% aluminum) and 2% of plastics. In 1980, the average weight of ferrous and nonferrous metals was around 74-75% (of which 4.5% aluminum) while the proportion of plastics increased to 8-10%. The use of lighter materials (aluminum and plastics) has in general reduced fuel consumption over the years and increased the fire load. The average composition of the European car produced in year 2000 or later thus indicates that the proportion of aluminum components, as well as the quantity of plastic materials in the car structure has increased.

Recent car fire testing results were published by British BRE *(2010)*. The test included 22 newer vehicles in various fire scenarios. The tests were mainly done in a closed compartment where underground parking garage conditions were simulated.

The BRE results can be compared with results published by the laboratories where fires on passenger vehicles have already been studied in the past.

1. Mangs and Keski – Rahkonen fire tests were performed on two vehicles *(Mangs, Keski-Rahkonen, 1994)*. The heat release rate during their tests was 3.5 MW. Their experiment did not cover larger vehicles.
2. Researchers in Profile ARBED laboratories analyzed two and three vehicles in their fire test *(European Commission, 1996)*. Their conclusions showed that the heat of combustion, generated during the burning of two vehicles after four minutes was 1.5 MW. It remained constant until about 24 minutes, rising to 8.5 MW. In 26 minutes the amount heat of combustion reached the peak value. Fire enters the declining phase at about 70 minutes. Three vehicles reached release rate of approximately 4 MW of heat after 12 minutes and reached the 16 MW at 26 minutes. The fire went to the declining phase after about 38 minutes.
3. In 1995 and 1996, Schleich has proved that the amount of heat of combustion from the vehicle manufactured in 1995 doubled in relation to older vehicles *(European Commission, 1996)*.
4. The tests made at EUREKA laboratory showed that a single vehicle reaches about 5 MW, while two to three vehicles reach approximately 8 MW of heat *(Fire Incidents…, 2001)*.
5. The results of other tests have shown that burning a single car can reach up to 8.5 MW, while two cars can reach up to 15 MW *(Li, Spearpoint, 2007)*. The results of the tests have shown that, for example large off-road vehicles emit significantly larger amounts of heat than normal cars.
6. In 2000, Steinert tested two vehicles simultaneously *(Zhao, Kruppa, 2004)*. The distance between the test vehicles was 80 cm. In most of the fire tests, fire spread (jumped) from one vehicle to the adjacent vehicle. Some of the fire tests lead to a flashover.

## CAR BURNING EXPERIMENT

For the purpose of defining the heat flux emitted by the vehicle during the combustion process, a fire test was performed. During the test the heat flux emitted by the vehicle during combustion process was analyzed. The testing car was a Seat Ibiza produced in 1992 with a mass of 900 kg (Fig. 2).

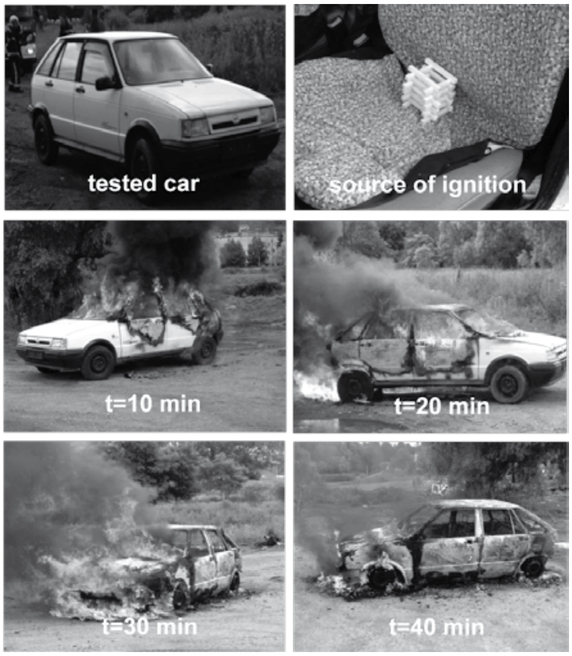


*Figure 2. Stages of a burning car*

*Slika 2. Faze gorenja automobila*

During the combustion of the vehicle the temperature was measured at seven different points (Fig. 3). Measuring points were selected in order to cover both sides of the vehicle and the area around the engine. Temperatures were measured with laser IR thermometers and IR thermal imagers. Both devices are usually used by firefighters. Based on the measurements the heat flow, emitted in the immediate environment of the test vehicle during combustion was calculated.

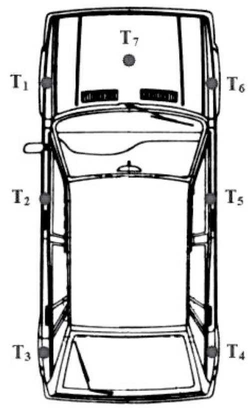


*Figure 3. Car measuring points*

*Slika 3. Mjerne točke na automobilu*

The results of the measured car temperatures are presented in the graph (Fig. 4).

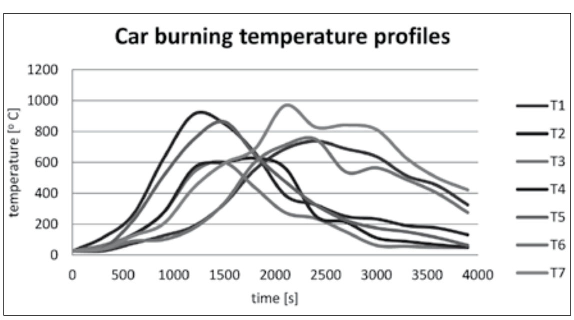


*Figure 4. Car burning temperature profiles*

*Slika 4. Temperaturni profili gorenja automobila*

The test has shown some significant characteristics of car fires. During the fire test the maximum temperature was measured at the measuring points T2 and T5, located at the driver and passenger doors. Combustion lasted longest on the engine compartment marked with measuring points T1, T6 and T7. The reason for this event is the quantity of combustible materials (plastics, oil). The highest temperature at measuring points T1, T6 and T7 was approximately 100 °C higher than elsewhere. This may be due to the type and amount of combustibles in the engine compartment. The measured values were compared with similar tests10, where we observed a significant overlap in the results. Based on the measured temperatures, the heat flux emitted by the burning vehicle was calculated (Fig. 5).

In a car park scenario, where the distance between vehicles in adjacent spaces is typically less than one meter, there is a realistic risk of fire spread due to radiation, convection and direct flame contact (from a liquid fuel or molten plastic pool fire). In the last decade the growing use of plastic components in modern vehicles has increased the potential for sustained flaming and fire spread outside the original source *(BRE Report, 2010)*.

The objective of this task was to determine approximate heat fluxes from burning car to nearby objects (cars). Heat flow emitted to the immediate neighborhood and generated by a burning vehicle, comprises a radiant and convective heat flow component. The heat flux data were obtained by applying the Stefan Boltzmann law and convection equation (Fig. 5).

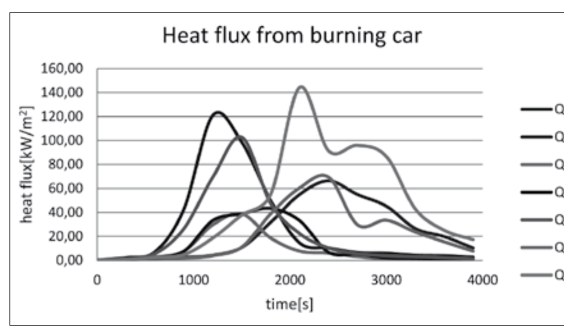


*Figure 5. Heat flux from burning car*

*Slika 5. Toplinski tok zapaljenog automobila*

They were calculated from data measured at seven measuring points. The calculated heat release rate (HRR) curves were compared to visually observed data later on. Calculated results are consistent with previous experiments, i.e. BRE fire tests, where it was shown that heat fluxes at all locations exceeded 25 kW/m$^2$. They show realistic ways of fire spread and give realistic temperature predictions with the overall flux about 3 MW.

The ignition of the subsequent car in underground car park is triggered by a burning car. The calculated heat flow values show that the ignition of neighboring vehicles is possible. This can be verified by the results of previous tests *(BRE Report, 2010)*.

Critical exposure conditions, e.g. intensity and duration of incident thermal radiation, for a range of external materials used on typical road vehicles, which have assisted determining the spread of fire between cars is shown in figure 6 *(BRE Report, 2010)*.

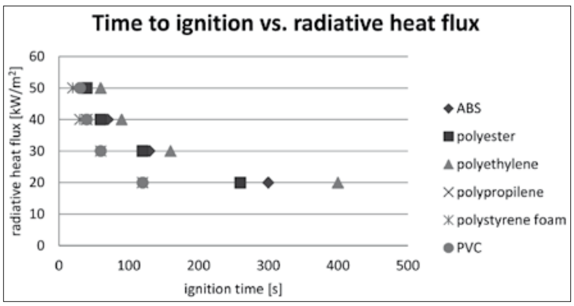


*Figure 6. Critical irradiance values for car ignition*

*Slika 6. Kritične vrijednosti zračenja za zapaljenje automobila*

According to realistic temperature profiles and calculated values, it is possible to predict fire spread to subsequent cars in a time frame from five to ten minutes.

## FDS PREDICTIONS OF CAR BURNING TEMPERATURES

For analyzing the measured temperatures and calculated heat fluxes a computer model was used. This is a model, based on computational fluid dynamics (CFD model), called Fire Dynamic Simulator (FDS). It is a specialized software package for simulating fire dynamics in three-dimensional environment.

FDS numerically solves the form of Navier-stokes equations for low-speed, thermally driven flow with emphasis on smoke and heat transport from fires. Historically, FDS has been successfully used to reconstruct several fire incidents and to predict fire development during the process of building construction.

FDS has been successfully used for analyzing the temperature emitted by the vehicle during imaginary car fires. The assumptions in the model application were that the car is burning in the open air while air supply is enabled on all sides (axisymmetric flame).

Computational geometry that was used had dimensions of 8 m x 8 m x 5 m. Computational domain was open on all sides. Vehicle position and the geometry are shown in Figure 7.

During the calculation the computational domain was divided into a grid with a total number of 69,984 cells. Total calculation time was set to 3600 s.

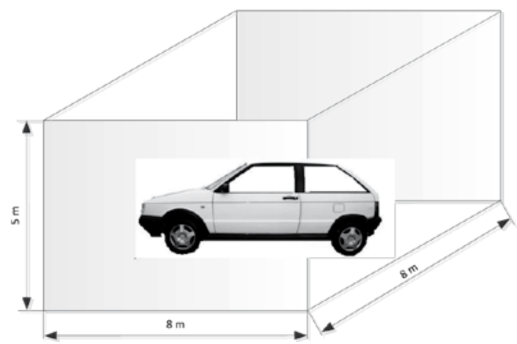


*Figure 7. Experimental car burning geometry*

*Slika 7. Eksperimentalna geometrija zapaljenog automobila*

Geometry walls were set as adiabatic, while Smagorinsky large eddy simulation model was used as turbulence model standard. The car was modeled as a rectangular shape. For the modeling approach based on heat release rate per unit area HRRPUA, the ignition temperature and the Cone Calorimeter HRRPUA curve of a specimen were specified in the simulation.

The prescribed HRRPUA was 211.86 $kW/m^2$.

*Figure 8. Car burning during FDS run (temperature profile after 600 s)*

*Slika 8. Gorenje automobila tijekom FDS-a (temperaturni profil nakon 600 s)*

The results, obtained through CFD model FDS, were compared with measurements from the fire experiment (Fig. 9).

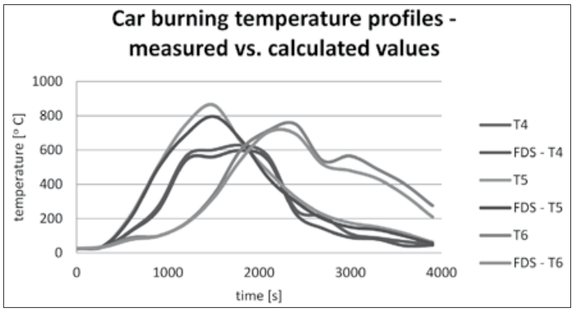


*Figure 9. Comparison of measured and calculated results*

*Slika 9. Usporedba rezultata izračuna s izmjerenim vrijednostima*

Comparisons show that the results obtained by the FDS follow the measured values fairly well. The results calculated with FDS deviated by less than 20 per cent from the measurements.

## FIRE IN AN UNDERGROUND CAR PARK

In addition the fire brigade response and travel times to fire scene in the underground parking garage on the address Barjanska cesta 52 in Ljubljana, which occurred on November 27th 2007 at 19:35 will be analyzed. Fire brigade arrival time will be compared with the fire development stages in the underground parking garage.

*Figure 10. Underground car park entrance (Photo Courtesy of Ljubljana Fire Brigade)*

*Slika 10. Ulaz u podzemnu garažu (fotografiju ustupila Vatrogasna postrojba Ljubljana)*

The response time of Fire department mostly depends on fast and reliable information about the fire. The underground parking garage, where the fire started was equipped with automatic fire detectors. They were permanently connected with a fire alarm panel, located in security guard room where 24-hour attendance is provided. When fire alarm notification was received, the security guard called the local emergency center at 19:40. The Center immediately switched the phone call to the Fire brigade Ljubljana where a dispatcher alarmed the firefighters. Fire brigade response times are shown in Table 1. Fire brigade Ljubljana normatively defined response time is one minute. This means that the first fire truck must respond in one minute.

**Table 1. Fire brigade activity**

**Tablica 1. Djelatnosti vatrogasne postrojbe**

| Time | Event/action |
|---|---|
| 19:44 | Fire brigade notification |
| 19:45 | Departing of fire truck 1 |
| 19:45 | Departing of fire truck 2 |
| 19:45 | Departing of fire truck 3 |
| 19:52 | Arrival at the scene |
| 19:55 | Departing of fire truck 4 |
| 19:55 | Departing of fire truck 5 |
| 20:00 | Arrival at the scene |
| 22:39 | End of intervention |

First water was released on a fire at 20:09 due to long access pathways. The car park was equipped with a classical ducted smoke control which was not operable during the fire.

When the first firefighters arrived to the burning cars, two cars had almost been burned down completely while the third car was engulfed with flames. It is expected that the fire on vehicles (when fire brigade arrived) already burn for more than 15 minutes. Since the fire started inside the vehicle, fire detection was delayed. Fire was suppressed by a mixture of approximately 3,000 liters of water and foam. Three cars were destroyed by fire and one person was injured during the fire. The police official report stated that the fire started in a car in the garage, and appeared to be arson fire.

*Figure 11. Cars at car park fire (Photo Courtesy of Ljubljana Fire Brigade)*

*Slika 11. Automobili u požaru u podzemnoj garaži (fotografiju ustupila Vatrogasna postrojba Ljubljana)*

## PROBABILISTIC ANALYSIS OF FIRE BRIGADE RESPONSE

In the pre-stage, to design a fire curve, performance-based fire designer can be used as Venn network diagrams. These diagrams represent choice events and possible outcomes. The first requirement of the Venn diagram is that probability must lie between 0 and 1. Mathematically, we write P(A|B) to represent the conditional probability of A that B occurs. If it is read as "Probability of A given B" the definition is

$$P\langle A|B\rangle = P(A \text{ and } B) / P(B) \qquad [1]$$

Network diagrams are used to organize an analysis and to structure evaluation. A network is a semi graphical framework that can be used to establish and analyze the established fire scenarios or fire brigade activities.

At this point we want to know what is the likelihood that the fire brigade started fighting the fire before the fire broke out in the adjacent vehicle.

After the ignition of the second vehicle, heat flow increases rapidly, therefore fire spread is faster.

Fire engulfs larger number of vehicles *(BRE Report, 2010)*, and for this reason firefighting operations are more complex, active and passive fire protection systems are exposed to higher fire loads and more prone to fail.

The main goal of fire brigade operations is to locate fire as soon as possible and to suppress the fire. The success of firefighting operation generally depends on:

- Fire detection,
- Alarm processing time,
- Fire brigade notification,
- Fire brigade travel time,
- Possibilities for fire attack (e.g. fire access pathways, water supply etc.),
- Fire size at the moment of fire brigade attack,
- Fire location,
- Building obstacles,
- Enviromental conditions (e.g. heat, visibility and wind conditions during fire.

In underground car parks fire firefighters need to start fighting fire within maximum seven minutes if they want to achieve the main goal, i.e. preventing fire to spread to adjacent vehicles (Fig. 12).

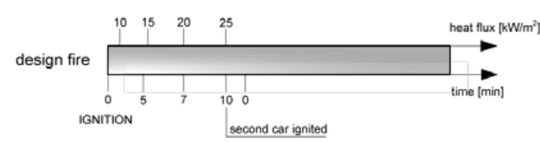


*Figure 12. Car fire propagation time frame*

*Slika 12. Vremenski okvir širenja požara na automobilu*

At this point we can establish a single value network to determine whether fire will be suppressed before it catches a nearby car. Probability values used in the diagram are given in Table 2.

**Table 2. Conditional probabilities for single value network**

**Tablica 2. Uvjetne vjerojatnosti za jednobrojnu mrežu vrijednosti**

| Activity | Probability |
|---|---|
| Fire detection (fd) | 0.99 |
| Fire department notification (fdn) | 0.80 |
| Fire department response time (fdr) | 0.99 |
| Building access (ba) | 0.90 |
| Water supply (ws) | 0.75 |
| Fire location (fl) | 0.70 |

With probabilistic model it is possible to predict fire conditions which will develop during the pre-flashover stages in a car park fire. The fire growth model consists of value network, where values are based on statistical, engineering and experienced data. A sample calculation is shown in Figure 13.

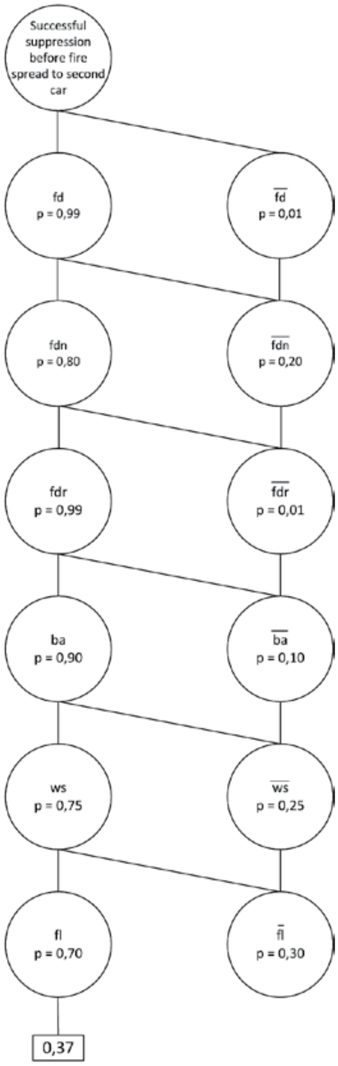


*Figure 13. Single value network*
*Slika 13. Jednobrojna mreža vrijednosti*

The single value network indicates that the Fire brigade Ljubljana had only about one third chances (P = 0.37) to extinguish the car fire in the car park before it spread to a second car. There are several reasons for the low calculated value. One among them is a distance between fire brigade and fire location, building access etc.

Major problems with manual fire suppression in car parks can be divided into two parts:

- Fire brigade notification time and
- Fire brigade response time and arrival to the site.

Fire brigade notification time can be shortened by installing fire detection systems and by direct transmission of the signal to fire departments. This is currently not a general rule in Slovenia since less than 5% of all buildings are directly connected to the fire brigade. We can certainly recommend it in case where rapid fire development and dangerous fire interventions can be expected.

It is clear that most problems with fire brigade operations in underground car fires appear at the fire scene where firefighters need to look for proper entrance, water supply, ventilation/smoke control possibilities, energy supply, etc.

This problem can be at least partially solved by changing relevant regulations and by implementing these, and by giving a chance to fire brigades to cooperate during construction of buildings.

## CONCLUSIONS

In this paper probabilistic and deterministic methods were combined. Using both methods, the response of fire departments to fire in an underground parking garage was analyzed.

A time based model where you can draw a straight line, and analyze fire brigade functions and operations through data from fire tests, computer models and probabilistic methods was established. The model proved to be very flexible and quick to adapt, which can be of great benefit during firefighter operations.

It is certain that fire brigades will respond to any car fire in underground parking garages. If the car park is equipped with fire suppression system, the role of fire brigades will be more or less passive, however, if there are no fire suppression systems installed fire brigades need to assume an active role. It is expected that the effectiveness of fire extinguishing by fire brigade will improve if the building is equipped with automatic fire suppression systems. Activation of sprinkler system will reduce the fire spread, heat release rates and smoke production. It'll improve and accelerate fire brigade operations and hence fire suppression.

Despite the new building fire brigade had several problems with smoke control systems, water supply and building access. In the future analysis conditional probability method will be used to analyze the reliability of other fire impact factors as well.

The facts on recent fires in underground car parks promote the need for fire analysis and constant searching for methods, to accurately and quickly predict the phases of fire development before fire brigade arrival.

By combining deterministic and probabilistic methods, we can accelerate demanding and helpful calculations by using computer models. This is especially valid when there is a need to obtain data in real time, perhaps from a computer in the fire truck during the fire brigade operation.

## REFERENCES

*BRE Report,* Fire spread in car parks, BD2552, BRE, December 2010, London, UK.

*European Commission,* Directorate General for Research, Recherches, Development of Design Rules for steel Structures Subjected to Natural Fires in Closed Car Parks, Profil ARBED, 1996, 51-94.

*Fire Incidents within General Vehicle Parking Areas 1998-2000*, Metropolitan Fire & Emergency Services Board, Melbourne, 2001, 45-73.

Grm, B., Jug, A.: *Analysis of the fire protection measures in buildings, research and development project,* Faculty of Chemistry and Chemical Technology, Ljubljana, 2002

Li, Y., Spearpoint, M.: Analysis of vehicle fire statistics in New Zealand parking buildings, *Fire Technol.,* 2007, Vol. 43, 93 – 106.

Mangs, J., Keski-Rahkonen, O.: Characterisation of the Fire Behaviour of a Burning Passenger Car, *Fire Safety J.*, 1994, Vol 23, 17-35.

Okamoto, K., Watanabe, N., Hagimoto, Y., Chigira, T., Masano, R., Miura, H., Ochiai, S., Satoh, H., Tamura, Y., Hayano, K., Maeda, Y. and Suzuki, J.: Burning behavior of sedan passenger cars, *Fire Safety J.,* 2009, Vol. 44, 301-310.

*Regulation on the Organization, Equipment and Training of Protection,* Rescue and Aid Forces, Ur. l. RS, No. 92/2007.

*Rules on fire safety in buildings act,* Ur. l. RS, No. 31/2004.

Zhao, B., Kruppa, J.: Structural Behavior of an open car park under real fire scenarios, *Fire mater.,* 2004, Vol. 28, 269 – 280.

## *VJEROJATNOST USPJEŠNOG SPREČAVANJA POŽARA U PODZEMNIM GARAŽAMA*

*SAŽETAK: Sprečavanje požara u podzemnim garažama među najopasnijim je vatrogasnim operacijama. Glavni uzroci visokog rizika su podzemna lokacija, veliki prostor, potencijalno visoko požarno opterećenje, nedostatak sustava zaštite od požara, itd. Pri analizi mogućih scenarija požara u podzemnoj garaži mora biti poznato požarno opterećenje, tj. karakteristike i broj vozila u podzemnoj garaži, osobitosti konstrukcije same podzemne garaže te mogući izvori paljenja. Na temelju ovih podataka može se predvidjeti razvoj požara. Kao pomoćni alat mogu se primjenjivati determinističke i probabilističke metode. Općenito će širenje požara jako ovisiti o početnoj gorivoj tvari, tj. o prvom vozilu koje se zapalilo, te o širenju požara na susjedna vozila. Uspjeh intervencije vatrogasne postrojbe ovisi o fazi razvoja požara zatečenoj po dolasku na mjesto požara.*

*U ovom radu analizirani su toplinski tokovi koji nastaju prilikom požara na vozilima. Eksperimentalni podaci provjereni su izračunima uporabom računalne dinamike fluida, pri čemu su utvrđene značajne podudarnosti. Probabilističkom metodom provedena je analiza stvarnog požara u podzemnoj garaži koji se dogodio 2007. godine u Ljubljani, kao i vrijeme odziva vatrogasnih postrojbi u konkretnom slučaju. Značajke gorenja automobila i stvarni podaci o požaru uspoređeni su s vrijednostima dobivenim probabilističkim metodama. Ove značajke često se predviđaju i procjenjuju na temelju iskustva stručnjaka, no takvom pristupu nedostaje uvjerljiva tehnička podloga kakva postoji pri analizi mjera zaštite od požara i odziva vatrogasnih postrojbi. U ovom radu prikazani su znanstveno utemeljeni pristupi analizi odziva vatrogasnih postrojbi i širenja požara u podzemnim garažama.*

**Ključne riječi:** *požar, podzemne garaže, računalna dinamika fluida, probabilističke metode*

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