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SENSITIVITY ANALYSIS OF FIRE-FOLLOWING EARTHQUAKE MODELS

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Abstract

Fire-Following Earthquake (FFEQ) is a secondary disaster to earthquakes which can cause significant losses and, in some cases, may comprise a large portion of the total loss by developing into large conflagrations (e.g., 1906 San Francisco earthquake). In order to estimate fire losses, conditioned on the occurrence of an earthquake, a probabilistic conflagration model is required. Such a model predicts the burnt areas based on the three-phases of the FFEQ process: fire ignition, fire spread and fire suppression. The first phase, fire ignition, estimates the number of fires that can occur in the aftermath of an earthquake and is a function of the intensity and time of occurrence of the earthquake, the square footage of the buildings in the impacted region, and the mix of construction and occupancy classes. The second phase, fire spread, estimates the propagation of each of the initial fires within a building, to other buildings, and among city blocks. This process is in general a function of building construction material and footprint size, separation between buildings and city blocks, wind speed and other modeling parameters. Lastly, fire suppression attempts at modeling all the activities associated with extinguishing a fire, beginning with its discovery, reporting, arrival of fire units, and fire control. This study adopts a simulation-based framework by dividing the area of interest into grid cells and carrying out the time-stepping analysis of all three phases of the fire process into a conflagration model. There is, however, a significant uncertainty in the parameters required for performing the simulation. Hence, each of these parameters is characterized by a proper probability distribution function and a Monte Carlo simulation approach is then used to characterize the probability distribution of the output variables of interest such as the number of initial fire ignitions and final burnt area. This study presents the sensitivity of the fire loss results for 24 metropolitan areas to different ignition and conflagration model parameters. Results of the sensitivity analysis show that FFEQ results are more sensitive to the density of fire stations, builtupness of the area, average PGA of earthquake footprint, wind speed and percentage of wood construction compared to the other input parameters.

Keywords: Fire following earthquake; Fire loss; Sensitivity analysis; Simulation

1. Introduction

Catastrophic conflagrations after the 1906 San Francisco and the 1923 Tokyo earthquakes proved that, in some situations, losses caused by fire following earthquake (FFEQ) can be comparable or even more than the direct losses caused by ground shaking [1]. Although modern fire suppression systems have been considerably enhanced since the early 20th century, FFEQ can still be a major source of losses caused by an earthquake. Estimation of losses caused by FFEQ includes high uncertainties due to the lack of enough historical data and numerous parameters involved in the problem.

The FFEQ process can be divided to three phases — ignition, spread and suppression — and for each phase there are several models available in the literature. Lee et al. [2] summarized the available models for each phase developed prior to 2008. Since then, newer models were proposed to simulate the three different phases of the FFEQ process. For instance, Davidson [4] proposed an statistical approach for modeling ignitions and applied the proposed model to California. Alternatively, the new HAZUS ignition model [4], proposed in 2009, predicts the number of ignitions per million square feet of building floor area as a function of the peak ground acceleration (PGA). While HAZUS model uses only PGA in the ignition function, Zolfaghari et al. [5] proposed a method to consider additional controlling factors such as gas pipeline network, urban development and time of earthquake. Similarly, Yildiz and Kamran [6] proposed a physics-based ignition model to include the effect of damaged utility systems and household appliances.

Lee [7] proposed a detailed physics-based model for the fire spread simulation considering room-to-room fire spread in buildings, percentage of radiation that a building receives from its neighbors and differentiating between roof flames and window flames. Lee and Davidson [8] compared this proposed model to Hamada spread model [9], which has been a popular spread model over the last six decades, and showed that despite some differences, such as burnt area in upwind direction, the predictions from their physics-based model were in good agreement with Hamada model. Later, Li [10] updated the physics-based model introduced by Lee [7] and Lee and Davidson [13] and verified it with Hamada model [12]. Another detailed model proposed by Thomas et al. [13], which is a GIS-based dynamic fire spread model that consists of seven distinct modes of spread such as direct contact and spread through broken windows.

There are also some recent studies on water supply and fire suppression. Scawthorn [14] studied the post-earthquake firefighting water supply system in California and concluded that the risk of conflagration due to the vulnerabilities of water agency systems is significant. Davis and O’Rourke [15] studied the damage to water distribution system caused by a magnitude 7.8 earthquake in the southern San Andreas fault and showed that such an earthquake can cause considerable damage to the water distribution system.

Due to the high uncertainty involved in the FFEQ process and the lack of enough historical data, developing and validating FFEQ models could be a challenging task. It requires an understanding of the parameters involved in the problem, level of uncertainty in the estimation of each parameter and sensitivity of outputs to model parameters. This study provides an insight on the sensitivity of FFEQ losses to the input parameters that are used in ignition, spread and suppression phases of simulation. A Fire loss index (FLI) is used as the measure of loss in this study. FLI is herein defined as the percentage of an area that is burnt due to fire after an earthquake that produced peak ground acceleration (PGA) of 0.4g at the location of interest. The sensitivity analysis in this study is performed on the FLI values obtained for 24 major metropolitan areas in North America. For running FFEQ simulations, a software tool developed at Risk Management Solutions (RMS) Inc. is used.

This paper has five sections. After the introduction, a brief review of data collection methodology is provided. The third section describes the details of conflagration model used in this study. Some results of FFEQ simulations along with sensitivity analysis on the results are presented in the fourth section and, finally, the last section is devoted to summary of research findings and conclusions of the study.

2. Data Collection

The data collected to run the FFEQ simulations include: (1) buildings and city data, which are used in the ignition and spread models, (2) seismicity data, which are used in generating footprints for ignition model, (3) wind data, which are used in spread model and (4) fire station and traffic data, which are used in both spread and suppression models.

FFEQ Simulations are conducted for 24 metropolitan areas in the United States and Canada. For each metropolitan area, a mesh grid with the resolution of 500m is created and for each grid, information about building dimensions (plan dimensions and height), distance between buildings, builtupness (percentage of area that is covered by buildings), city block dimensions and width of streets are collected. Seismicity data of each location are used to generate PGA footprints that are fed into the ignition model. Monthly wind data for each city including wind speed and direction are collected from multiple stations. Wind speed is modeled with Weibull distribution, where scale and shape parameters are calculated from monthly wind data. Wind direction is sampled from 16 directions using a Multinomial distribution, where probability of wind being in each specific direction is obtained using wind data. Fire station data that are used in this study include the location of fire stations in a city and number of fire engines available in each fire station. Traffic data are also collected for each city to adjust the speed of fire engines during the suppression phase.

3. Conflagration Model

The conflagration model used in this study is characterized by three phases: ignition, spread and suppression. The ignition phase estimates the number and spatial distribution of the fire ignitions caused by a given ground motion. Spread and suppression phases of the model are coupled because fire spread depends on the firefighting capacity of the system. For each metropolitan area, millions of simulations are conducted. In each simulation, the number and spatial distribution of ignitions are determined first and then fires start to spread until enough number of engines assigned to them or until there is no more material to burn. Details of the ignition, spread and suppression models are described in following subsections.

3.1 Ignition model

The ignition curves used in this study are the updated version of previously developed RMS ignition models [16]. The updated models are developed by calibrating the existing models based on the ignition data from recent earthquakes. Separate ignition curves are used for different sets of occurrence time (summer or winter), occupancy (residential, commercial or industrial) and building material (wood or non-wood). Table 1 compares the number of ignitions obtained from the updated RMS model with the actual number of ignitions in Northridge and Loma Prieta earthquakes [1]. In Table 1, current exposure is used to estimate number of ignitions from RMS and HAZUS models. The higher predictions of the updated RMS curves are due to the new urban developments in Los Angeles since 1994 and in San Francisco Bay Area since 1989.

Table 1 – Comparison the actual number of ignitions in Northridge and Loma Prieta earthquakes with predictions of updated RMS curves and HAZUS model

Number of ignitions	**Northridge 1994**	**Loma Prieta 1989**
Actual	92	59~83
Updated RMS model	103	128
HAZUS	19	92

PGA is obtained for each simulation grid by generating footprints for different magnitude of earthquakes in different metropolitan areas and the rate of fire ignition is calculated by using the updated ignition models. The final ignition in a grid depends on the distribution of occupancy and building material in the grid. Additionally, month of earthquake occurrence is also randomly sampled, from which it is determined if a winter, summer or a combined curve should be used. Having the rate of ignition, probability of starting an ignition in a grid can be computed assuming a Poisson process for spatial distribution of ignitions. Using the spatial probability distribution (probability of ignition per grid) obtained for the whole simulation grids, some fires initiate and start to grow. According to HAZUS 2009 [4], 20% of the ignitions occur within the first hour, about half occur within 6 hours, and the rest by the end of the first day. The same temporal distribution of ignitions is used in the RMS model.

3.2 Spread and suppression models

Since RMS FFEQ simulations are conducted for large metropolitan areas with large number of simulation grids and the analyses are carried out for large number of simulations, physics-based spread models are not appropriate candidates to be used. Physics-based models such as the ones proposed by Lee [7] or Himoto and Tanaka [17], which are very detailed models are not appropriate for large scale high resolution simulations because the computation time is very long and it is very expensive to collect detailed data for all the buildings in a large metropolitan area. Therefore, two less detailed popular spread models, Hamada model [9] and TOSHO model (developed by Tokyo Fire Department) [18] are combined with a logic tree approach and used in the RMS FFEQ simulation tool. Both models are developed based on the data collected in Japan, where building material and occupancy distribution are different from North America building characteristics. Therefore, both models are calibrated with North America historical data [19] before using them in the simulations. The data shows that the TOSHO model underestimates the spread velocity while Hamada model overestimates it. Therefore these model parameters are adjusted to the average of observed historical fire spread velocities in North America.

For each simulation, wind speed and direction as well as humidity (which is an input parameter for the TOSHO model) are sampled from the corresponding distributions based on the sampled month of earthquake occurrence. Once simulation starts, fires start to spread and the status of all active fires is tracked. Time of discovery and report of fires are estimated based of HAZUS recommendations [4]. Time of the arrival of fire engines to active fires depend on the distance between the fire and the assigned fire engine locations. Engine speed is a random variable and it depends on the traffic data of the city and street conditions. Location of all the fire engines are also tracked during the simulations and the assignment of fire engines to active fires is based on a closest distance algorithm, where the closest fire engines to active fires are progressively assigned until there is no more engines available or there is no fire that still needs additional engines. Each simulation is a dynamic process where the status and spatial distribution of all fires as well as the location of all engines are updated at each time step. An elliptical shape is assumed for each spreading fire and the fire progress is tracked at upwind, downwind and two side-wind points. Once any of the four tracking points of fire reach a fire break such as a street, then depending on the width of the fire break, there is a chance that fire cannot cross the fire break and stop at that point. The probability of crossing is calculated using probability functions provided in HAZUS 2009 [4]. Also, if any side of a spreading fire reaches a point that has been already burnt by another fire, the fire progression on that particular side is stopped. If a fire enters a grid in any of its sides, the input parameters for the fire spread model on that side are updated based on the properties of the new grid. If the number of fire engines assigned to a fire is less than the required number of engines to suppress fire completely, the fire still progresses but at a reduced rate as described in HAZUS. Since some of the fire engines may not be able to provide service due to damage to fire stations, the probability that an engine can provide service is adjusted based on the level of PGA. Therefore, depending on the PGA values at fire station locations, some of the engines are removed from the simulation at the first time step. The whole simulation ends once there is no more active fire and no more ignitions are going to start later according to the temporal distribution of ignitions . Once the simulation is completed, burnt areas in the whole metropolitan area are recorded and burnt percentage in each grid is calculated as a function of PGA. FLI values are obtained from smoothed burnt percentage curves at PGA of 0.4g. Fig. 1 shows a flowchart that summarizes the major steps in RMS FFEQ simulations. There are more details in the model that are out of scope of this paper.

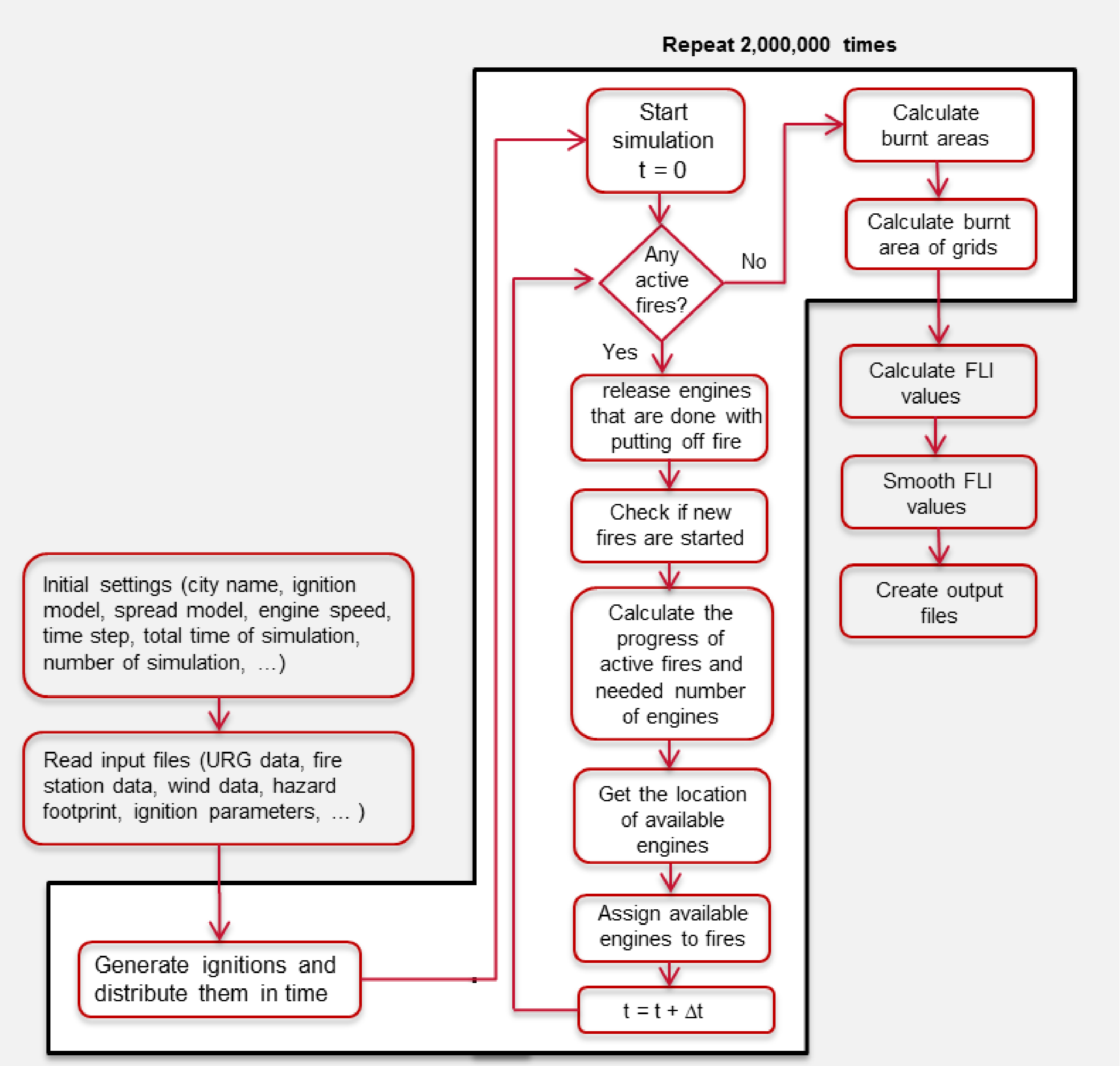

Fig. 1 – Flowchart of main steps in RMS FFEQ simulation

4. Simulation Results and Sensitivity Analysis

Following the simulation methodology described in the previous section, FLI values are obtained for all the grids in metropolitan areas. Fig. 2 shows the distribution of computed FLI values in the San Francisco Bay Area. It can be seen in this figure that areas in the south and north east side of the simulation area, (which correspond to newer developments) have higher FLI values compared to the other areas. In the San Francisco Bay Area new developed areas have higher density of buildings due to the rising price of properties. Also in newly developed parts of the Bay Area, density of fire stations are not as high as older parts. This can be seen clearly in Fig. 3, which shows the distribution of builtupness and fire engines in the Bay Area. Comparing the input parameters shown on maps with the corresponding FLI maps of the simulated areas shows that FLI values are more sensitive to the ratio of ignitions to fire engines, where, in turn, the number of ignitions is very sensitive to builtupness and PGA values. This highlights the importance of PGA footprints used in the simulations. If a PGA footprint with low average PGA is used in the simulations, there is a small chance that the firefighting system of the simulated area is put under stress, but, on the other hand, a PGA footprint with high average PGA can completely collapse the system and lead to large conflagrations. Average PGA in a footprint has a direct relation with the footprint size. This means that the size of the footprint for FFEQ simulations should be selected with care so that the number of times that the firefighting capacity collapses during the simulations is neither overestimated nor underestimated. Fig. 4 shows the sensitivity of the mean FLI value to the average PGA in footprint. Small PGAs (around 0.2g) in Fig. 4 correspond to huge footprint sizes while high PGAs (around 0.6g) correspond to small footprint sizes.

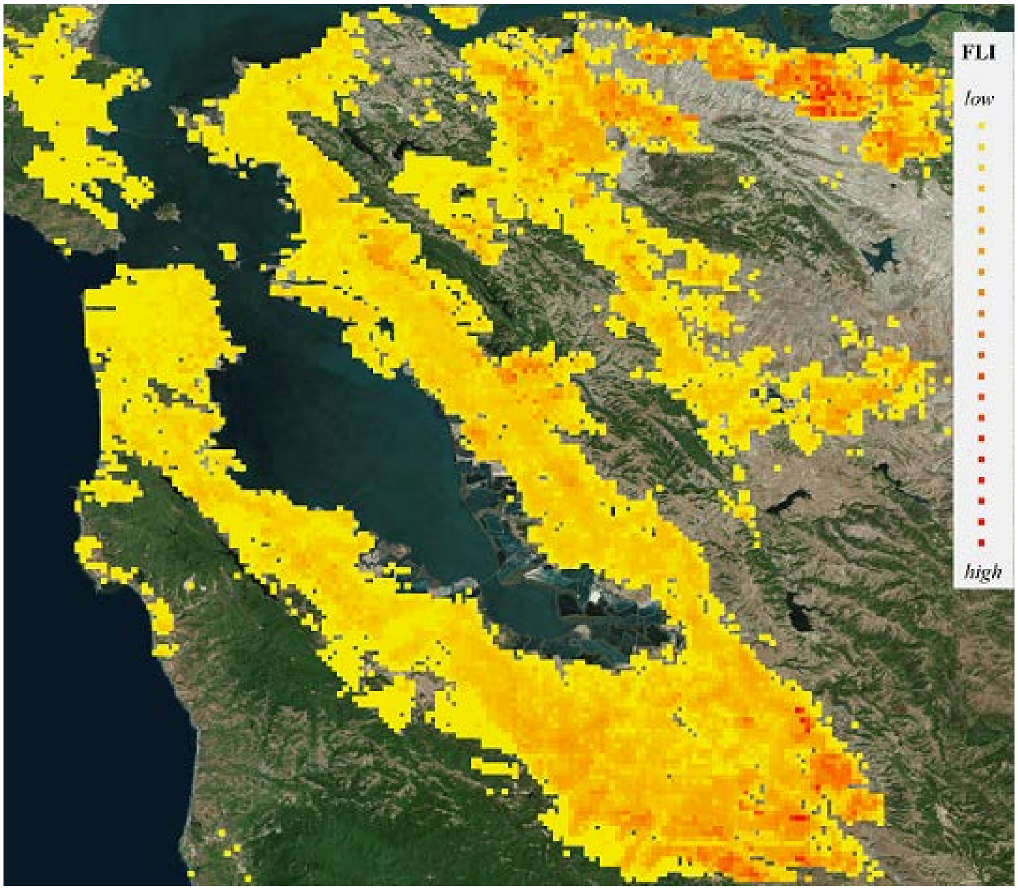

Fig. 2 – FLI distribution in San Francisco Bay Area

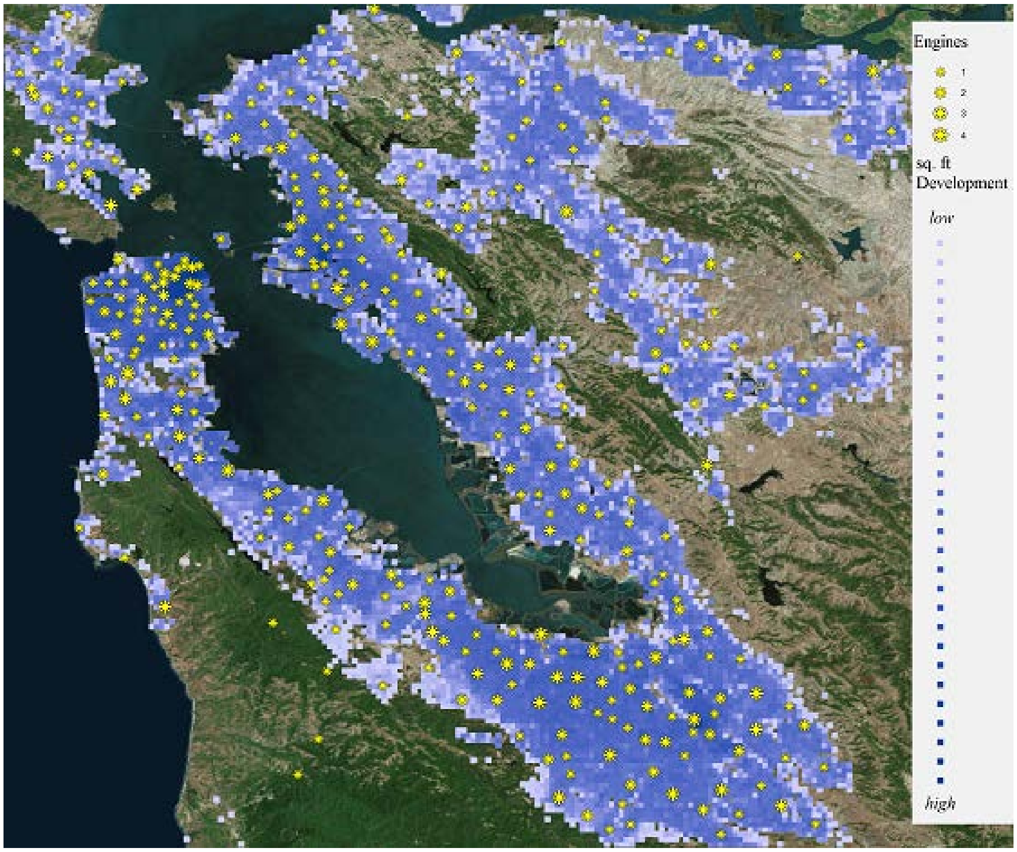

Fig. 3 – Distribution of builtupness and fire stations in San Francisco Bay Area

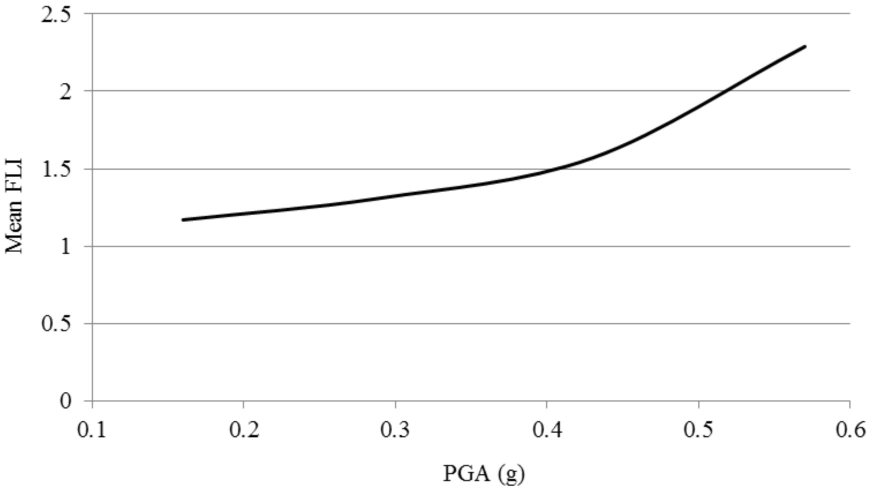

Fig. 4 – Change of FLI value with the mean value of PGA in footprint

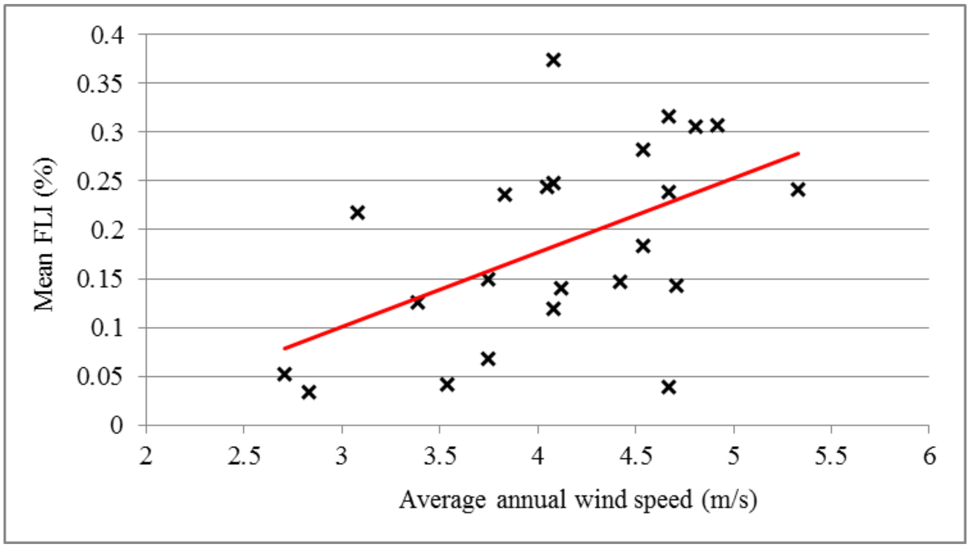

Fig. 5 – Change of FLI values with average annual wind speed.

Fig. 6 – Change of FLI values with percentage of wood construction.

Average annual wind speed and percentage of wood construction in the simulated area are other critical parameters as shown by the sensitivity results reported in Figs. 5 and 6. It's worth noting that there are many other important input parameters as discussed in previous section but the change of the simulated mean FLI values at the scale of large metropolitan areas due to a change in those parameters are less critical than the ones presented in Figs. 3 through 6.

5. Summary and Conclusions

This paper presented an overview of the main steps used in large scale FFEQ simulations for 24 metropolitan areas in North America. Parameters used in ignition, spread and suppression models as well as methodology to implement them in simulations were described. Sensitivity of the obtained FLI values to input parameters were investigated. Among numerous input parameters involved in the problem, FLI values were found to be sensitive to fire engine density, builtupness of the area, average PGA in footprint, average annual wind speed and percentage of wood construction more than any other input parameters. Although there are several models for each phase of FFEQ simulation, there is still a notable layer of uncertainty between reality and available models. Most of this uncertainty is driven by the lack of enough historical data, which inevitably puts more weight on engineering judgement and leads to ongoing discussions in academic and industrial fields on appropriateness of available models and validity of the FFEQ simulation results.

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