A METHOD OF SMOKE DISPERSION MODELLING OF EXHAUSTED TUNNEL FIRE SMOKE IN URBAN AREAS

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Abstract. In many urban areas around the world, underground rapid transit systems are increasingly utilized for daily transportation. These systems are often equipped with tunnel ventilation systems (TVS) used to evacuate smoke away from underground stations in a train fire scenario. This is achieved by pulling fresh air in from station entrances to replace contaminated exhaust air. While typically many CFD studies are performed to optimize smoke ventilation strategy within station and platform areas, it has also become desirable to review the impact of the evacuated smoke in a station fire to the surrounding urban areas, to optimize smoke ventilation shaft design and location. Additionally, by studying the smoke dispersal effects on nearby buildings in an urban area, implementation of proposed solutions can improve the safety protocols for occupants in adjacent buildings thus reducing their exposure risk during a station fire emergency. Since TVS ventilation shafts are usually located adjacent to station entrances, recirculation of smoke can pose a risk in certain wind scenarios. his risk of short-circuiting smoke could result in evacuating passengers encountering the very smoke they are evacuating from. This paper outlines a method for using Fire Dynamics Simulator (FDS) for modelling smoke dispersal analyses (SDA) in urban and suburban areas, setting up wind parameters and determining wind effects on exhausting tunnel smoke from underground ventilation shafts.

1. INTRODUCTION

Light rail transit (LRT) continues to be a major player for transportation for many people around the world. Fire life safety and standards give station designers the requirements to follow during emergency evacuation procedures. Tenability criteria as outlined in code specifications, such as Standard for Fixed Guideway Transit and Passenger Rail Systems (NFPA 130, 2014), allow for engineers to provide solutions to adhering to tenability criteria during emergency evacuation scenarios.

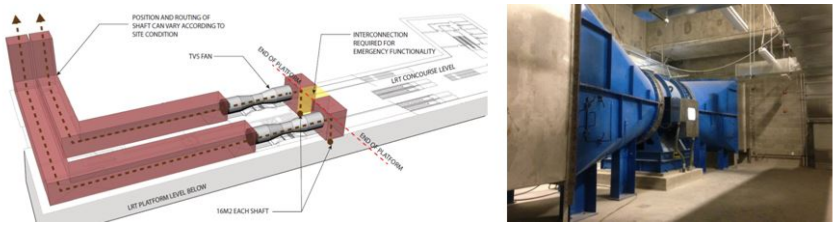

Figure 1. Typical Underground Station Cross Section and typical TVS Fan Room

Tunnel Ventilation Systems (TVS) are used to extract smoke from underground transit systems during emergency scenarios. For modern underground rail transit systems, they are utilized for pulling fresh air in during different operating modes, but more importantly, for emergency scenarios, TVS systems provide tenable conditions for escaping passengers from tunnel fire emergency situations. A typical TVS cross section for an underground station is shown in Figure 1, with a fan and silencer assembly.

While underground station fire analysis using computation fluid dynamics (CFD) has been investigated extensively, recent interest has been given into evaluating the effects of the extracted smoke from the TVS systems, after the smoke has been evacuated to grade level. Smoke discharged from ventilation shafts need to be evaluated so that LRT station entrances air intakes during a station emergency are not drawing in the evacuated smoke from the TVS system, creating a short-circuit of smoke back into the egress routes, affecting the passengers the TVS system was intended to protect. In addition, the smoke discharged from the tunnel ventilation shafts should not adversely affect nearby adjacent buildings and structures. Wind-induced flows of smoke may be harmful to nearby building occupants or pedestrians. Typically, the buoyancy of smoke and the turbulence of wind effects will cause mixing of the smoke with outdoor air and will reduce the concentration of smoke. The level of dilutions will be affected by the wind speed and the complexity of the building surroundings, exhaust velocity and location, and many other parameters.

This paper outlines a method using Fire Dynamics Simulator (FDS) software to perform a Smoke Dispersion Analysis (SDA) in an urban area, where the smoke source is from an underground train fire emergency in an underground LRT system.

2. PHYSICAL MODEL AND BOUNDARY CONDITIONS

Typical underground station fire analyses will analyze a train burning within the station, with the incident smoke being exhausted by the TVS system to grade-level. An SDA is a follow up analysis of smoke, now at street level. A physical model of this study utilizes urban city building data, correlated with Google

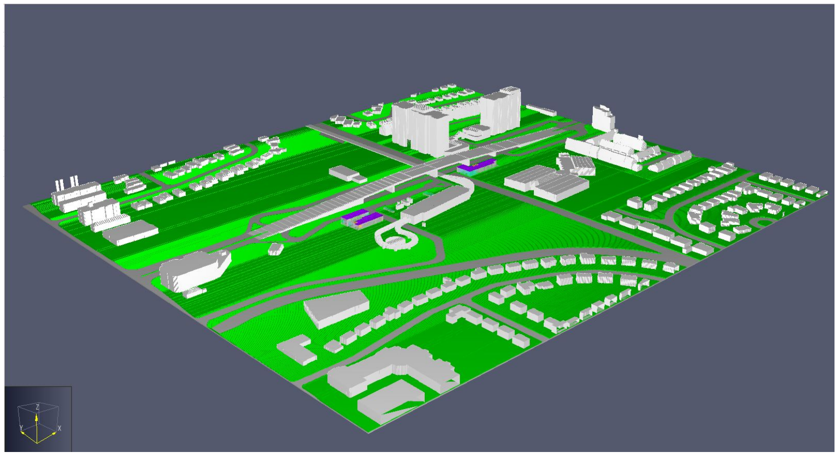

Figure 2. Physical Model of Area of Interest with proposed LRT Entrances added

Maps to construct a model of the scope as outlined in Figure 2 . This model size is in line with realistic computational limits for meshing.
SDA simulations were carried out using FDS version 6. The modeled geometry of the urban areas was then combined with the model geometry of the underground LRT station, with Station entrances. In addition, the smoke ventilation locations are also added into the model. Typically smoke ventilation grills are located at-grade, or integrated into the design of the station entrances. Often it is not feasible to locate the smoke vents well away from Station entrances; thus an SDA should be performed to witness the behavior of smoke in an emergency station scenario. Since often in urban areas, smoke ventilation grills located on the sidewalk where the ejection of smoke combined with a wind means smoke is not normally dissipated away easily, as smoke stacks or relocating the vents high above may not be feasible design options.

3. CONCENTRATION OF PHYSICAL SMOKE AND DISCHARGE TEMPERATURE

In order to cover the most onerous scenario, SDA models will employ the assumption that all of the smoke generated from a single car train fire will be extracted by a pair of TVS fans at one end of the station, and is split equally within the two adjacent vent shafts.

The following section outlines the equations of fuel burning rate of a train fire, leading to the production of the smoke ppm.

3.1. Equations

To calculate the fuel burning rate for the train leading to smoke production, incorporating the real-world conditions of burning efficiency, the following equations are used:

Fuel Burning Rate:

$$\dot{m}_{fuel} = \frac{\dot{Q}_{max}}{\Delta H_c \cdot \chi} \tag{1}$$

Where:

$\dot{m}_{fuel}$ = Mass loss for train burn $\dot{Q}_{max}$ = Peak Burning Rate ΔH_c = Specific Heat of Combustion χ = Burning Efficiency (approximately ~0.75 for trains)

For a given Air/Fuel ratio, the Smoke Production Rate, essentially resultant mass from the smoke generation is defined as:

$$\dot{m}_{smoke} = \dot{m}_{fuel} \cdot (1 + AFR) \tag{2}$$

Rate of Soot Production is then defined:

$$\dot{m}_{soot} = \dot{m}_{fuel} \cdot (Y_s) \tag{3}$$

Where Y_s = species yield, in this case, Soot.

Rate of CO Production is then defined as:

$$\dot{m}_{co} = \dot{m}_{fuel} \cdot (Y_{CO}) \tag{4}$$

Where Y_{CO} = species yield, in this case, Carbon Monoxide.

Concentration of combustion products, leading to the concentration of smoke is derived by:

$$C_{smoke} = \frac{C_{Soot}}{Y_s}(1 + AFR) \tag{5}$$

The discharging smoke temperature was calculated from running a full train fire in a station with a TVS exhausting the smoke to the surface, and measuring the air temperature of the reaction. To reduce effects of the buoyancy driven flow, the coolest discharge temperature was selected to minimize thermal effects of smoke rising in the analysis and ran in conjunction with the warmest ambient temperature of region, according to temperature data. Selecting the underground station with the tallest smoke discharge shafts would yield the most conservative smoke discharge temperature, thus, individual FDS runs were performed for various TVS fan discharge heights with concrete TVS discharge shafts, with an example shown in Figure 3

4. WIND PARAMETERS

To seek guidance for wind parameters, NFPA Standard 92 references a selection of 1% wind probability to be used in smoke system design. A 1% Wind results to 88 hours in a calendar year, which correlates to the most onerous scenario. The wind profile can be determined from climate data for major cities. For example, the wind profile for the city of Toronto, Canada, can be found in Figure 4 below. ASHRAE Fundamentals Handbook in Chapter 24 describes a method to convert wind speeds measured from Airport measurement tools into wind

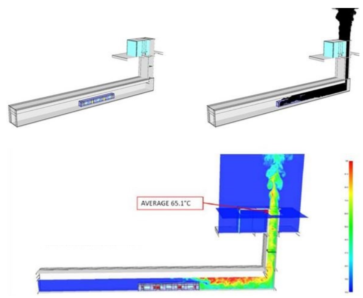

Figure 3. Modelling of Smoke Discharge Temperatures relative to shaft height

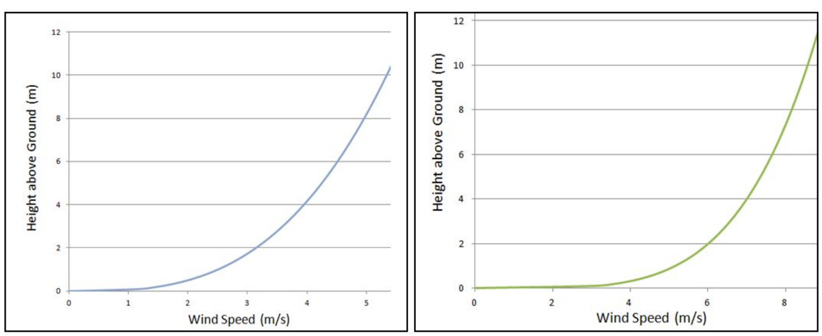

Figure 4. City of Toronto Urban (left) and Suburban (right) Wind Profiles

profiles suitable for urban and suburban areas, which then can be used for the the area of interest in the SDA.

$$U_H = U_{met} \left(\frac{\delta_{met}}{H_{met}} \right)^{a_{met}} \left(\frac{H}{\delta} \right)^{a} \tag{6}$$

where:

U_{met} = airport wind speed (m/s)

δ_{met} = boundary layer thickness at the measurement from the airport [typically 275m (900 ft)]

a_{met} = boundary Layer Power Law Exponent (Typically 0.14)

H_{met} = anemometer height [typically 10m (33ft)]

H = building height (m)

a = boundary layer power law exponent at the site (typically suburban = 0.22, urban = 0.33)

δ = boundary layer thickness at site [typically 365m (1200ft) suburban, 460m (1500ft) urban].

For simplicity, the SDA runs will be aligned with major streets, taking advantage of the Wind Canyon effect, with wind direction running North, South, East, West. Additional wind directions could be simulated, however, due to the rectilinear meshing elements of FDS, full rotation of models would be required to run different wind directions. The total run time should consist of the wind fully leaving the domain, as once the flow stabilizes, the smoke spread could be assessed.

There is always much discussion over the turbulence models and their suitability for any given CFD simulation. FDS utilizes Large Eddy Simulation (LES) with the default turbulent viscosity using the Deardorff model, although different turbulence models have been used with varying degrees of success. RANS and LES have been the subject of several previous studies, with LES showing some good agreement with validation testing in simple street canyon models. (Tominaga 2010).

5. MESH AND DOMAIN BOUNDARY CONDITIONS

Meshing around station areas and smoke vents utilize a mesh cell size of 0.4m, and for sky regions, are up to 1.6m. Computational limits dictate the amount of mesh elements that can be solved in a reasonable time. If more powerful computing resources are available, decreases in mesh elements sizing could be accommodated. Wind domain parameters are important to consider in order to characterize the flow through the domain in a representative manner. Relative to the tallest building the domain, the size of the ceiling domain should be carefully considered. The domain sides running parallel to the wind flow direction is preferred to be modeled as mirror vent, to minimize any momentum dissipation out of the domain. With the top of the sky domain ceiling modelled as a free-slip boundary condition, this will allow the wind profile to be preserved and correctly represented at domain ceiling.

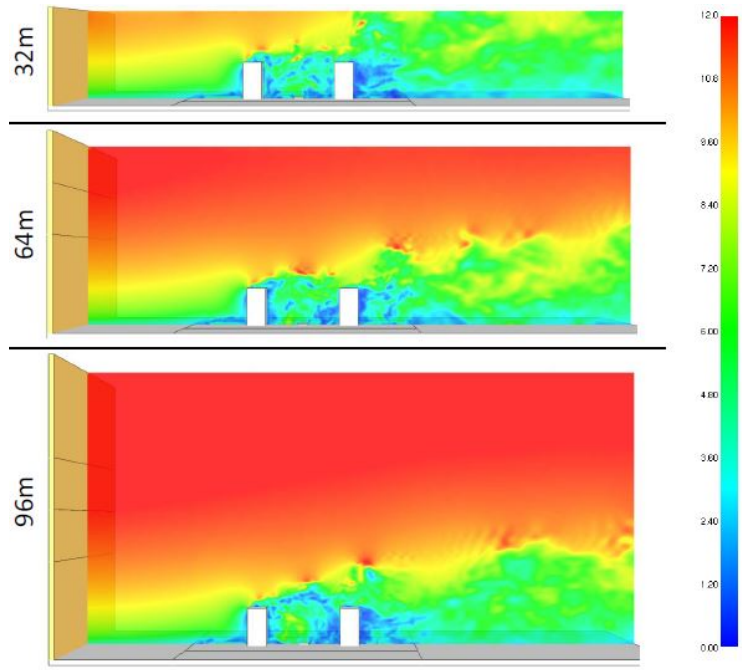

Figure 5. Wind Domain Heights

Performing a sensitivity analysis for the building to determine minimum domain height can lead to a better selection for the minimum domain ceiling height. In Figure 5 below, a minimum domain height of 100m was selected after some sensitivity analyses.
As a general rule, extension of the domain is suggested to be at least 5H, where H is the height of the tallest building in the analysis. Longitudinally of both the area in front and behind the domain is recommended to be at least 5H and 15H, respectively, with the latter being larger to allow for flow re-development behind the wake region. (Franke 2007)

Boundary layer effects related to radiative heating, soil moisture content, evaporation and energy balance are not yet considered in the smoke dispersion analysis as these variables can be difficult to determine in urban areas.

6. AIR INTAKES FROM STATION ENTRANCES AND ADJACENT BUILDINGS

During a station emergency when the TVS systems are active, makeup air is pulled into the station entrances from the outside atmosphere. While the overall station intake airflow could be determined through other well-developed software such as Subway Environmental Software (SES), data gathered from previous underground station runs using FDS can also be utilized. From the collected

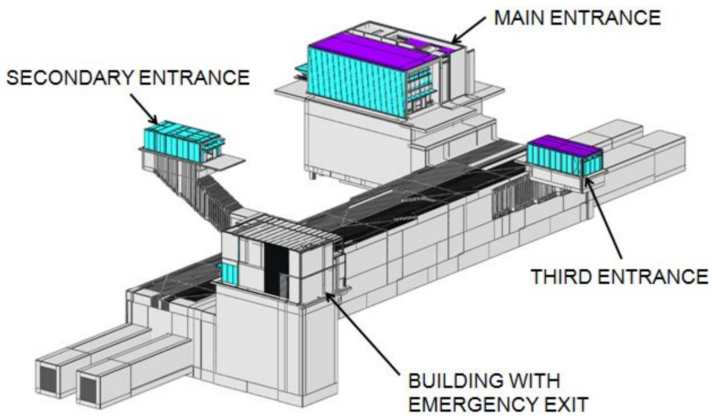

Figure 6. Typical Station Layout and applying airflows at entrances

data, airflows for the doors and air intake louvers is applied to the setup for the SDA analysis, with examples locations identified in Figure 6. The flows through doors and station air intake louvers are applied along with the measurement devices in the software. These measurement devices will then used to determine contamination levels of the areas of interest.

If computer hardware capability allows, then both the underground and above ground runs could be combined, although the resulting domain size and mesh size would require significant computing resources. Due to the very large nature of this type of analyses (could be over 40 million mesh elements), breaking up the analysis in a separate underground and above ground version is recommended.

For a typical SDA analysis, smoke concentrations and CO concentrations are of interest, as they align with NFPA 130 visibility requirements, and ASHRAE 62.1 requirements of Carbon Monoxide limits. Thus, in SDA analyses, appropriate Carbon Monoxide and Soot measurement devices are required to monitor these levels, as any re-entrained smoke from the winds from an particular direction can cause the smoke to migrate to the entrances of the station.

7. RESULTS ANALYSIS AND MITIGATION MEASURES

For analyses of the acceptability of a particular station design for above ground SDA analyses, a variety of tools can be used.

Measuring PPM of smoke or CO intake at the station entrances is one way to analyze the effect of the discharged smoke onto a station entrance, as shown in in Figure 7. Using iso-surfaces is also another powerful way to visualize the migration of zones of CO that are exceedance of the determined criteria. The limit of CO can be set as strict as required, and exceedance areas can be visualized clearly through these iso-surfaces such as in Figure 8.

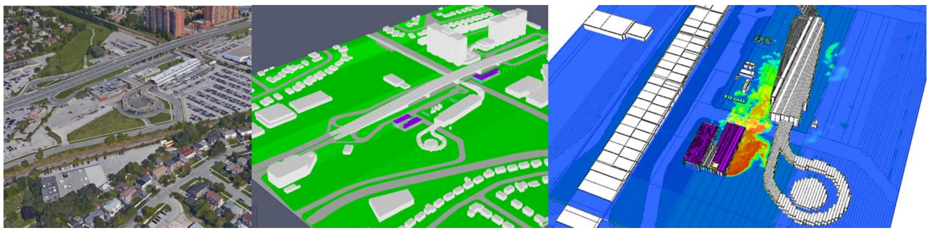

Figure 7. Analysing contamination levels at entrances

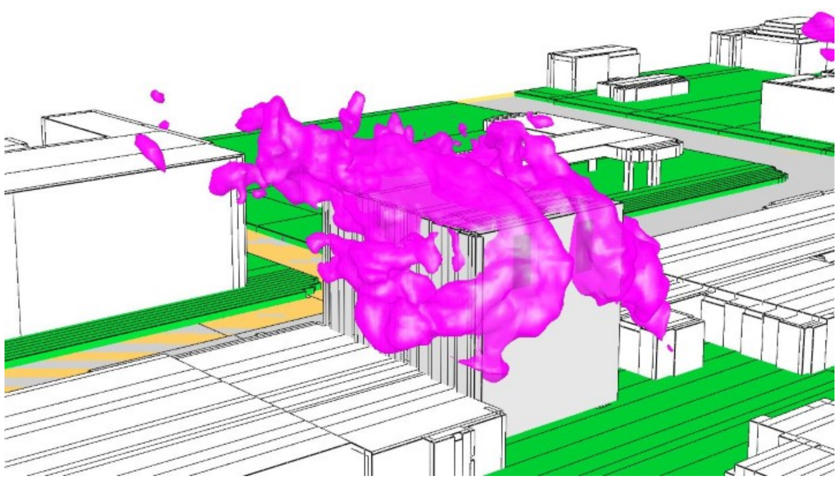

Figure 8. Visualizing Carbon Monoxide exceedance regions with IsoSurfaces

Finally, placing a 2.0m visibility slice above-grade can allow for contamination information for evacuating passengers and evaluating their visibility at head level.

For situations where criteria is exceeded beyond the recommendations of NFPA 130 and ASHRAE, mitigation measures can be recommended, such as relocated the smoke discharge vents to a higher elevation, or ducting the vents to a different location to be discharged. For example, for analyses that show station entrances engulfed in smoke, a repositioning of the smoke discharge vents would be required, or if a particular air intake louver is affected, the affected damper could be closed during an emergency. SDAs can be very helpful to determine the design recommendations needed for station designs to achieve the acceptance criteria.

8. CONCLUSIONS AND FUTURE WORK

Modelling of smoke dispersion analyses continues to be an area of interest as the LRT transit areas usually serve highly populated urban areas congested with buildings. Due to the difficulty in validating large scale wind flows in FDS, as well as limited computing resources restricting domain size, more work is required in looking at the best practices in doing large-scale outdoor wind modelling within FDS along with model optimization. The vast number of variables that can affect smoke dispersion may be difficult to completely encompass. SDAs can be helpful to be used as generic design tool to ensure smoke discharge vents are optimized in terms of placement. Further research alongside full size wind validation of atmospheric flows is required to further these studies to the next level.

9. ACKNOWLEDGMENTS

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