PROCEEDINGS, Fire and Evacuation Modeling Technical Conference (FEMTC) 2014
Gaithersburg, Maryland, September 8-10, 2014

MODELING OF CARBON MONOXIDE DISPERSION FROM VEHICLE EXHAUST IN A PARTIALLY ENCLOSED ROADWAY USING FDS

Haavard R. Boehmer., Jason E. Floyd, Michael J. Ferreira

Hughes Associates, Inc
3610 Commerce Dr, Suite 817
Baltimore, MD, 21227, USA
e-mail: hboehmer@haifire.com

ABSTRACT

The design for a partially enclosed roadway raised concerns regarding the potential for development of hazardous carbon monoxide (CO) concentrations. The proposed roadway section is covered by buildings on three sides with one side open to a river. There were concerns that wind conditions may cause vehicle exhaust to become trapped in the roadway during stalled traffic conditions.

The interaction of wind with the roadway and the local cityscape creates a complex system. The potential for wind conditions that may confine CO to the roadway is difficult to accurately analyze solely based on engineering experience or using simple engineering correlations. Instead, Fire Dynamics Simulator (FDS) version 5.5 was used to model the dispersion of the vehicle exhaust. An FDS model was created that encompassed several hundred meters around the enclosed portion of the roadway up to a height of 80 m. The height was selected to capture the tallest buildings in the domain. Tall buildings surrounding the roadway were included in the model to approximate the wind conditions that would develop as closely as possible within the computational restrictions.

Dispersion of CO from stalled vehicles was modeled under a range of different wind scenarios selected based on a previous pedestrian wind study. Wind speed and direction were varied. Assumptions were made regarding the CO production of each vehicle, exhaust temperature and the density of vehicles in the tunnel.

Based on the FDS model results it was found that the critical limit for 15-minute average CO concentration of 120 ppm was never exceeded at any point. This analysis showed that the natural ventilation of the partially enclosed roadway was sufficient and no additional mechanical exhaust systems were required.

BACKGROUND

A partially enclosed roadway is being built along a river in a major metropolitan area. The roadway is enclosed along one wall and the ceiling but open on the side facing the river. Prevailing wind conditions are into the open face of the roadway for both the summer and winter months. This may prevent vehicle exhaust from escaping and serve to push it back into the partially enclosed roadway.

The Federal Highway Administration (FHWA) and the Environmental Protection Agency (EPA) have established maximum levels for CO concentrations that shall not be exceeded over given timeframes. Given the design of the roadway and the prevailing winds, local authorities raised concerns that during peak traffic conditions vehicle exhaust could accumulate and exceed FHA and EPA maximum levels. If this were to occur, then a mechanical exhaust system would have to be incorporated into the design for the partially enclosed roadway section.

An analysis was performed to determine whether additional exhaust systems were required for the partially enclosed roadway to maintain safe CO levels, and if so determine the minimum required exhaust flow rate. The potential temperature and wind conditions that may confine CO to the roadway creates a complex system that is difficult to accurately analyze solely based on engineering experience with existing, similar structures or by using simple engineering correlations. To evaluate the CO concentrations in the partially covered roadway the Computational Fluid Dynamics (CFD) model Fire Dynamics Simulator (FDS) was used. Simulations were performed to model the air flow in and around the roadway to evaluate how the CO emission from the cars would migrate under different wind conditions and whether the critical limits are exceeded under any scenario.

ROADWAY AND SURROUNDING BUILDINGS

The proposed design of several new structures in a dense urban area will extend over a section of an existing six-lane roadway. The affected roadway section is approximately 930 ft (283 m) long and would be covered by buildings on three sides and open to the river on one side. Two large office-tower type buildings are located at either end of the roadway section. Under the north building the roadway is fully covered, creating a 770 ft (235 m) long tunnel. The south end of the tunnel enters directly into the partially enclosed section, which ends after the second building at the south end. Between the two buildings atop the roadway is a pedestrian park and lower height buildings. The next obstruction to the east across the river is over 800 ft (244 m) away. A 3D rendering of the proposed design of the partially enclosed roadway and surrounding buildings is shown in Figure 1.

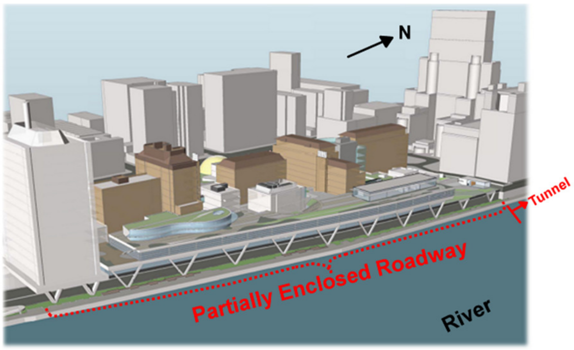

Figure 1 – Rendering Showing the Proposed Design of the Partially Enclosed Roadway and Surrounding Buildings

Between the partially enclosed roadway and the river is an open pedestrian walkway. The distance from the edge of the river and the east-most traffic lane is approximately 26 ft (8 m). The pedestrian walkway and the traffic lane is separated by an 8 ft (2.4 m) high, solid acoustic barrier, which is not shown in the renders above. This wall will serve to contain much of the car exhaust within the partial enclosure, further exacerbating adverse conditions as well as blocking some of the wind blowing from the river. The ceiling of the partial enclosure is 15 ft (5 m) above the height of the roadway. The opening between the acoustic wall and the ceiling is 8.2 ft (2.5 m) and the geometry is shown in Figure 2.

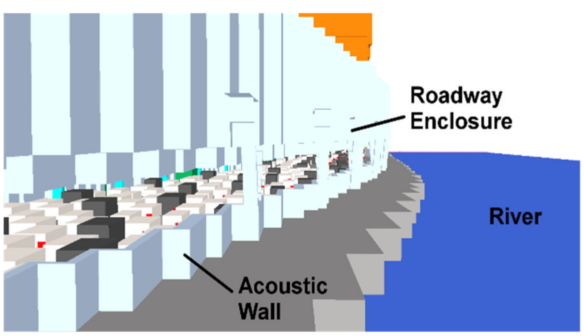

Figure 2 – Smokeview Rendering of FDS Geometry Model Showing the Roadway Enclosure and the Acoustic Wall

The roadway allows traffic in both directions, with three lanes for northbound and three lanes for southbound traffic. The roadway is heavily used, and during stalled traffic conditions caused by congestion, accidents or other road closures there is potential for a larger number of slow moving or idling vehicles on the roadway.

The north section of the roadway is fully enclosed and considered a tunnel so is provided with six exhaust vents placed at the tunnel ceiling, each capable of extracting 90,000 cfm (42.5 m^3/s). It was reported that the exhaust system is currently operating at a lower rate of 50,000 cfm (23.6 m^3/s) per vent, which was modeled in FDS.

CARBON MONOXIDE LIMITS

The CO concentration on the partially covered roadway was evaluated against tenability criteria established by the FHWA and the EPA. Several different exposure criteria exists based on the timeframe of exposure (for example 4 hours, 8 hours etc.). The FHWA/EPA criteria allows a maximum 15 minute average CO exposure of 120 parts per million (ppm) in tunnels. Even going at 1 mph a car would pass through the partially enclosed roadway section in less than 15 minutes. It was therefore determined that as a conservative assumption the tunnel criteria would be used and the CO concentration limit in the partially enclosed roadway was set to the 15-minute average maximum of 120 ppm.

In the FDS model the CO concentration in parts per million was evaluated as a 2D slice time-averaged over 15 minutes at different levels above the roadway with focus on concentrations encountered by passengers in vehicles; assumed to be between 3.3 ft (1 m) and 5 ft (1.5 m) above the roadway.

FDS MODEL SETUP

Version 5.5.3, SVN Revision 7031 of the FDS model was used for the analysis. The FDS model is a large eddy simulation model and is appropriate for use in evaluating conditions created by turbulent flows [McGrattan, Rehm, Baum, 1984, McGrattan et.al. 1999, Zhang, et.al. 2001]. Because FDS is designed primarily as a fire model, FDS is capable of modeling the dispersion of the small individual buoyant plumes for each auto exhaust input into the model [McGrattan et.al. 2010a].

Model Domain

To allow realistic airflow to develop, the wind field must be modeled out to some distance away from the area of interest [McGrattan et.al, 2010a, McGrattan et.al, 2010b]. The FDS model included a large area upstream of the wind direction to allow the wind to stabilize and develop vortices from adjacent buildings that will affect the flow field in the vicinity of the partially enclosed roadway. Downstream from the roadway this distance can be shorter, as it is only necessary to allow the wind to dissipate without affecting the flow upstream in an unrealistic manner. The extent of the area included in FDS model domain therefore varied based on which wind direction was being modeled.

To reduce the number of cells in the FDS model, and the computational time required, progressively coarser grids where used for the areas further from the partially enclosed roadway, as the level of detail required to establish the wind flow field decreases further away from the building. In the partially enclosed roadway a grid resolution of 20 in. (0.50 m) was used, and increased out to a cell size of 177 in (4.5 m) at the furthest locations. This yielded a total of just over 4 million cells.

As all objects must conform to the rectilinear grid, the resolution of the buildings also decreases. Buildings closer to the roadway include smaller architectural details, as these can have a greater effect on the flow in the roadway as compared to similar objects a greater distance away.
The FDS model of the partially enclosed roadway and the surrounding area are shown in Figure 3and Figure 4. A close up view of the covered roadway is shown in Figure 5.

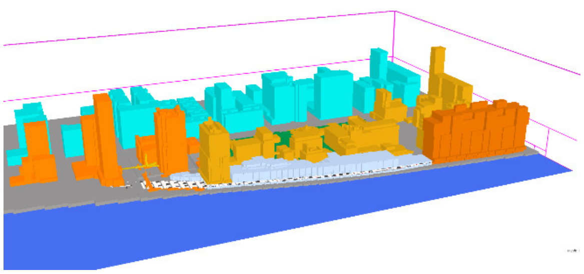

Figure 3 – Overview of the FDS Model of the Partially Enclosed Roadway and Surrounding Buildings Viewed from the East

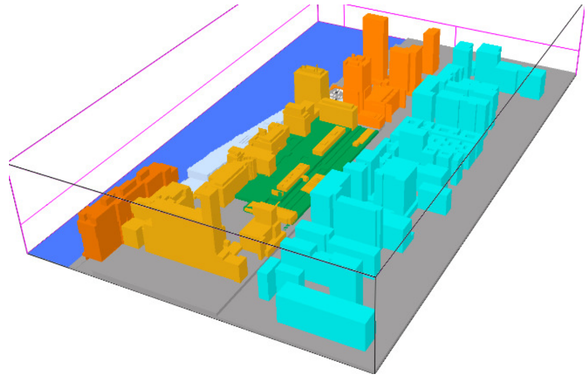

Figure 4 - Overview of the FDS Model of the Partially Enclosed Roadway and Surrounding Buildings Viewed from the North

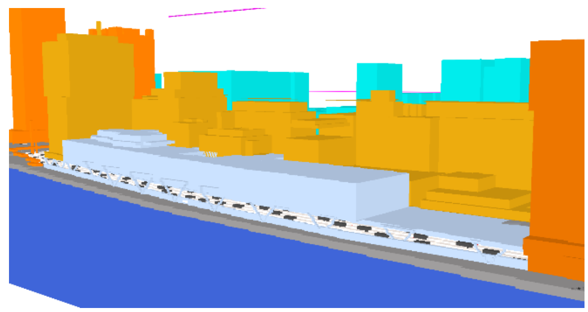

Figure 5 – Close Up View of the Partially Enclosed Roadway as Seen in the FDS Model. White and Black Boxes Represent the Cars

<u>Vehicle Carbon Monoxide Sources</u>

Carbon monoxide emissions from the cars driving on the partially enclosed roadway section were prescribed in the input to the FDS model. The most important assumptions that must be made are the number of cars, the emission from each car and the temperature of the exhaust. The section of roadway included in the analysis is limited to light duty vehicles, so emissions from heavy-duty vehicles and diesel trucks are not a concern. The cars were modeled in FDS as square boxes, approximating as closely as possible the size of popular sedans and SUVs. The exhaust was released in the back corner of the vehicles, at the approximate location of a typical tailpipe.

Worst-case assumptions about the vehicle emissions were based on an EPA emission factor used for environmental engineering calculations for the project. This yielded a total CO emission of 46.9 g/hour from each vehicle based on traffic conditions that were assumed to be stalled traffic in both directions with a 17 ft (5.2 m) spacing between the cars (front bumper to front bumper), or 24.3 g/mile/s for all six lanes. This represents a worst case scenario from an emissions standpoint, where the cars are idling, releasing more CO than they would while moving.

As a simplification, it was assumed that the tailpipe exhaust from the vehicles only consisted of air and CO. Idle fuel consumption of passenger vehicles is reported to be about 1.9 L (0.5 gallon) of gasoline per hour [EPA]. Assuming a gasoline density of 0.75 kg/L [Chevron] and a stoichiometric fuel-to-air ratio of 14.7, the total air consumed and exhausted per second $\dot{m}_{air} = 5.796$ g/s. Converting the CO emission rate above, gives a mass flow rate of CO, $\dot{m}_{CO} = 0.013$ g/s from each vehicle. In the FDS model the tailpipe exhaust for each vehicle was prescribed as consisting of two components:

$$\dot{m}_{total} = \dot{m}_{air} + \dot{m}_{CO} = 5.81\ g/s \qquad \text{Eq. 1}$$

and;

$$\dot{m}_{total} = \chi_{CO}\dot{m}_{total} + \chi_{air}\dot{m}_{total} \qquad \text{Eq. 2}$$

Where χ_{CO} and χ_{air} are the mass fractions of CO and air respectively. The FDS model automatically accounts for the different physical parameters such as density, specific heat etc. for air and CO when modeling the flow dispersion.

Critical to the dispersion is the buoyancy of the vehicle exhaust, which will be governed by the temperature of the gas as it exits the exhaust pipe. This can vary by the type and size of the vehicles, as well as model year and other factors. Exact data was difficult to obtain, but based on an older study, the air and CO mixture being exhausted from the cars in FDS was assumed to be at a temperature of 500 °F (260 °C) [Harrison, 1977].

<u>Wind</u>

A pedestrian wind study of the proposed building and surrounding area was conducted by a wind consultant. As part of the study the prevailing wind climate at the site throughout the year was identified. The wind data gathered for the study are shown in Figure 6. This data represents a blend of wind data from several surrounding weather stations.

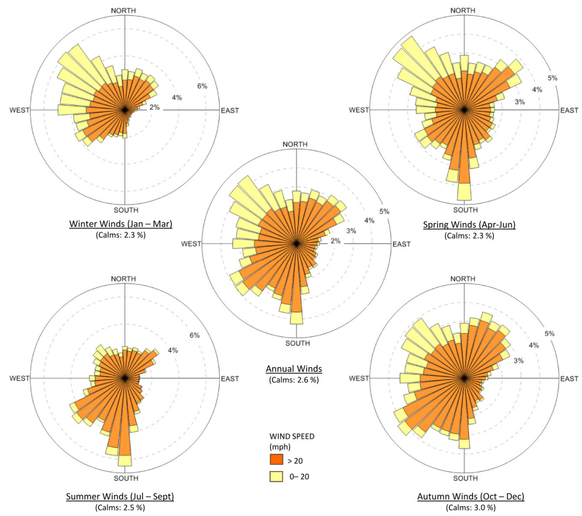

Figure 6 – Seasonal Wind Data for Blended Data of Surrounding Locations

Based on this data a series of different wind directions and ambient temperatures were selected to be included in the FDS model to identify the potential worst-case scenarios with respect to build-up of CO on the partially enclosed roadway. Preliminary runs were simulated in FDS with wind from a number of directions:

- Calm/No wind
- North-West
- North-East
- South
- East
- South-West

Analyzing the results from the preliminary scoping runs it was found that winds from the east and from the south resulted in the worst-case CO conditions and these were selected for further model iterations. The North-East and South-West wind directions were also included in these FDS simulations for further evaluation and for comparison to the worst case scenarios. Winds velocities of 2.2 mph (1.0 m/s), 11 mph (5.0 m/s) and 22 mph (10 m/s) were evaluated based on historic weather data for the area but only resulted in minor differences in results. In all cases the slower wind resulted in worse case CO conditions so the 2.2 mph (1.0 m/s) and 11 mph (5 m/s) wind velocities were included in the reported results. In comparison to the simulations evaluating the various wind conditions, the calm (no wind) case showed the lowest CO concentrations on the roadway. An atmospheric velocity profile was invoked in FDS, with a wind velocity measurement height, Z0, of 10 meters.

The wind field and the interaction with the buildings around the partially enclosed roadway can be seen in Figure 7 and Figure 8, which show the wind velocity at approximately 40 ft above ground level in the model scenario with wind from the east (bottom and right in the figures respectively). The vector field is denser in the center due to the finer numerical grid around the partially enclosed roadway.

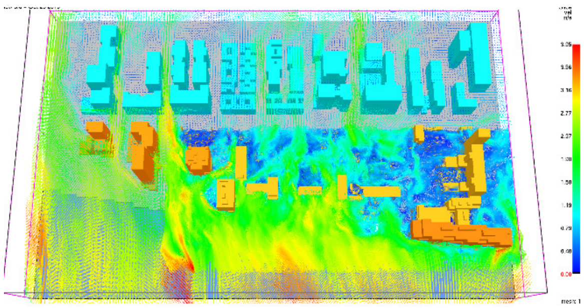

Figure 7 – Wind Velocity at 40 ft above the Ground with Wind from the East

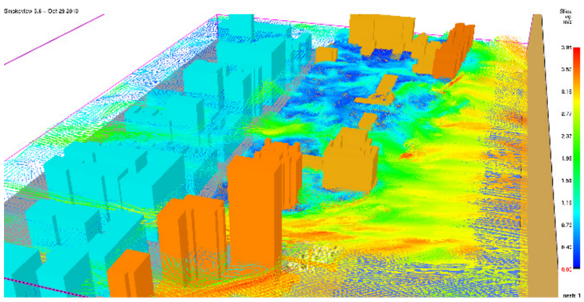

Figure 8 - Wind Velocity at 40 ft above the Ground with Wind from the East

RESULTS

The FDS results evaluated for this analysis were focused on the 15-min averaged CO concentration in parts per million visualized as 2D slices at prescribed heights above the roadway. The results are presented as a colored scale from 0-120 ppm or 0-40 ppm, where blue represents the lowest concentrations and solid red represent a CO concentration exceeding the upper bound of the scale. While only the 120 ppm limit needed to be evaluated, graphics showing the 0-40 ppm scale are provided for better graphical illustration of the CO dispersion pattern in the roadway.

The preliminary runs showed that the highest CO concentrations developed for summer ambient temperatures and a wind speed of 1 m/s. For the no wind conditions, CO migrates out of the enclosed roadway and concentrations are relatively low. For the higher 5 m/s and 10 m/s wind speeds evaluated, the wind acts to flush CO from the roadway out the open side of the roadway. For the 1 m/s wind speed, wind from certain directions can help confine CO to the roadway, although adequate venting appears to occur.

The different parameters in the FDS model scenarios used for the final analysis are shown in Table 1. Approximate maximum 15-min average CO concentrations seen over a significant area (e.g. larger than a few cells) are also shown in the table for each simulation.

As the table shows, none of the scenarios resulted in CO concentration exceeding the tenable limit of 120 ppm over 15 min. Neither did any scenario exceed 50 ppm. The resulting CO concentrations at 5 ft (1.5 m) above the roadway are shown for select wind scenarios in the figures below. The CO figures show concentrations averaged over 15 minutes, after the flow stabilized. In all cases the steady state conditions occur shortly after the wind field has been established. As both the vehicle exhaust and wind velocity are constant inputs in the FDS model the resulting CO concentrations will not change once steady state have been established, except for small, local random fluctuations

Table 1 – Summary of FDS Simulation Results

Scenario	Wind Direction	Wind Speed	Ambient Temperature	15-min Max CO
1	North-East	5 m/s	29° C	24 ppm
2		1 m/s		48 ppm
3	South	5 m/s	29° C	26 ppm
4		1 m/s		33 ppm
5	East	5 m/s	29° C	41 ppm
6		1 m/s		30 ppm
7	South-West	5 m/s	29° C	33 ppm
8		1 m/s		32 ppm
9	Calm	-	29° C	27 ppm

The slice results from FDS were used to visualize the flow of wind into the tunnel, which would serve to both push vehicle exhaust out, or trap in inside the enclosure. An example of the vector field showing the air velocity at 5 ft (1.5 m) above the roadway is shown in Figure 9.

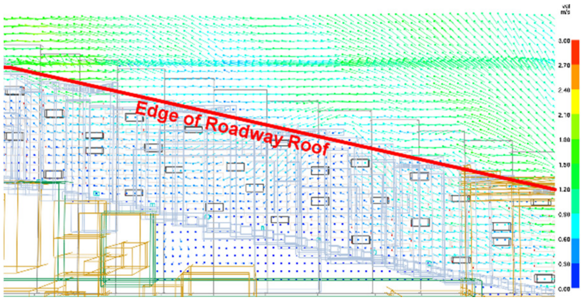

Figure 9 – Air Velocity above the Roadway

When the wind came from the east or the north-east the velocity vectors in FDS showed that the acoustic wall block the lower half of the opening, causing one-directional flow into the enclosure. Without the acoustic wall bi-directional flow developed at the opening which would serve to push vehicle exhaust out of the enclosure. The wind flow into the opening is shown in Figure 10 with wind from the north-east.

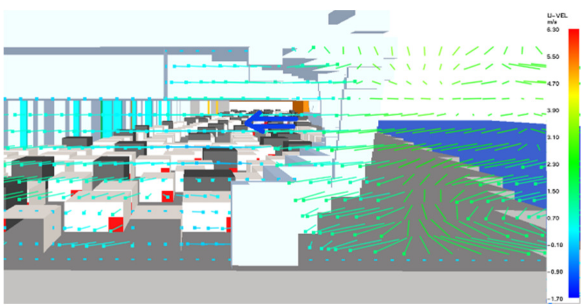

Figure 10 – Vertical Slice of Velocity Vectors at Opening

The highest concentrations were seen in the scenarios where the wind is blowing from the north-west. The wind came in through the open side and pushed the exhaust south along the roadway and out the south end. The acoustic wall prevented any significant flow of vehicle exhaust out the side of the partially enclosed roadway. The maximum, 15-minute average CO concentrations is shown in Figure 11 and Figure 12 with the surrounding buildings overlaid. The two figures show results for 11 mph (5.0 m/s) and 2.2 mph (1.0 m/s), wind speed respectively. The scale is set to a maximum of 40 ppm to better show the gas dispersion throughout the domain.

The figures show a marked difference in the dispersion of CO depending on the wind velocity. The higher 11 mph (5.0 m/s) wind causes the vehicle exhaust to migrate southward, with only some increase in concentrations near the center of the roadway section. With a lower wind velocity of 2.2 mph (1.0 m/s) the vehicle exhaust is forced southward but not as strongly, resulting in increased concentrations along the wall in the south half. A significant amount of vehicle exhaust is also pushed north and trapped there as shown by the red area, which indicate higher concentration of CO.

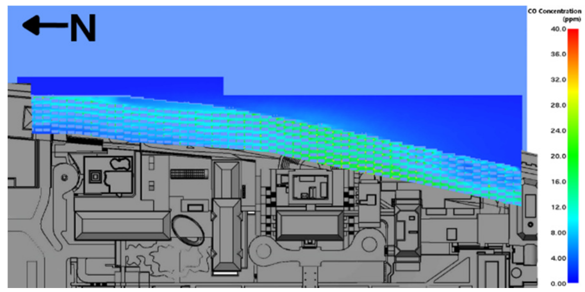

Figure 11 - CO Concentrations (40 ppm scale) at 5 ft Above Roadway Floor with Wind from North-East at 11 mph (5.0 m/s)

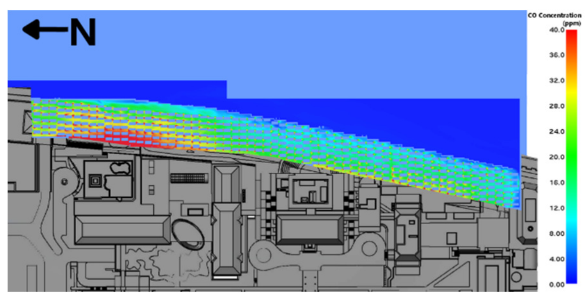

Figure 12 - CO Concentrations (40 ppm scale) at 5 ft Above Roadway Floor with Wind from North-East at 2.2 mph (1.0 m/s)

CONCLUSIONS

As part of a large commercial construction project concerns were raised regarding the potential for development of hazardous CO concentrations under a partially enclosed roadway. The proposed roadway section is covered by buildings on three sides with one side open to a river. There were concerns that wind conditions may cause vehicle exhaust to become trapped in the roadway during stalled traffic conditions. The FHWA and the EPA have established maximum levels for CO concentrations that shall not be exceeded over given timeframes.

The complex interaction of wind with the roadway and the local cityscape was analyzed through a serious of simulations performed with the Fire Dynamics Simulator. A large section of the surrounding area was modeled and different temperature and wind scenarios could be analyzed to determine the worst-case environmental conditions. The release of vehicle exhaust during worst-case stalled traffic conditions was prescribed and the FDS model was able to accurately model the resulting dispersion of CO throughout the roadway and the influence of wind conditions and different ambient temperatures.

Based on the FDS model results it was found that the critical limit for 15-minute average CO concentration of 120 ppm was never exceeded at any point. This analysis showed that the natural ventilation effects of the partially enclosed roadway was sufficient and no additional mechanical system were required.

REFERENCES

Chevron Corporation (2013), “Material Safety Data Sheet; Chevron and Texaco premium unleaded gasolines”.

Drysdale, D., (1998), “An Introduction to Fire Dynamics”, John Wiley & Sons Ltd.

EPA (2013) – “Driving More Efficiently”. Retrieved on 07/03/2013.

Harrison, Robin, T. (1977). “Catalytic Converter Exhaust System Temperature Tests”. Forest service, U.S. Department of Agriculture. San Dimas, California.

McGrattan, K. B., Baum, H. R., Rehm, R. G., Hamins, A., Forney, G. P., and Mell, W. (1999), *Industrial Fire Simulation*, National Institute of Standards and Technology, Gaithersburg, MD.

McGrattan, K., McDermott, R., Hostikka, S., Floyd, J. (2010a) "Fire Dynamics Simulator (Version 5) User`s Guide". NIST SP 1019-5, SVN Repository Revision 6997. National Institute of Standards and Technology, Gaithersburg, MD.

McGrattan, K., Hostikka, S., Floyd, J., Baum, H., Rehm, R., Mell, W. McDermott, R. (2010b) "Fire Dynamics Simulator (Version 5) Technical Reference Guide". NIST SP 1018-5, SVN Repository Revision 3125. National Institute of Standards and Technology, Gaithersburg, MD.

McGrattan, K.B., Rehm, R.G., and Baum, H.R. (1984) “Fire Driven Flows in Enclosures,” *Journal of Computational Physics*, **110**, 285-291.

Zhang, W., Hamer, A., Klassen, M., Carpenter, D., and Richard, J.R. (2001), “Verification of the Turbulence Statistics for Fire Dynamic Simulator in a Room Fire Model,” *Proceedings of the Third Technical Symposium on Computer Applications in Fire Protection Engineering*, Society of Fire Protection Engineers, Baltimore, MD, September 12-13.