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Development of an Air Dispersion Model to Study Near-Road Exposure

This month, *YP Perspective* showcases innovative research being conducted by young professionals (YPs). The research described below fits nicely with this month's focus topic on near-road emissions monitoring.

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Many epidemiological studies show that short- and long-term exposure to vehicle-related pollutants increases the risk of respiratory, as well as cardiovascular, diseases and can exaggerate the medical conditions of individuals with asthma and emphysema.[1] A statistical analysis by Edwards et al.[2] revealed that children diagnosed with asthma are more likely to live within 500 m of major roadways. Concentrations of nitrogen oxides and particulate matter can be an order of magnitude higher along a roadway than background levels.[3]

Assessment of the exposure to traffic-related pollutants requires an accurate estimate of concentrations within short distances of the roadway. In the past 30 years, there were many attempts done by industry and academia to understand the dispersion of vehicular emissions in the atmosphere and consequently its impact on human health. The major outcomes from these efforts were air dispersion models such as the California Line Source Dispersion Model (CALINE) and the Hybrid Roadway Model (HYROAD), which are used to estimate the concentrations at source-receptor distances of tens to hundreds of meters.

Sound Walls: Potential Strategy to Reduce Exposure

In the mid-20th century, transportation agencies began constructing sound walls around major highways, as suggested by Title 23 of the U.S. Code of Federal Regulations, Part 772, "Procedures for Abatement of Highway Traffic Noise and Construction Noise." Although the primary purpose of sound walls is to reduce the noise levels in residential areas next to highways, they can have a significant impact on the dispersion of traffic-related pollutants. Therefore, since early 2000, the U.S. Environmental Protection Agency (EPA) has initiated several projects to address the impact of sound walls and surrounding vegetation on the dispersion of vehicular emissions. The results from these projects unanimously showed that the incorporation of roadside structures can cause a 50% reduction in the near road concentrations, as compared to an unobstructed roadway.[4]

Although these studies provide a thorough insight on the air quality impact of sound barriers, the question that remained unanswered is how to reflect their impact into currently available dispersion models? Over the past five years, there have been some efforts to model the dispersion affected by roadway structures. Bowker et al.[5] used Quick Urban and Industrial Complex model[6] (QUIC) developed by Los Alamos National Laboratory to describe the results from I-440 field study. Another modeling practice was the work done by Steffens et al.,[7] where they introduced the Comprehensive Turbulent Aerosol dynamics and Gas chemistry model (CTAG) to estimate the concentrations in Idaho Falls field study.[4]

While these studies showed some abilities in describing the impact of noise barriers, none of them provided a generic solution. Both QUIC and CTAG are numerical-based models and necessitate computational resources that can become impractical for exposure analysis. This article presents another effort conducted by researchers at University of California Riverside (UCR) to develop a simple dispersion model that can reflect the impact of roadside structures on the near roadway concentrations, and at the same time, is computationally efficient.

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A Simple Tool for Transportation Planners

Development of a dispersion model requires a clear understanding of the mechanisms involved with the transport and diffusion of vehicular emissions in the presence of sound barriers. Achieving such understanding through field tests can become very expensive and impractical in certain cases. This motivated UCR researchers to look at the air quality impact of sound walls through systematic water channel simulations. Results from these measurements were used to develop a very simple, but effective, tool that can be utilized by regulatory agencies to examine the air quality impact of sound walls and help transportation planners to design roadside structures in a way that minimizes human exposure.

The resulting product from this project is computer software that uses a digital catalog of tested configurations, along with a user-friendly modeling system, to enhance dispersion model estimates in support of future transportation planning. The modeling software, shown in Figure 1, takes the emission rate, roadway/sound walls geometry, and meteorology as inputs and provide the user with the concentrations in the units of $\mu g/m^{-3}$. The user has the ability to choose between different sound barrier configurations studied over this project to find the configuration and geometry that gives the most reduction in concentrations downwind of the sound walls. This software is designed to serve users with different levels of knowledge on the air dispersion modeling. Compared to comprehensive dispersion models (e.g. CFD models), the UCR Line Source Model (UCRLSM) is computationally efficient and relatively easy to implement, which makes it an appropriate candidate for traffic-related air pollution exposure assessments. Once approved by South Coast Air Quality Management District (SCAQMD), the model will be available to the public for free.

Understanding the Mechanisms

The UCRLSM tool was developed based on results obtained from water channel simulations. In our laboratory setup, we simulated vehicular emissions by injecting a green dye into water (see Figure 2) and recording its diffusion using a long exposure imaging technique. Such visualizations provide details on the mechanisms involved with the dispersion of emissions, which are necessary for the model development. During our laboratory experiments, we tested several road model configurations with sound walls of different heights. From the visualization experiments (Figure 2), we observed that, in general, sound walls enhance the vertical mixing of the plume and increasing the height of the sound walls increases the initial vertical spread of the plume proportionally. Visualization experiments also revealed that the presence of vegetation barriers is much less effective than solid sound wall structures in dispersing pollutants.

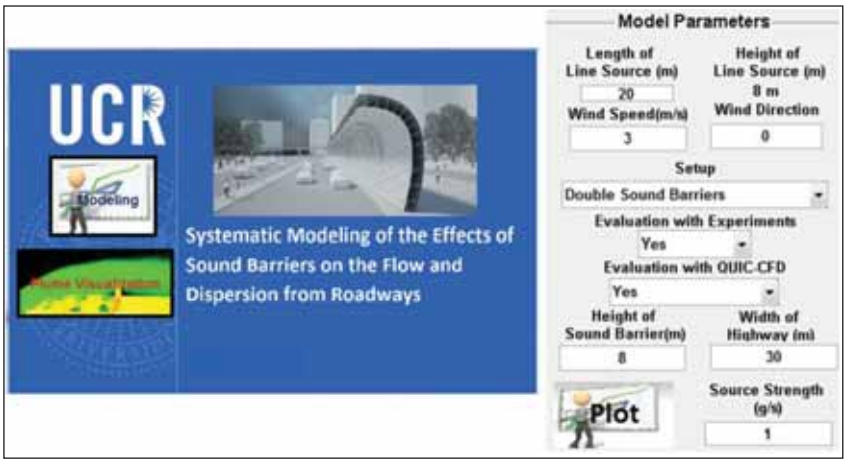

Figure 1. UCR Line Source Model (UCRLSM) developed by the researchers at University of California, Riverside.

Although visualizations provide a clear perspective on the plume spread and diffusion, the underlying mechanisms that cause such plume behavior are flow and turbulence. Therefore, results from visualization were supplemented with quantitative flow measurements using the Particle Image Velocimetry (PIV) system. These flow measurements showed that the major flow pattern governing the mixing

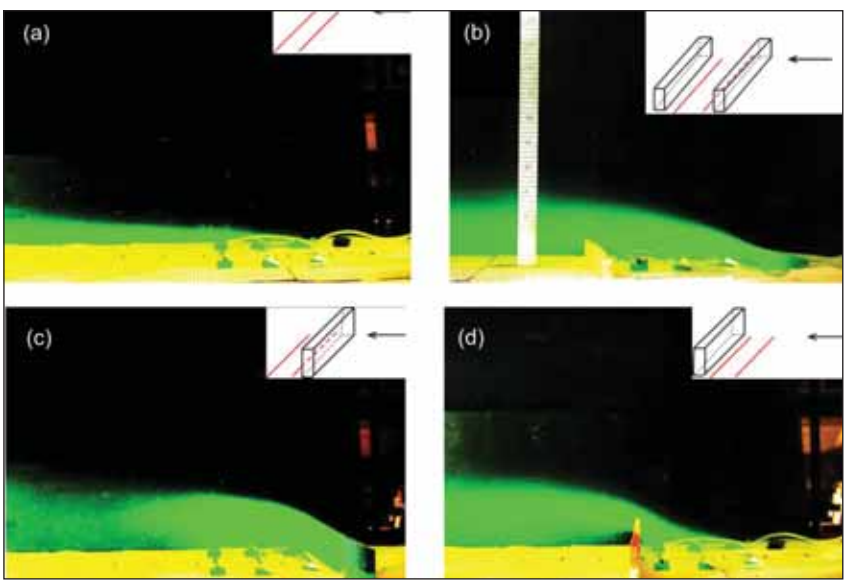

Figure 2. Plume visualization for (a) without sound walls, (b) with sound walls of equal height (H_{SB} = 4 cm), (c) upwind only sound wall (H_{up} = 8 cm), and (d) downwind only sound wall (H_{down} = 8 cm). Arrow on the schematic represents the flow direction.

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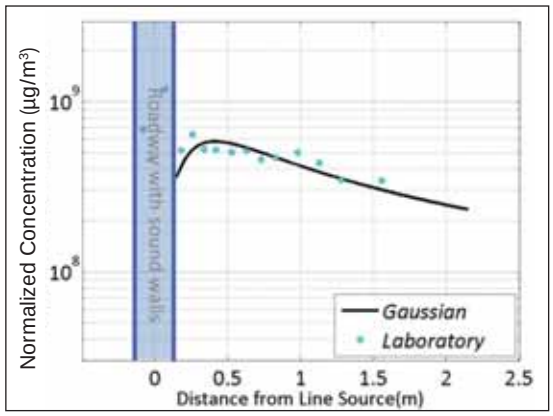

Figure 3. Evaluation of UCRLSM using measured concentrations in the water channel for the case of roadway with double sound walls. Concentrations are normalized with respect to the source emission rate.

of pollutants within the sound walls is the recirculating flow that occurs as a result of the cavity produced by the barriers. The measurements revealed that the recirculating flow diminishes rapidly as the wind direction deviates from normal to the sound walls.

Modeling Framework

Since development of a sophisticated numerical model can be very time-consuming and expensive, it was more practical to adjust existing dispersion models to address the impact of sound walls. As a starting point, Gaussian plume dispersion-modeling framework was used. One should keep in mind that Gaussian-based models are not made to reproduce the mean flow field disturbances caused by various obstacles and can only try to account for such disturbances by adjusting plume spread formulations, initial spread, or even source location. This project focused on the modeling of vehicular emissions, which is usually modeled using line sources. We modified the Gaussian model to simulate line sources by integrating over a large number of point sources.

Looking at the plume visualization (Figure 2), we found out that one approach to adapt this model to roadways with sound walls is to place the line source on top of a sound wall, thus eliminating the presence/effects of obstacles. When placing the source on top of a sound wall, initial spread is adjusted to account for the plume spread that has occurred between the release on the roadway and top of the sound wall. The plume initial spread and height of the line source above the sound wall are proportional to the sound wall height where the proportionality constant is determined empirically using the plume visualization results shown in Figure 2.

To evaluate the performance of the above-mentioned model, we compared the concentration obtained by the modified Gaussian model with the observation made in the water channel, as shown in Figure 3. In the view of the complexities involved with the dispersion close to obstacles, this simple model showed reasonable performance in predicting the ground-level concentrations in the presence of sound walls. The simplicity of this model lies within the use of the Gaussian dispersion model, which is an analytical solution to the advection-diffusion equation. This important feature allows the model to be an appropriate candidate for long-term exposure analysis that requires concentrations over long averaging periods.

Future Milestones

Design and development of air dispersion modeling tools requires substantial data collection and evaluation studies. At this time, few studies have focused on roadways with sound walls. This article shows the necessity of having additional field and laboratory measurements on the air quality impact of roadside structure in nearby communities. With the new EPA requirements on near-road nitrogen dioxide monitoring stations, we can expect of having a valuable dataset in the near future where the concentration data can be used to fine-tune the currently available dispersion models, and construct a solid platform for future comprehensive modeling efforts. em

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