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Simulation of rail yard emissions transport to the near-source environment

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ABSTRACT

Rail yards are important nodes in the freight transportation network. However, they are also a focus of public health concern when located in highly populated areas. Field characterization of near-rail yard air quality is challenging due to spatially- and temporally-variable emissions. Numerical models can provide valuable insight into factors affecting emission dispersion and resulting near-field air pollution. This study utilizes computational fluid dynamics (CFD) modeling to investigate near-field air pollution surrounding a generic, moderate-sized intermodal rail yard with emissions of a neutrally buoyant gaseous pollutant. Rail yard and surrounding neighborhood structures were added in succession to a base case to study the influence of surface roughness on the generic pollutant's spatial concentration profile. A spatially weighted emissions scenario revealed highly variable pollutant levels in downwind neighborhoods, strongly affected by wind direction. Rail yard topography resulted in a modest increase in near-field pollution levels. Densely located two-story homes surrounding the rail yard reduced downwind concentrations by 16% and 15% at 25 m and 100 m downwind of the rail yard boundary, respectively. A 6 m boundary wall surrounding the rail yard, with four open sections enabling traffic flow, reduced downwind pollution levels by 25% and 12% at 25 m and 100 m downwind, respectively. While average pollution levels were lower with the addition of neighborhoods and a surrounding boundary wall, high spatial variability in pollution levels resulted in some near-field areas experiencing increased pollution that are offset by reductions in other areas.

1. Introduction

Air pollution in close proximity to major transportation sources – such as a highway, rail yard, or port – has been an issue of increasing concern in the public consciousness. A significant number of studies have found repeatable evidence of elevated air pollution in close proximity to major highways (Karner et al., 2010 and references therein) and a recent synthesis of health studies indicated adverse health effects associated with proximity to a major roadway (HEI Panel on the Health Effects of Traffic-Related Air Pollution, 2010). Comparatively fewer studies have measured local air pollution trends related to other major transportation facilities, such as ports, rail yards, intermodal facilities, and airports. Understanding air pollution related to freight transportation is an ongoing topic of concern, with an increasing interest in higher-spatial resolution analyses to understand microenvironments, local scale (hundreds of meters), and regional-scale (tens of kilometers) air pollution trends and effects of changing source emissions (Bickford et al., 2014; Hagler et al., 2013; Joe et al., 2014).

Rail yards, the primary focus of this study, are complex environments with a variety of emission sources distributed over a large area. Sources vary from one rail yard to another. For example, classification rail yards move freight between trains and therefore have primarily locomotive and container-handling equipment emissions, and intermodal rail yards additionally have truck traffic transporting freight to and from the rail yard. In addition to the heterogeneous rail yard emissions, other major sources in close proximity (e.g., manufacturing, highways), local meteorology, and the built environment can induce additional variability in local air pollution. Project-based risk assessments have been conducted

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using regulatory models for numerous rail yards in the United States based upon state requirements (e.g., Health Risk Assessments in California available at http://www.arb.ca.gov/railyard/hra/hra.htm). In addition, dispersion modeling has been conducted in research studies to estimate local-scale increases in particulate matter (Turner et al., 2009, Galvis et al., 2015), as well as to explore the potential benefit of changing to new locomotive engine technology (Galvis et al., 2015). Field characterization of local air quality near rail yards has been conducted at only a handful of locations in the United States. Local-scale effects of rail yard emissions were quantified at a major classification rail yard in California (Cahill et al., 2011), a moderate-sized intermodal facility in Illinois (Rizzo et al., 2014), and two adjacent intermodal rail yards in Georgia (Galvis et al., 2013). Collecting representative field data can be challenging given local meteorology and the higher likelihood of confounding sources nearby in industrial areas. For example, while a model of an intermodal rail yard in Michigan was found to locally impact fine particulate matter concentrations ($PM_{2.5}$, particulate mass smaller than 2.5 μm), major facilities in close proximity to the rail yard confounded field characterization of local air pollution (Turner et al., 2009).

Given the complexity of resolving local air pollution trends related to rail yard emissions, high resolution models complement field characterization through simulating the distribution of pollutant concentrations in the near-field environment and isolating influential factors. Computational fluid dynamics (CFD) modeling is one approach that supports a very fine-grained assessment of emissions transport in a complex environment. For example, CFD simulations can be used to investigate how surrounding neighborhood buildings may alter the near-rail yard concentrations and whether a boundary wall would improve or degrade local air quality. To date, the application of CFD modeling for rail yard environments has been primarily utilized for emergency-related analyses, such as evaluating the dispersion of an accidental release of dense chlorine gas (e.g., Hanna et al., 2009). This present study focuses on estimating effects of rail yard emissions related to freight movement and uses a neutrally buoyant tracer that would be more representative of common gaseous air pollutants emitted from combustion (e.g., oxides of nitrogen, carbon monoxide). This study utilizes CFD modeling to simulate a rail yard environment and understand the effect of emissions location, rail yard terrain elements, surrounding topography, and wind direction on predicted pollutant concentrations. The research approach balances the desire for a realistic simulation with a goal of providing generalizable findings, utilizing a published emissions inventory to inform emissions weighting, and an existing rail yard to guide the physical dimensions and topography.

2. Methods

2.1. Model geometry

A series of 3-dimensional computer models of an idealized rail yard were constructed to be similar in scale to a moderate-sized intermodal rail yard in Illinois studied by Rizzo et al. (2014). Five surface scenarios were developed with incrementally added terrain features (Table 1) including, (1) base model with uniformly distributed emission source elements; (2) base model with rail containers, buildings, and cranes added; (3) addition of a surrounding boundary wall to scenario (2); (4) addition of surrounding neighborhood buildings to scenario (2); and, (5) addition of surrounding neighborhood buildings to scenario (3).

As shown in Fig. 1, the simulated rail yard area resembled an oval spanning 2700 m along the rail track direction and 500 m across, i.e. length to width ratio of 5.4 to 1. A total of 2656 ground-placed source elements, each measured 2 m × 2 m × 4.5 m (L × W × H), were added with the center of each element's base plane located on a 20 m grid. The source elements were transparent to mean flow, i.e., they don't obstruct flow but serve as sources of turbulence and emission of an inert gaseous tracer with the same density as air during the CFD simulations. The source strength of each element can be adjusted individually. This approach allows flexibility in simulating various emission scenarios, such as homogeneous emissions across the rail yard, or higher emissions along the main rail track and certain high locomotive activity areas. The 3D computational domain measured 3700 m × 1500 m × 200 m, which extended 500 m outside the rail yard.

Terrain elements observed in a typical rail yard, including rail containers, buildings and cranes, were added to the base model to study their influence on pollutant transport. All containers were 12.5 m long by 2.5 m wide by 2.5 m high. There were 146 containers along the main through rail track (shown in yellow), and 95 containers on each of the 7 parallel tracks spaced 20 m apart (shown in green). Three container parking areas were included (shown in teal): 2 arrays of 8 by 25 containers on either side of the tracks, and 1 array of 24 by 14 containers at the east end of the rail yard, oriented at a 45° angle. The added six buildings, modeled after typical 1-story storage structures, were 24 m wide by 10 m high, and either 36 m or 72 m long. Four cranes with dimensions of 6 m × 16 m × 14 m (L × W × H) were placed among the parallel train tracks.

To study the impact of a boundary barrier on near-rail yard air pollutant concentrations, a solid 0.5 m thick wall was added surrounding the rail yard. The wall had breaks at each end where the main train track passed through and one break on the NW side and one on the SW side supporting truck traffic. Four different wall heights were simulated: 3 m, 6 m, 9 m, and 18 m (0.5H, 1H, 1.5H, and 3H).

The final addition to the rail yard model was the surrounding neighborhood, which consisted of approximately 96 idealized residential blocks. Most blocks were 20 lots wide and 2 lots deep (200 m by 90 m), while a few blocks near either end of the rail yard were cropped to make room for the rail yard. All blocks were spaced 20 m apart. Within the blocks, each lot had a footprint of 40 m by 10 m and includes a two-story house in the front and a one-story garage/shed in the back. Their dimensions were 14 m × 8 m × 11.25 m and 8 m × 8 m × 7.5 m respectively.

2.2. Modeling approach

Volume meshes were constructed using the commercial software Harpoon (Sharc Ltd., Manchester, UK), which produces a body-fitted, hex-dominant mesh based on octree decomposition of the domain. This mesh method generates a high percentage of hexahedral cells to deliver accurate fluid flow results (Shephard and Georges, 1991). Several tests, similar in approach as described in an earlier study of roadside barrier effects (Hagler et al., 2011), were performed to verify grid size independence with increasing number of mesh cells until further refinements produced no significant improvements. Four different mesh configurations (trial meshes) were tested. Each of the trial meshes was characterized by a "base" size, which is the length of the side of the largest cell in the domain. The base sizes of the trial meshes were 16, 12, 8, and 6 m, while the corresponding smallest cell sizes were 0.5, 0.375, 0.25, and 0.1875 m respectively. A steady-state flow was simulated with 0° wind. Vertical profiles of velocity were monitored at 50 m both upstream and downstream of the rail yard and at three locations near terrain elements within the rail yard. The coarsest mesh (base = 16 m) failed to resolve the flow gradients near the ground and terrain elements. The remaining cases did a better job of