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ABSTRACT
The Alameda corridor provides a crucial rail link for moving freight in and out of the Ports of Los Angeles and Long Beach, also known as the San Pedro Bay Ports (SPBP). While the benefits of this trade are enjoyed by the whole nation, the associated air pollution costs are born mostly by the people who live in the vicinity of the Alameda corridor and the two freeways (the I-710 and the I-110) that serve the Ports. Although they are more energy efficient than trucks, trains contribute heavily to regional air pollution; in addition, rail traffic in the South Coast Air Basin is projected to almost double in the next twenty years. This paper presents an analysis of the emissions and the dispersion of PM and NO_x emitted by train operations in and around the Alameda corridor. We find spatial and temporal variations in the dispersion of these pollutants, which justifies our approach. Moreover, the railyards in our study area are responsible for the bulk of PM and NO_x emissions (compared to line haul operations). While PM emissions from train operations contribute only a fraction of the recommended maximum concentration, NO_x emissions go over recommended guidelines in different areas. The affected population is mostly Latino or African American. Our approach is also useful for better understanding trade-offs between truck and rail freight transport.

INTRODUCTION

The economic importance of the contiguous Ports of Los Angeles and Port of Long Beach in Southern California, also known as the San Pedro Bay Ports (SPBP), is difficult to overstate: a 2007 economic impact study finds that these two Ports handle more than 40% of the nation's total containerized cargo import traffic and 24% of the nation's total exports (1). The SPBP also play a critical role in California's economy: a February 2007 trade impact study found that over 886,000 jobs in California are related to international trade activities conducted through the SPBP, which also generated more than $6.7 billion in state and local tax revenue benefits.[1] Before slowing down in 2008, container traffic at the ports soared 65% from 2000 to 2007, and it is expected to continue expanding once the economy recovers.

However, this growth and its associated economic benefits are threatened by increasing congestion and pollution generated by the SPBP complex. Indeed, according to the draft Emission Reduction Plan for Ports and International Goods Movement in California published by the California Air Resources Board (2), roughly one-third of all goods movement emissions statewide are generated in the Los Angeles region. Moreover, on a typical day, more than 400 tons of NO_x are emitted from port and goods movement activities in California, which represents 10% of the statewide NO_x inventory. Diesel particulate matter emissions are also a problem: according to the South Coast Air Quality Management District (SCAQMD)'s MATES II study, diesel PM emissions are responsible for 70% of excess lifetime cancer risk from toxic air pollutants in the region. In addition, SCAQMD's MATES III study reveals that diesel exhaust is the major contributor to air toxics risk (it contributes approximately 84% of total toxic emissions) (3). Although USEPA has determined that DPM is likely to be carcinogenic to human by inhalation from environmental exposures, the available data are not sufficient to develop a confident estimate of cancer potency (4).

Air pollution from the SPBP originates from sources on the ocean-side (ships), within the ports (heavy equipment used for moving containers), and on the land-side (due to heavy reliance on diesel locomotives and large diesel trucks to transport containers to and from the ports). In particular, the major freight corridor that provides access to the port (the Alameda Corridor) comprises a major rail-line, which presently carries 50 trains per day on average, flanked by the I-110 and I-710 freeways, which both carry thousands of trucks per day. These links connect the SPBP complex road to railyards, as well as intermodal and other freight terminals both within the corridor itself and near downtown Los Angeles some 22 miles away, as shown in Figure 1, but also in the inland empire region.

Although the economic benefits of the SPBP are enjoyed by the whole country, the burden of the resulting air pollution is carried by the primarily low income communities who live and work around the I-110 and I-710 freeways, and along the Alameda corridor. As documented in the medical literature (5, 6), these communities are at increased risk of respiratory problems, cancer and even death. Indeed, previous studies suggest that pollutant concentrations near sources are elevated (7) and one recent study finds that PM concentrations increase between 10% and 50% after the passage of a locomotive (8). Given the width of the Alameda Corridor and the volume of freight movement, air quality and health impacts of freight operations in the corridor could be quite extensive.

Estimates of air pollution from trains are often quite crude, however, as they typically rely on fuel use to quantify the amount of pollutants released (9). One key reason is the reluctance of railroad companies to release information about their fleets of locomotives and

[1] www.allbusiness.com/services/business-services/4310036-1.html.

their railyard operations. Air pollution studies also tend to focus on truck traffic although train operations are one of the largest sources of air pollution in the South Coast Air Basin according to the Air Quality Management District (AQMD): NO_x pollution from railroad operations in the South Coast Air Basin exceeds the emissions from the largest 100 oil refineries, power plants, chemical plants and other industrial facilities combined (10). In addition, Rail traffic in the South Coast Air Basin is projected to almost double in the next twenty years (11).

Figure 1 Study Area

In this context, this paper presents an analysis of PM and NO_x train emissions in the Alameda Corridor, California, and a preliminary estimate of the resulting health risks for the neighboring population. A map of the study area is presented in Figure 1. Although we focus on the SPBP, our methodology is widely applicable.

BACKGROUND

The SPBP Ports are served by three railway companies: Burlington Northern and Santa Fe (BNSF); Union Pacific (UP); and Pacific Harbor Line (PHL). The first two are Class 1 railroads that provide line haul service to the Port; line haul refers to the movement of cargo over long distances; it occurs within the Port as cargo is either picked up for transport across the country or is dropped off for shipment overseas. By contrast, PHL is a much smaller Class 3 railroad that focuses on switching operations in and around the Ports.[2] Switching refers to the assembling and disassembling of trains at various locations in and around the Port, sorting of the cars into "fragments" for delivery to terminals, and the short distance hauling of rail cargo within the Port. It was created in 1998 to take over the Harbor Belt Line (HBL), as the Alameda Corridor was nearing completion.

Almost all locomotives in the U.S. come from two manufacturers: General Electric Transportation Systems and Electro-Motive Diesel (EMD). Their lifetime can reach 40 to 50 years but they are remanufactured periodically to maintain the performance of their engines.

Most locomotives used in the U.S. are diesel-electric locomotives. They use a diesel engine to power electric motors that drive the wheels, so the speed of the diesel engine is not related to the speed of the locomotive. Instead, diesel engines in locomotives operate at a series of steady-state points, known as notch settings. Typically, there are eight notches for power settings, one or two idle settings, and one or two settings for dynamic braking. Emission measurements from locomotives are made at each notch setting in terms of an emissions rate, e.g., grams per hour, and average emissions for a locomotive are computed from an assumed duty cycle (representing normal operation in the field). The average emission rate from a locomotive can then be computed based on the relative time spent in each notch setting, either on a brake-specific basis (i.e., in terms of an emission rate per unit power output), or on a fuel specific basis (i.e., as an emission rate per unit of fuel consumed).

Line Haul

Locomotives used for line haul operations are typically large, powerful engines of 3,000 to 4,000 hp or more. Line haul locomotives are operated in the Port by BNSF and UP. Since line haul locomotives transport freight to and from destinations across the country, line haul locomotives that call on the Port are representative of BNSF and UP's nation-wide fleets.

According to the information provided by BNSF for the baseline emissions inventory study of the Ports, a representative locomotive is the 6-axle GE C44-9W (also known as Dash 9), which has an average of 4,256 horsepower.

Information about the UP fleet was obtained from its website. In 2005, it had approximately 6,500 line haul locomotives, which had an average power rating of 3,655 horsepower. Most of these locomotives were six-axle units, such as the 4,000-horsepower

[2] The Association of American railroads defines Class 1 railroads as having an operating revenue exceeding $346.8 million in 2006. A regional railroad has from $40 million to $346.8 million in operating revenues, and/or it is operating over 350 miles of tracks. Local line-haul railroads with less than $40 million in annual operating revenues and less than 350 miles of tracks. See www.ibisworld.com/industry/default.aspx?indid=1133.

Electromotive Division (EMD) SD70s (the others were 4-axle units.)

Depending on the size and weight of a specific train and the horsepower capacities of available locomotives, line haul locomotives are typically operated in groups, which often vary between two and five units, with groups of four being fairly common. Multiple locomotives in a train are jointly operated by the train engineer from one of the locomotives.

Switching Locomotives

Locomotives used for switching tend to have smaller engines, typically between 1,200 and 3,000 hp. Older line haul locomotives have often been converted to switch duty as newer line haul locomotives with more horsepower have become available.

Most switching activities within the Port is conducted by PHL, although BNSF and UP also conduct switching, primarily at their yards outside of the Ports. In 2005, PHL’s fleet consisted of 20 switch engines ranging from 1,200 to 2,000 hp, with an average of 1,823 hp, all of which were powered by 12- or 16-cylinder EMD engines. Early in 2006, PHL, the SPBP concluded an agreement with PHL whereby they will help fund the replacement of all of PHL’s locomotives with new low-emission Tier 2 locomotives (defined in the next section). According to PHL, the switch engines used by BNSF and UP are typically powered by EMD engines, with an average power rating of 2,167 hp.

Emissions regulations

Regulation of off-road vehicles (which includes locomotives) is relatively recent. The first locomotive emissions regulations were promulgated by the U.S. EPA in 1998 and came into effect in 2000. These regulations were criticized for failing to provide a reliable methodology for estimating the local emissions impacts from rail traffic (12).

In addition to engine emissions standards, these regulations require that locomotives first built after 1973 meet emissions standards when they are remanufactured. This standard for the remanufacture of existing locomotives is referred to as Tier 0. In addition, there are two standards for newly manufactured locomotives: Tier 1 applies to locomotives manufactured between 2002 and 2004, and Tier 2, applies to locomotives manufactured in 2005 or later.

Increasing awareness of the pollution impacts of locomotives has driven more regulatory activity recently. First, in May 2004, the U.S. EPA introduced new requirements for off-road diesel fuel that will decrease by 99 % the allowable levels of sulfur in fuel used in locomotives. Then, in June 2005, the Air Resources Board (ARB) entered into a pollution reduction agreement with UP and BNSF to achieve a 20% reduction in locomotive diesel particulate matter emissions near railyards (13).

More recently, in March 2008, the U.S. EPA finalized a three part program that will drastically cut emissions from diesel locomotives of all types: it will reduce their PM emissions by as much as 90% and NO_x emissions by as much as 80% when fully implemented (14). This program creates new emission standards for existing locomotives that are remanufactured. In addition, it provisions for clean switch locomotives, and introduces requirements for idle reduction for all locomotives. Finally, it creates Tier 3 emission standards for new locomotives, and beginning in 2015, Tier 4 standards for newly-built engines based on the application of high-efficiency catalytic after-treatment technology (15).

EMISSION ESTIMATION

Line haul emissions

For modeling emissions form line haul activities, we divided the Alameda Corridor into three segments (north, mid-corridor, and south segment), which are characterized by different speed limits (25, 40, and 25 mph respectively); their length is 2, 10, and 8 miles respectively.

Table 1 Estimated line haul emissions in the study in the study area

				PM		NO_x	
Segment	Segment Length (mi)	Speed Limit (mph)	Assumed Notch	Emission Factor (g/hr)	Emissions (metric ton/year)	Emission Factor (g/hr)	Emissions (metric ton/year)
1	8	25	3	427.0	9.6	7267.0	163.0
2	10	40	5	348.0	6.1	25584.0	448.2
3	2	25	3	427.0	2.4	7267.0	40.7
Total	20	NA	NA	NA	18.1	NA	651.9

Notes: Each train is assumed to consist of four Tier1 locomotives; each train is assumed to travel at the speed limit for each section. Moreover, we assume two trains per hour around the clock, every day of the year. Our calculations ignore the grade in the Alameda corridor.

Table 2 Estimated railyard emissions in the study area

		PM		NO_x	
Railyard	Area (acres)	Trains only (metric ton/year)	All activities (metric ton/year)	Trains only (metric ton/year)	All activities (metric ton/year)
Combined Commerce (UP Commerce, BNSF Hobart, BNSF Eastern, and BNSF Sheila)	530	13.0	41.2	113.9	797.3
ICTF/Dolores (UP)	233	1.2	8.1	50.1	351.0
Wilmington-Watson (BNSF)	17	0.4	1.3	3.6	25.2
Transfer (PHL)	6	0.1	0.3	1.2	8.4
UP Mead (PHL)	10	0.3	1.0	2.2	15.4
Pier A (PHL)	23	0.6	1.9	5.0	35.0
Pier B (PHL)	14	0.3	1.0	3.1	21.7

Notes:

- PM emissions for the combined Commerce railyards and for ICTF/Dolores are respectively from (18) and (19). PM emissions for other yards were assumed to have the same rate of emissions per unit area and per unit time as Commerce Eastern. Railyard areas were measured with Google Earth.
- NO_x emissions for ICTF/Dolores are from (18). Other yards were assumed to have the same rate of NO_x emissions per unit area and per unit of time as ICTF/Dolores.
- “All activities” includes all locomotive emissions, as well as emissions from drayage trucks, cargo handling equipment, as well as heavy equipment and transport refrigeration units (17).

Based on conversations with representatives from PHL and from the Ports, we assume that line haul is primarily done by Tier 1 locomotives, which are in notch five on the mid-corridor segment, and in notch three on the other two segments. We then obtained the corresponding representative emission factors from (12), which is used in the State Implementation Plan to prepare locomotive emission inventories. After that, we calculated PM and NO_x emissions based on four locomotives per train. To find total annual emissions of these pollutants, we assumed an activity of two trains per hour around the clock. This is a slight overestimate for 2005 since the Alameda Corridor Authority recorded an average of 47 trains per day that year (16). A summary of line haul emissions is presented in Table 1.

Railyard emissions

As shown on Figure 1, seven railyards are associated with freight transportation from the SPBP, but two of them (the Commerce railyards, which consist of UP Commerce, BNSF Hobart, BNSF Mechanical Sheila and BNSF Commerce Eastern, and the combined ICTF/Dolores railyard) are much larger than the others. Our starting point for estimating emissions is a series of recent health risk assessments of major California railyards conducted for the EPA (17). These studies only covered PM and NO_x emissions from the two main railyards in our study area.

To estimate emissions from the five smaller railyards in our study (Watson, Transfer, Mead, Pier A, and Pier B), we assumed that their emissions are proportional to their area, which was measured using Google earth. We then based their emissions of PM and NO_x on those of the Commerce railyard. A summary of railyard emissions is presented in Table 2. Note, however, that our dispersion analysis is restricted to "train only" emissions.

AIR DISPERSION MODELING

Tools

To model the dispersion of various air pollutants, we relied on the CALPUFF modeling system, which is a generalized non-steady-state air quality modeling system initially designed by Sigma Research Corporation for the California Air Resources Board (CARB). This set of models has been improved over time to meet the needs of various federal agencies. In 1998, the U.S. EPA recommended this modeling system for estimating air quality impacts for the National Ambient Air Quality Standards (NAAQS) and prevention of significant deterioration (PSD) increments. This non-steady-state puff dispersion model simulates the effects of time- and space-varying meteorological conditions on pollution transport, transformation, and removal. CALPUFF can be applied for long-range transport and for complex terrain.

More specifically, we relied on CALPUFF View 5.8, which adds a friendly user interface to CALPUFF. This software has three main components: CALMET, CALPUFF, and CALPOST. CALMET is a meteorological model that creates hourly temperature and wind fields on a three-dimensional grid corresponding to the modeling domain. CALPUFF is a transport and dispersion model that advects "puffs" of pollutant from specific sources while simulating dispersion and transformations. Finally, CALPOST processes output files from CALPUFF to generate final results. In addition, CALPUFF View provides a variety of pre-processing programs that interface with 2005 MM5 datasets, which integrate extensive geophysical data (terrain, land use, meteorology). The MM5 (National Center for Atmospheric research/Penn State Mesoscale Model) is a regional weather model used for creating weather forecasts and climate projections (20).

Pollutants considered

We focus here on two criteria pollutants associated with train operations: PM (particulate matter) and NO_2 (Nitrogen oxides).

Indeed, ARB studies have shown that Diesel PM emissions are the dominant toxic air contaminants in and around railyards. In California, diesel PM is responsible for approximately 80% of the estimated potential ambient air toxic cancer risks; moreover, residents of the South Coast Air Basin are exposed to higher risks than average in California (16). Exposure to diesel PM is hazardous, particularly to children (their lungs are still developing) and to the elderly with serious health problems. A key concern is that diesel PM particles from locomotives are very small: approximately 94% by mass of these particles have a diameter of less than 2.5 microns (21). As a result, diesel PM particles can penetrate deep into the lung and enter the bloodstream with a variety of toxics. A number of population-based studies around the world have demonstrated a strong link between elevated PM levels and premature deaths (22, 23, 24), increased hospitalizations for respiratory and cardiovascular causes, asthma and other lower respiratory symptoms, as well as acute bronchitis (25).

According to the U.S. EPA (9), NO_x causes a wide variety of health and environmental impacts as it reacts with different compounds to create harmful derivatives in the family of nitrogen oxides. First, NO_x can react with volatile organic compounds (VOCs) in the presence of sunlight to create ground level ozone. This compound can damage lung tissue and reduce lung function in children, people with lung diseases (such as asthma), and people who work or exercise outside. Ozone can be transported by wind and affect the health of people far from original sources. In addition, ozone can damage vegetation and reduced crop yields. Second, NO_x can react with sulfur dioxide and other airborne substances to form acids which may be deposited as rain, fog, snow or dry particles. This phenomenon can cause pollution hundreds of miles away. It can damage cars, buildings, and causes lakes and streams to become acidic and unsuitable for many fish. Third, NO_x can react with ammonia, moisture, and other compounds to form nitric acid, which can damage the respiratory system and even cause premature death. Finally, nitrate particles and nitrogen dioxide can reduce visibility in urban areas.

In the following, we do not distinguish between NOx and NO2 because it is reasonable to assume that they are roughly the same for NO_x concentrations below 80 $\mu g/m^3$ (26).

RESULTS

Estimates of twenty four hours average dispersion concentration for both PM and NO_x are summarized in Table 3 and Figures 2 to 6.

Particulate Matter (PM)

Results for PM emissions (from both line haul and railyard operations) are presented in Figures 2 and 3, and in Table 4. The maximum estimated PM 24-hour average concentration is 1.82 $\mu g/m^3$ in the winter, and 2.13 $\mu g/m^3$ in the summer, so PM pollution is slightly more problematic in the Summer, compare to other season,. Comparing Figures 2 and 3, we see that the extent of PM pollution is larger in the winter, but not uniformly so because of the combined effect of the built environment and wind speeds.

To put these results in context, we note that the current California Ambient Air Quality Standards for the 24-hour average concentration for $PM_{2.5}$ is 35 $\mu g/m^3$ (27), which is the relevant threshold here given that 94% of PM particulates emitted by locomotives are smaller than 2.5 μm. The PM concentrations we found are well below the Air Quality Standard, but it does not mean that they are safe. Indeed, according to the WHO (28), adverse health effects associated with $PM_{2.5}$ have been demonstrated for background concentrations ranging between 3 and 5 $\mu g/m^3$. In addition, PM concentrations from train operations are combined with PM emissions from other sources such as drayage trucks that transport containers to and from the ports and industrial polluters, but their contribution can only be described as incremental.

Table 3 Results for emissions dispersion in the study area

24 hours average	AQS	NOx (µg/m3)		AQS	PM10 (µg/m3)	
		Min	Max		Min	Max
Winter	35	8.14	73.20	50	0.20	1.82
Spring		4.78	43.00		0.19	1.74
Summer		8.33	75.00		0.24	2.13
Fall		3.08	27.70		0.23	2.02

Table 4 Characteristics of the population impacted by PM emissions

Category	Winter	Spring	Summer	Fall
Total Population (in thousands)	1,338	471	552	1,247
Percentage of female residents	50.6%	50.6%	50.4%	50.4%
Age				
Under 5	9.8%	9.2%	9.5%	9.6%
5 to 21	31.5%	30.2%	30.8%	30.8%
65 and up	7.6%	8.1%	7.6%	7.6%
Ethnicity				
African American	9.8%	9.1%	7.5%	8.4%
Hispanic	39.6%	38.1%	40.1%	39.3%
Weighted Household Income	$34,692	$38,023	$36,100	$37,298

Notes: The numbers above are based on the 2000 Census. They are upper bounds because they include all of a census block even if only one part of it is polluted at the concentration indicated above. The maximum 24-hour average concentration is 1.82 $\mu g/m^3$ in the winter, 1.74 $\mu g/m^3$ in the spring, 2.13 $\mu g/m^3$ in the summer and 2.02.$\mu g/m^3$ in the fall

Table 4 illustrates the characteristics of the people affected by PM pollution due to train operations in the Alameda corridor. The population exposed to the highest PM concentrations is primarily Hispanic or African American, with a fairly low household income (for California) of $34,000 to $38,000 per year. The most at risk population (children under 5 years old and adults over 65) is approximately 230,000 for winter and fall, and 90,000 for spring and summer.

Nitrous Oxides (NO_x)

First, our investigations showed that NO_x concentrations from line haul activities are smaller compared to those from switching (railyards operations). This is illustrated by Figure 4, where the maximum 24 hour concentration of NO_x from line haul operations for the first week of the 2005 summer is 4.89 $\mu g/m^3$, or about half the maximum concentration from switching activities (8.69 $\mu g/m^3$). These result hold for each of the seasons investigated.

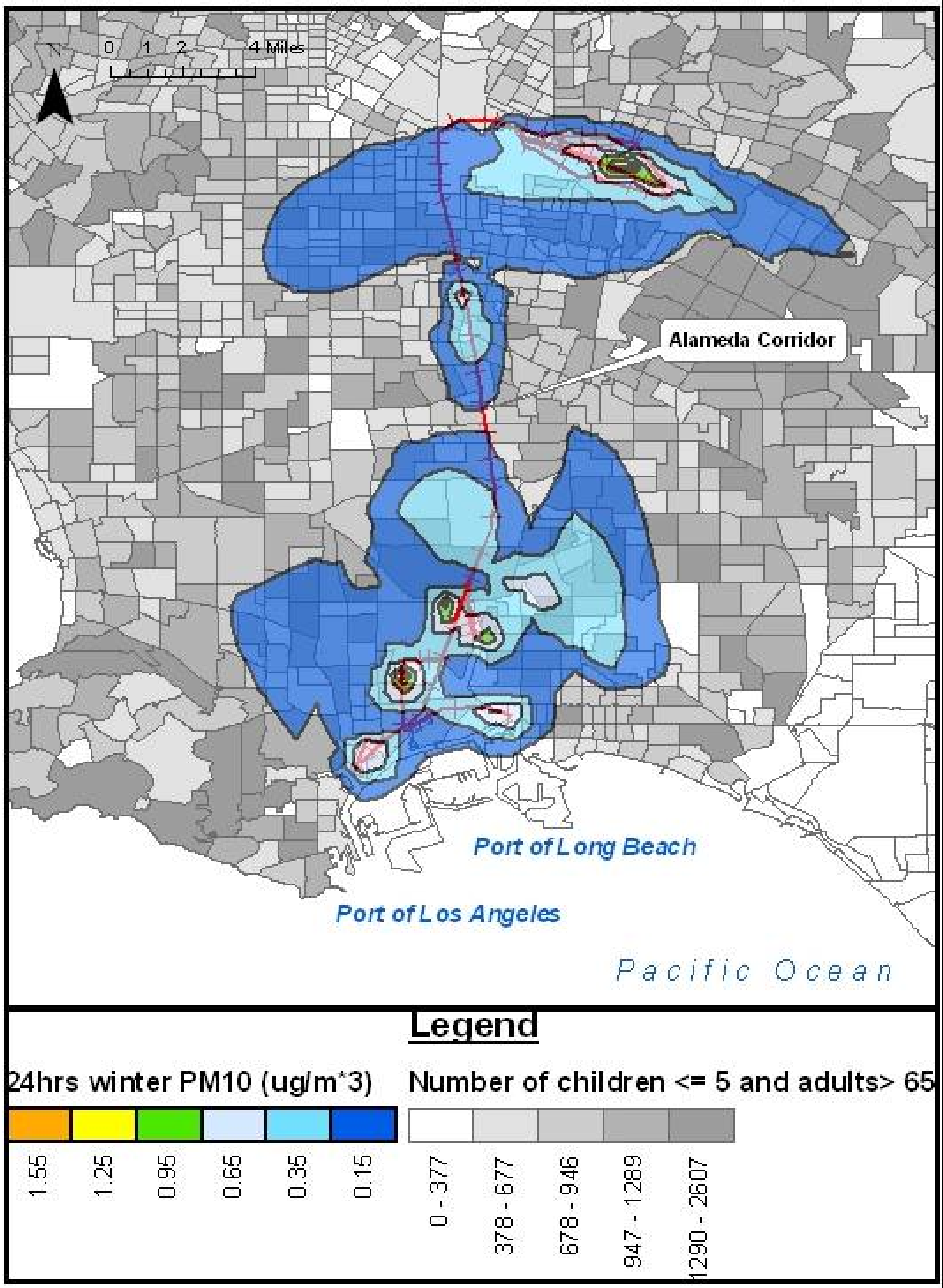

Figure 2 Winter PM exposure for children under 5 and adults over 65.
Note: the maximum 24-hour average winter concentration of PM is 1.82 $\mu g/m^3$.

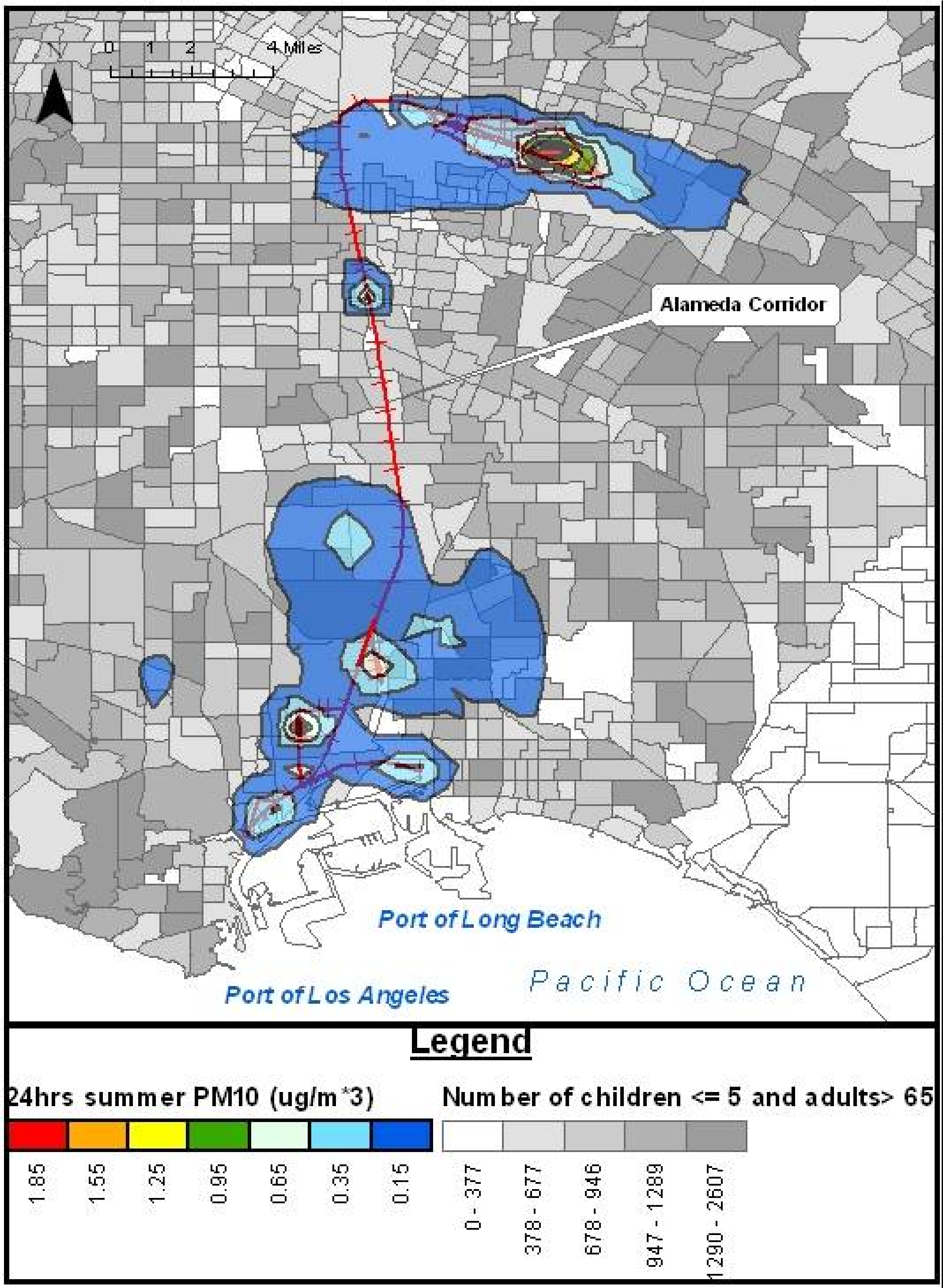

Figure 3 Summer PM exposure for children under 5 and adults over 65.
Note: the maximum 24-hour average summer concentration of PM is 2.13 μg/m^3.

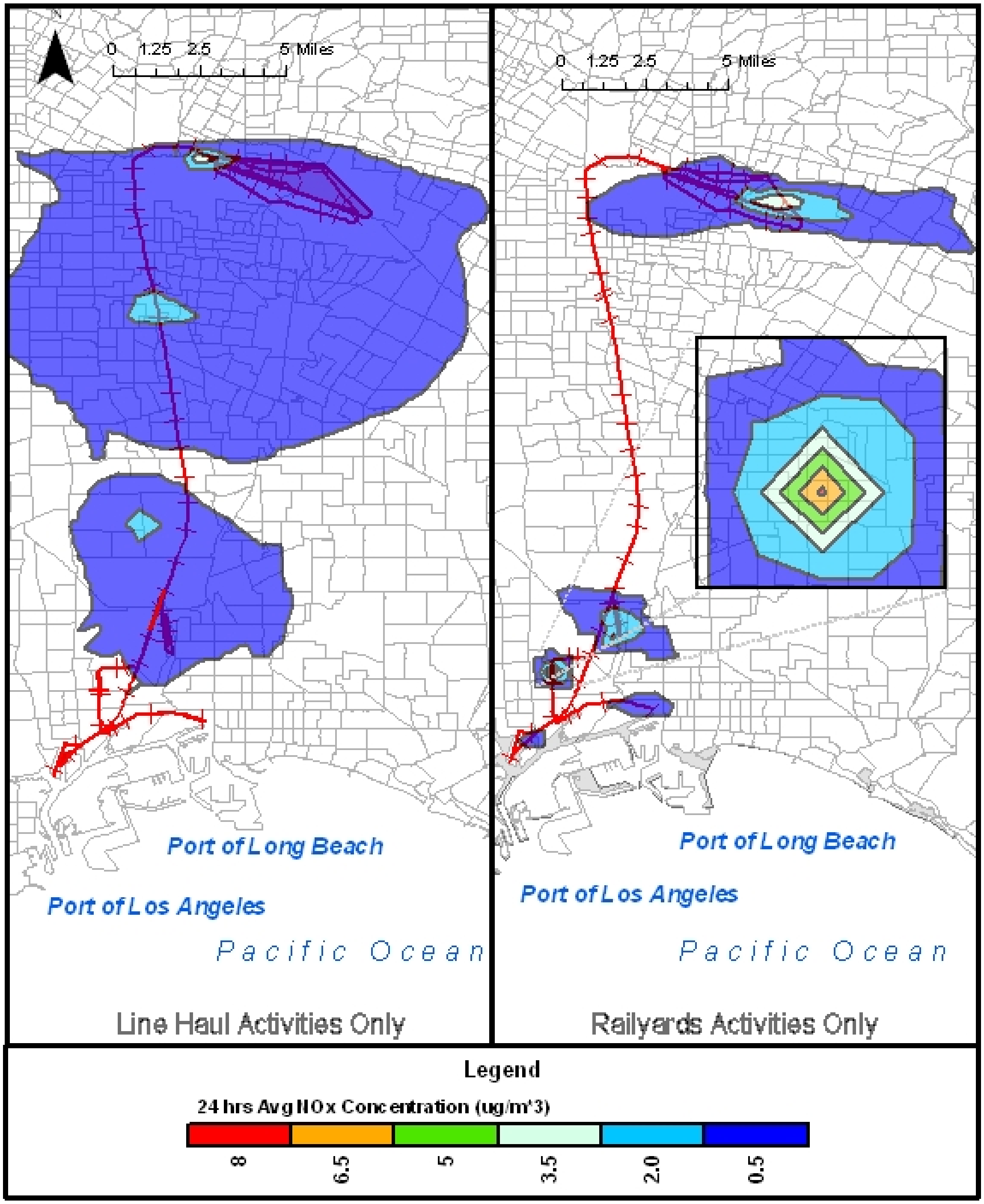

Figure 4 Comparison of 24-hour average concentration of NO_x.

Note: These concentrations were estimated for the first week of summer. They are representative of average concentrations resulting from both line haul and railyards operations.

Table 5 Characteristics of the population impacted by NO_x emissions

Category	Winter		Spring		Summer		Fall	
	≥3 μg/m^3	≥40 μg/m^3	≥3 μg/m^3	≥40 μg/m^3	≥3 μg/m^3	≥40 μg/m^3	≥3 μg/m^3	≥40 μg/m^3
Total Population **(in thousands)**	1,312	28	404	5	403	17	920	NA
Gender								
Female	50.8%	50.6%	50.6%	49.8%	50.6%	50.6%	50.4%	NA
Age								
Under 5	10.2%	11.1%	9.8%	11.6%	9.8%	11.5%	9.9%	NA
5 to 21	32.8%	36.8%	32.4%	35.2%	31.9%	36.4%	32.0%	NA
65 and up	6.6%	4.2%	7.0%	4.2%	7.1%	3.9%	6.9%	NA
Ethnicity								
African American	13.6%	6.9%	10.3%	6.4%	7.5%	7.3%	10.4%	NA
Hispanic	40.0%	45.9%	40.7%	46.5%	42.4%	45.8%	40.1%	NA
Weighted Household Income	$32,803	$28,208	$35,521	$30,913	$34,922	$28,084	$35,067	NA

Notes: The numbers above are based on the 2000 Census. They are imperfect estimates because they include all of a census block even if only one part of it is polluted at the concentration indicated above. The maximum 24-hour average concentration is 27.7 μg/m^3 in the fall and 75 μg/m^3 in the summer.

Seasonal results for both line haul and railyard operations are presented in Figures 5 and 6 and summarized in Table 5. We see that NO_x emissions from train operations appear to cause more serious public health and environmental problem than PM emissions. As for PM, railyard operations cause higher concentrations than line haul operations, which explains some of the observed spatial concentration of NO_x, especially in the summer.

The maximum estimated NO_x 24-hour average concentration is 27.7 μg/m^3 in the fall, and 75 μg/m^3 in the summer, so NO_x pollution is more problematic in the summer (this differs from PM). From Figures 5 and 6, we see clear seasonal differences. In the fall, the whole Alameda corridor is exposed to NO_x, although these concentrations are below EPA standards. By contrast, in the summer, a smaller area is exposed to NO_x but concentrations are higher. However, even during the summer, a sizable population (see Table 5) is exposed to relatively high 24-hour average concentrations of NO_x, which should be cause for concern.
Although the EPA does not provide guidelines for the 24-hour average concentration of NO_x, WHO recommends that the maximum annual mean concentration of NO_2 be below 40 μg/m^3; in addition, the recommended maximum one-hour mean concentration for NO_2 is 339 μg/m^3. Yet between 5,000 people (in the spring), 18,000 people (in the summer) and 28,000 people (in the winter) are exposed to 24-hour average concentrations of NO_x that exceed 40 μg/m^3. The percentage of population at risk (children under 5 and adults over 65) is slightly lower than for PM, but as above, the bulk of the populations exposed are Hispanic and to a lesser degree, African American, with a median household income between $28,084 and $30,913 based on 2000 Census data.

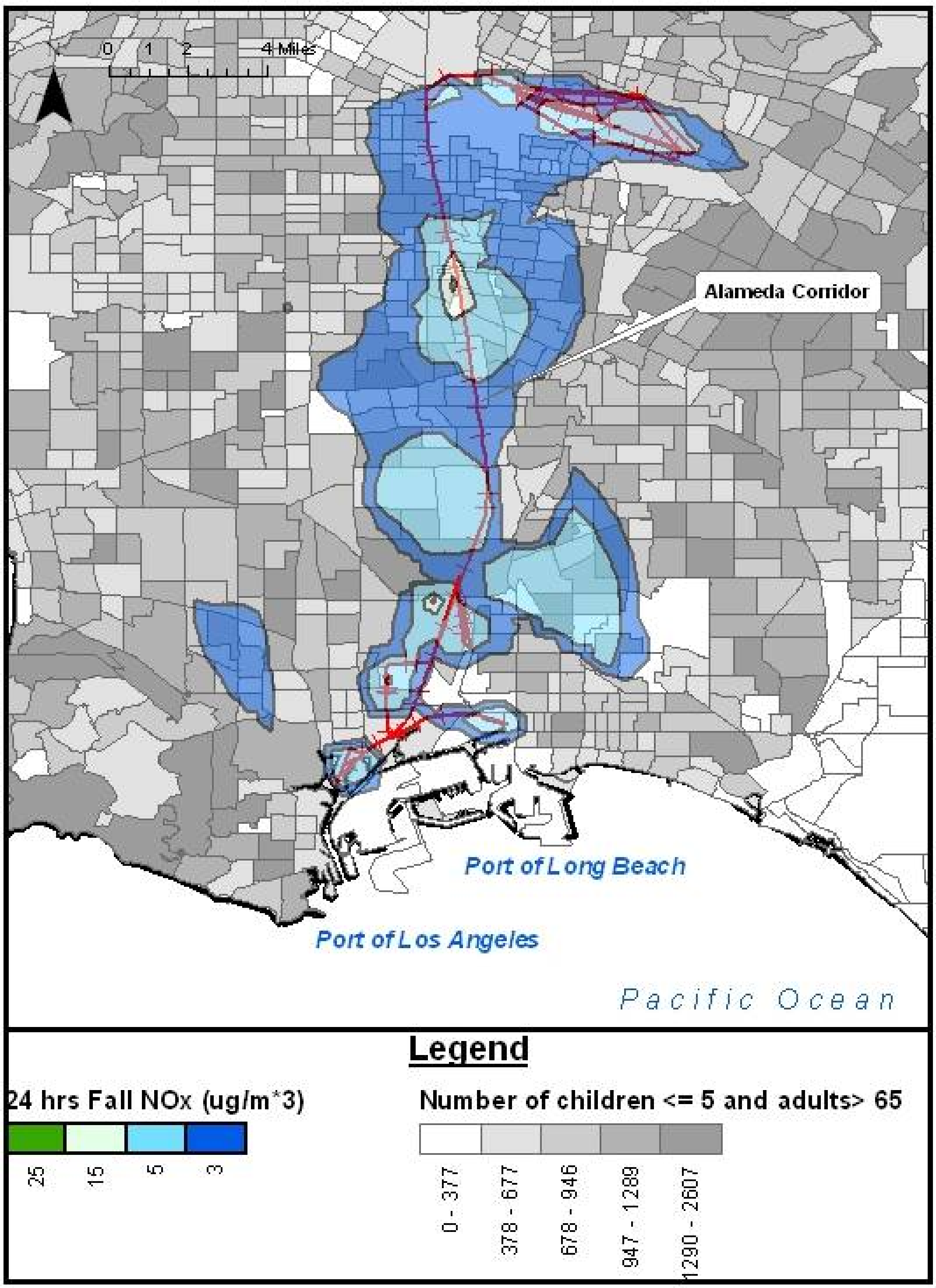

Figure 5 Fall NO_x exposure for children under 5 and adults over 65.
Note: the maximum 24-hour average winter concentration of NO_x is 27.7 $\mu g/m^3$.

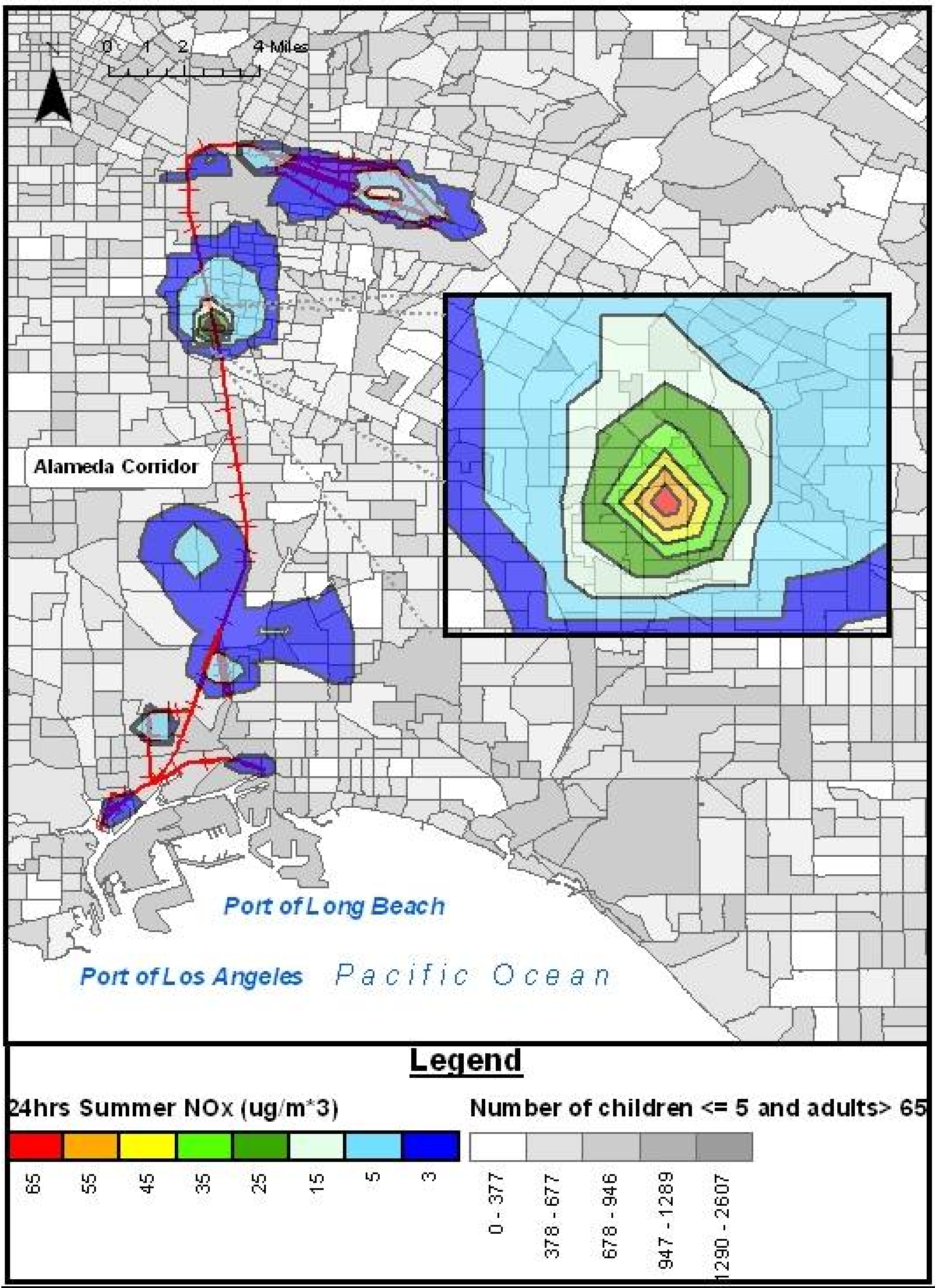

Figure 6 Summer NO_x exposure for children under 5 and adults over 65.
Note: the maximum 24-hour average winter concentration of NO_x is 75 $\mu g/m^3$.

These results are still preliminary, as we use a rough approximated of the potentially affected populations, for example, but they suggest (also see (7)) the importance of accounting for the spatial and temporal impacts of pollutant emissions from train operations in the Alameda corridor.

CONCLUDING REMARKS

In this paper, we analyze the spatial and the temporal distribution of PM and NO_x, which are two key pollutants generated by train operations in the Alameda corridor. We find seasonal effects and complex spatial dispersion patterns, which result from land use and wind directions. Moreover, emissions of PM and NO_x from line haul are significantly smaller compared to those of the different railyards operating in the Alameda corridor. Estimated PM concentrations from train operations are well below international health standards, but this does not mean that they do not have health impacts, as they contribute to background levels from industrial sources and traffic from nearby freeways. NO_x emissions from train operations in the Alameda corridor, however, should be a serious cause for concern as they exceed by themselves recommended health guidelines.

Our results should be interpreted with caution and they should be refined to better estimate of at-risk populations. Unfortunately, our efforts were slightly impaired by the railroads' reluctance to share data about their operations and the characteristics of their locomotives. A look at various studies (e.g., see 9 and 12) suggest that this is a common problem. As train operations use clean air, which is a public resource, we believe that they should release information about the characteristics of their line-haul locomotives operating in California, and more importantly, about their switching locomotives in regional yards. This information is critical for understanding the contribution of train operations to local air pollution, especially in non-attainment areas such as the Los Angeles basin.

Better information will allow better pollution impact studies that take into account the spatial effect of criteria pollutants that are not uniformly mixed in urban areas. This is necessary to understand the potential benefits of various measures, such as retrofitting older locomotives or installing devices that limit idling. It is also necessary to quantify the benefits of shifting freight transportation from trucks to trains (the modeling of truck emissions is addressed in a companion paper (29)). This is left for future work.

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