APPENDIX D: POTENTIAL IMPACT FROM INDUCED WINDS

1 BACKGROUND

The operation of a high-speed train causes aerodynamic forces such as airflow induced by these trains. These aerodynamic forces are influenced by factors such as train speed and distance from the train. The moving train creates a boundary layer along the length of the train and a wake behind the train that results in airflow in the general direction of the moving train. Turbulent fluctuations at the wake behind the train and sideways turbulent fluctuations accompany the airflow. Trains for the California High-Speed Rail (HSR) System along the Burbank to Los Angeles Project Section could reach a maximum speed of 140 miles per hour (mph).

This technical report summarizes existing credible scientific evidence related to evaluating potential impacts from induced winds from high-speed trains on the environment. Specifically, it evaluates the potential for generating fugitive dust emissions. It also includes a discussion of the relevance of incomplete or unavailable information to evaluating potential impacts.

2 INDUCED WIND

The Federal Railroad Administration (FRA) document titled *Assessment of Potential Aerodynamic Effects on Personnel and Equipment in Proximity to High-Speed Train Operations* (FRA 1999) made conclusions on induced winds for trains with speeds of 150 mph or less based on reviews of the theoretical and experimental data available at the time. The document concludes that at a distance of 26 feet from a train traveling at 150 mph, the induced wind would be in the range of 10 mph to 40 mph. There is a range of induced wind speeds because of variations between trains and uncertainties in the experimental data.

A literature search for high-speed train aerodynamics showed that most research in this area is concerned with determining the dynamic forces on the high-speed train itself (Schetz 2001; Baker 2010) and has been conducted to facilitate the design of high-speed trains that are both safe and comfortable. In addition to that body of work, Chris Baker and Mark Sterling have produced recent papers on the induced wind caused by high-speed trains (Baker et al. 2001; Sterling et al. 2008; Jordan et al. 2010).

Sterling and Baker are both professors at the School of Civil Engineering at the University of Birmingham, Birmingham, UK. Their studies focus mainly on the impact of the induced wind (which they refer to as the “slipstream”) on the safety of both workers and the public waiting along the track. The paper *Modelling the Response of a Standing Person to the Slipstream Generated by a Passenger Train* (Jordan et al. 2010) illustrates that, due to the complex nature of the fluid flow around a high-speed train (such as the shape of the train and the resultant turbulent fluid flow), there is no simple mathematical formula for the induced wind as a function of train speed.

Jordan et al. (2010) notes that the induced winds caused by a high-speed train have three distinct components: (1) flow around the nose of the train, (2) flow along the train, and (3) flow in the wake of the train. As explained above, exact analytical solutions for these flow fields are not possible. This is especially true of the flow in the wake of the train. However, the average magnitude of the induced wind does diminish as the distance from the train increases. For the analysis in their most recent paper, the authors represent the induced velocity in the wake of the train as the product of an exponential and parabolic function of the distance, with each function having a separate decay constant (Jordan et al. 2010).

While an exact analytic solution to the induced winds from high-speed trains is not possible, it is nevertheless possible and useful to quantify certain aspects of the flow, such as average and peak speeds, in order to evaluate the potential impacts on the environment. Consequently, URS and CH2MHill developed a methodology based on papers by Li and the FRA (Li et al. 2008; FRA 1999) to estimate induced wind speed as a function of distance.

2.1 Methodology to Estimate Induced Winds

A study on the potential aerodynamic forces created by a passing high-speed train on nearby objects (such as humans standing in the proximity of the train) are influenced by train speed, distance from the train, and the geometry of the train. *A Study of the Influence of Aerodynamic Forces on a Human Body near a High-Speed Train, Aerodynamics of Heavy Vehicles, Trucks, Buses, and Trains* (Li et al. 2008) analyzed the maximum wind velocity around a human body (assumed to be a cylinder with a height of approximately 5.7 feet) for a specific train speed, as a function of human-train distance, based on different train shape models (Li et al. 2008). The range of distance from train specified for Equation (Eq.) 1 is between 0 feet and 11 feet.

$$u = (1.2319)^{0.072v-4} \times (0.4575d^2 - 3.5496d + 9.1545) \text{ (Eq.1)}$$

Where:

u: maximum wind velocity around a human body near the train (mph)
d: human-train distance (feet)
v: train running speed (mph)

Based on the FRA-computed model, induced air flow beyond 10 feet would be significantly less because induced airflow tends to plateau, as shown on Figure 1. Again, a cylinder of approximately 5.7 feet was assumed to represent the human body for this analysis.

Table 1 Induced Air Flow from a Passing Train Traveling at 140 Miles per Hour

Distance from Train-Body[1] (feet)	Wind Speed u (mph)
0	23
3	14
7	8
10	6

[1] The values in Table 1 were developed using the methodology listed in Section 2.1 using the following equations:
For distance of 0 to 11 feet, the following equation is used to estimate induced air flow: $u = (1.2319)^{0.072v-4} \times (0.4575d^2 - 3.5496d + 9.1545)$ (Eq.1)
Where:
u: the maximum wind velocity around human body near the train.
d: human-train distance.
mph = mile(s) per hour

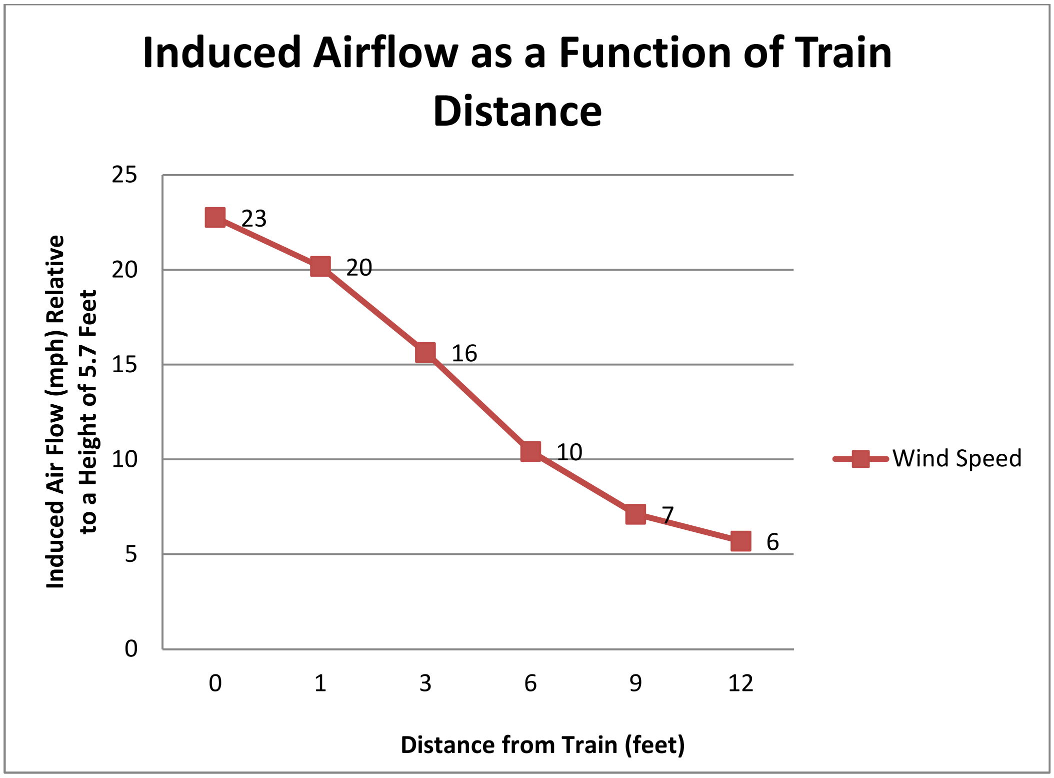

Figure 1 Induced Airflow as a Function of Train Distance for a Train Traveling at 140 mph

2.2 Check of Induced Wind Speed Methodology

A number of assumptions are made regarding the methodology described in Section 2.1 to estimate the induced wind from the California HSR System. As an independent check of the estimates from this approach, the data from the high-quality measurements of the InterCity Express HSR recommended by Sterling and Baker (2010) were used. In Table 1 of *A Study of the Slipstreams of High-Speed Passenger Trains and Freight Trains* (Sterling et al. 2008), distances at which induced velocities were measured are defined as, “Distance from train side or platform edge” in meters. The data provided in Figure 18 of that study show that, for trackside measurements, the induced winds are between 5 percent and 10 percent of the speed of the train at a distance of 9.8 feet (3 meters). Using this relationship, for a high-speed train traveling at 140 mph, 5 percent and 10 percent of the train speed would be 7 mph (10.3 feet per second) and 14 mph (20.5 feet per second), respectively. The 9.56 feet per second (6.5 mph) calculated using Eq. 1 in Section 2.1 is aligned with the lower end of this range. The agreement between Eq. 1, which was derived from the *Assessment of Potential Aerodynamic Effects on Personnel and Equipment in Proximity to High-Speed Train Operations* (FRA 1999), and independent experimental measurements is indicative of the validity of both approaches for estimating induced winds from the proposed California HSR System.

2.3 Induced Wind Speed and Elevation

While the wind speed generated by a train does vary relative to its elevation above the ground, Li et al. (2008) states:

> *The aerodynamic force acting on human body produced by train wind is related to many factors, such as train running speed, human-train distance, train head/tail shapes, smoothness of train surface, relative height between human and train, temperature and moisture of ambient air and so on. But the main*

> *factors are three: train running speed, human-train distance and train head/tail shape.*

Thus, distance from the train dictates the force and wind speed substantially more than the elevation does.

In the FRA paper, different trainsets were modeled to understand the impacts of high-speed use at existing stations in the Northeast Corridor (FRA 1999). One of the conclusions was that the "Induced airflow effects from a passing Acela trainset will be greater at 2.5 feet above a platform than at 5.0 feet above the platform, whether the platform is high-level or low-level." The paper also shows that, as the platform is elevated, wind speed and force are reduced at both 2.5 feet and 5.0 feet above the platform, respectively. This means that maximum wind speeds and forces modeled by the equations presented in this report likely represent the highest wind speeds and forces created by the train, as the studies took the maximum force from the ground at a height of approximately 5.7 feet.

Therefore, while the elevation relative to the ground does affect the induced wind speed from the train, the effect is small compared to the main factors (i.e., train speed, distance from train, and train head/tail shape), and this report likely captures the maximum wind speed and forces produced by the train. For an elevated guideway, it is not anticipated that the wind speed and forces at-grade would be any greater than those calculated and presented in this report.

3 WIND-GENERATED FUGITIVE DUST EMISSIONS FROM A PASSING HIGH-SPEED TRAIN

Wind erosion occurs when drag forces or shear stresses exerted by the wind exceed the retention forces acting on particles or debris at the surface. Once the minimum wind speed required to initiate particle motion (i.e., threshold friction velocity) has been reached, wind erosion occurs as a function of wind power or wind speed. The strong, turbulent airflow along the sides of a moving train and the wake at the rear of the train may resuspend erodible debris and fine particulates from the surface of the surrounding impacted area, similar to particle resuspension from wind erosion.

3.1 Methodology

To estimate the fugitive dust emission from the particle resuspension, the AP-42 guidance Chapter 13.2.5 Industrial Wind Erosion (U.S. Environmental Protection Agency 2006) was used to quantify the emission factor for wind-generated fugitive particulate emissions from a passing high-speed train. This section presents the approach used to estimate the annual emissions of particulate matter smaller than or equal to 10 and 2.5 microns in diameter (PM10 and PM2.5, respectively) from high-speed train operation, based on the AP-42 guidance and project-specific data such as the impacted area.

Annual wind-generated fugitive dust/particulates emissions from a passing high-speed train are a function of the impacted zone area and the wind erosion emission factor (per unit area). According to the AP-42 guidance, the wind erosion emission factor (in terms of mass per unit area) is a function of the disturbance frequency (where disturbance is defined as an action that results in the exposure of fresh surface material) in a year and erosion potential (which depends on friction velocity and threshold friction velocity).

3.1.1 Wind Erosion Emission Factor

Based on the AP-42 guidance, the emission factor for wind-generated dust emissions from the surface material of the impacted zone should be calculated as follows:

Emission factor (g/m^2):

$$k\sum_{i=1}^{N} P_i \qquad \text{(Eq. 3)}$$

Where:

k = particle size multiplier

N = number of disturbances per year

P_i = erosion potential corresponding to the observed (or probable) fastest mile of wind for the i^{th} period between disturbances ($grams/feet^2$)

3.1.2 Particulate Emission Factor

As described in Eq. 3, the emission factor is a function of the disturbance frequency and erosion potential. The disturbance frequencies for various HSR alignments were provided by the project engineers and are discussed in the *California High-Speed Rail Project Burbank to Los Angeles Project Section Air Quality Technical Report* (Authority and FRA 2017).

The erosion potential is the finite availability of erodible material (mass/area) on a surface. The AP-42 equations 1 and 3 for erosion potential were substituted into Eq. 3 above, and the following emission factor (grams/feet2) as a function of induced wind was derived:

$$k\sum_{i=1}^{N} [58\ (0.038955u - 0.19)^2 + 25\ (0.038955u - 0.19)] \qquad \text{(Eq.4)}$$

Where:

k = particle size multiplier (0.5 for PM_{10} and 0.075 for $PM_{2.5}$)
u = induced wind speed at a certain height above the surface (mph)

3.1.3 Induced Wind Speed

As shown in Eq. 4, the emission factor can be expressed as a function of induced wind speed along the side of the train body. The induced wind profile could be estimated using Eq.1 from Section 2.1 of this report.

3.1.4 Impacted Zone Area

The impacted zone area for the HSR system is defined as the surface area within both shoulders of the train track or within the right-of-way, at which the maximum friction velocity on the surface material is higher than the threshold friction velocity (i.e., the minimum wind speed required to initiate particle motion). The length of the impacted zone area is equal to the length of the at-grade track, and was obtained from the *California High-Speed Rail Project Burbank to Los Angeles Project Section Air Quality Technical Report* (Authority and FRA 2017)

3.2 Fugitive Dust Calculation

By integrating the emission factor function in Eq. 4 across the induced wind speed values within the impacted zone boundary area and multiplying the emission factor by the number of disturbance (N) and the particle size multiplier (k), the annual fugitive dust emissions from high-speed train activity can be estimated.

Dust emissions generated by the wake at the rear of the train were not added to this calculation so as to avoid double counting. The erodible dust is already suspended in the air when the rear end of the train passes through, so additional turbulence or the rear wake will not contribute to more raised dust in the air.

The emission factor profiles over the distance from the train body are presented on Figure 2, and the emission factor over the impacted zone area is summarized in Table 2.

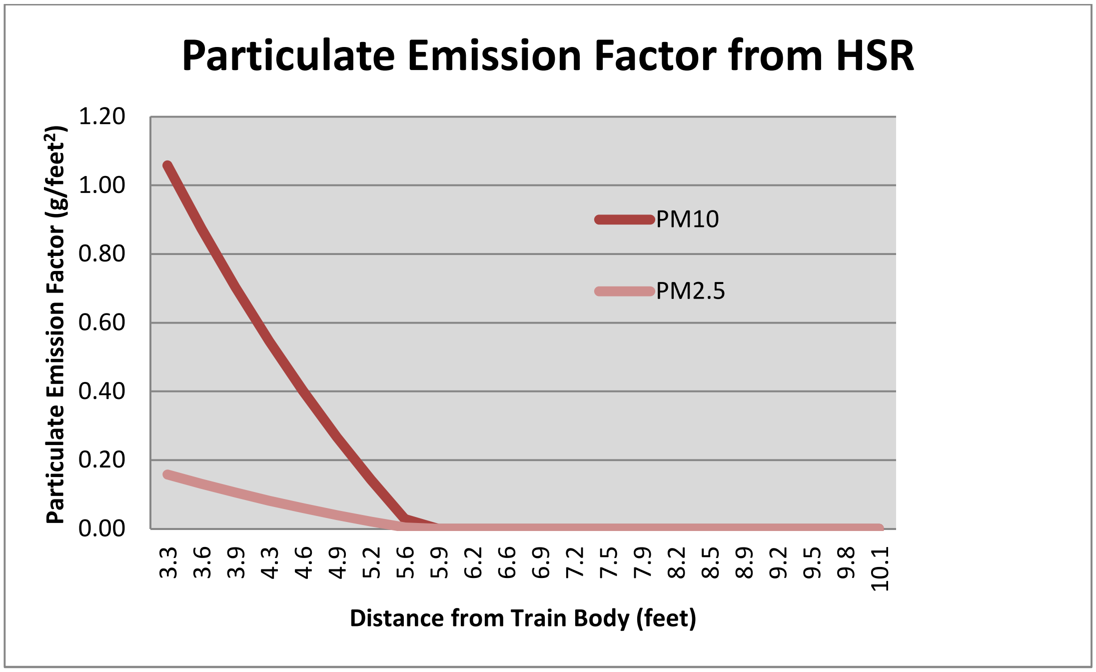

Figure 2 Particulate Emission Factor from Passing Train

Table 2 Emission Factor from Passing Train at 140 Miles per Hour

Distance from Train Body (feet)	Emission Factor (grams/feet²)	
	PM_{10}	$PM_{2.5}$
3.3	1.06	0.16
3.6	0.87	0.13
3.9	0.70	0.11
4.3	0.55	0.08
4.6	0.40	0.06
4.9	0.27	0.04
5.2	0.14	0.02
5.6	0.03	0.00
5.9	0.00	0.00
6.2	0.00	0.00
6.6	0.00	0.00
6.9	0.00	0.00

Distance from Train Body (feet)	Emission Factor (grams/feet^2)	
	PM_{10}	$PM_{2.5}$
7.2	0.00	0.00
7.5	0.00	0.00
7.9	0.00	0.00
8.2	0.00	0.00
8.5	0.00	0.00
8.9	0.00	0.00
9.2	0.00	0.00
9.5	0.00	0.00
9.8	0.00	0.00
10.1	0.00	0.00

$PM_{2.5}$ = particulate matter smaller than or equal to 2.5 microns in diameter
PM_{10} = particulate matter smaller than or equal to 10 microns in diameter

The emission factor for wind-generated particulate emissions from a passing high-speed train moving at speeds between 20 and 140 mph was calculated using the following steps:

- Using Eq. 1 and Eq. 4, integrate the emission factor over the distance of 3.3 feet to 10.1 feet from the train body.
- Multiply by particle size multiplier, k (0.5 for PM_{10} and 0.075 for $PM_{2.5}$)
- Multiply by the length of at-grade track for each train speed (impacted zone length).
- Multiply by 2 (to account for the left and right shoulders).
- Multiply by the number of disturbances per year (N).

The trapezoidal rule for numerical integration is used to estimate the results for the particulate emission factor for a passing high-speed train moving at speeds of 20 to 140 mph. The trains would travel at different speeds in different portions of the project section. For the proposed Burbank to Los Angeles Project Section, the PM_{10} fugitive dust entrainment from wind induced by the high-speed trains is 0.15 tons per year, and the $PM_{2.5}$ fugitive dust is 0.02 tons per year. These emissions represent the total fugitive dust that will be suspended within the HSR impacted zone area along the entire length of the alignment. As can be seen from Figure 2 and Table 2, the amount of fugitive dust suspended beyond 5 feet will be insignificant due to the low wind speeds generated at this distance from the train. The detailed results of these calculations can be found for various alignments in the *California High-Speed Rail Project Burbank to Los Angeles Project Section Air Quality Technical Report* (Authority and FRA 2017).

4 INCOMPLETE AND UNAVAILABLE INFORMATION

As noted earlier, an exact, analytical equation describing the induced wind from passing high-speed trains is unavailable because the technical means of obtaining it do not exist. Consequently, generally accepted scientific methods were used to extrapolate data from existing HSR studies to approximate the induced winds expected from the California HSR System. The level of uncertainty in these estimates is sufficiently small to be inconsequential to the evaluation of potential impacts from induced wind from the proposed California HSR System.

5 REFERENCES

Baker, Chris. 2010. “The Flow Around High Speed Trains.” *Journal of Wind Engineering and Industrial Aerodynamics*. Volume 98, pages 277–299.

Baker, C.J., S.J. Dalley, T. Johnson, A. Quinn, and N.G. Wright. 2001. “The Slipstream and Wake of a High-Speed Train.” *Proc. IMechE, Part F: Journal of Rail and Rapid Transit*. Volume 215, pages 83–99.

California High-Speed Rail Authority and U.S. Department of Transportation Federal Railroad Administration (Authority and FRA). 2012. *Air Quality Technical Report.* Sacramento and Washington, D.C.: California High-Speed Rail Authority and USDOT Federal Railroad Administration.

Bennett, Mark, Avanti Tamhane, Jonathan Tamimi, and Nathalia Prasetyo Jo. 2012. “Potential Impact from Induced Winds for High-Speed Trains.” March 28, 2012.

Federal Railroad Administration (FRA). 1999. *Assessment of Potential Aerodynamic Effects on Personnel and Equipment in Proximity to High-Speed Train Operations: Safety of High-Speed Ground Transportation Systems.* DOT-NVTSC-FRA-98-3. Washington, D.C. December 1999.

Li, Renxian, Jing Zhao, and Shu Zhang. 2008. *A Study of the Influence of Aerodynamic Forces on a Human Body near a High-Speed Train, Aerodynamics of Heavy Vehicles, Trucks, Buses, and Trains.*

Jordan, S.C., M. Sterling, and C.J. Baker. 2010. “Modelling the Response of a Standing Person to the Slipstream Generated by a Passenger Train.” *Proc. IMechE, Part F: Journal of Rail and Rapid Transit*. Volume 223, pages 567–579.

Schetz, Joseph A. 2001. “Aerodynamics of High-Speed Trains.” *Annual Review of Fluid Mechanics.* Volume 33, pages 371–414.

Sterling, M., and C.J. Baker. 2010. Telephone call from Mark Bennett, CH2M HILL, to Mark Sterling and Chris Baker about induced winds from high-speed trains. August 23, 2010.

Sterling, M., C.J. Baker, S.C. Jordan, and T. Johnson. 2008. “A Study of the Slipstreams of High-Speed Passenger Trains and Freight Trains.” Proc. *IMechE, Part F: Journal of Rail and Rapid Transit*. Volume 222, pages 177–193.

U.S. Environmental Protection Agency. 2006. AP 42, Fifth Edition, Volume I. Chapter 13.2.5. Industrial Wind Erosion. November 2006.

URS Corporation. 2010. *Wind-Generated Fugitive Dust Emissions from a Passing High-Speed Train.* Prepared by Nathalia Prasetyo Jo. July 12, 2010.

Watson, J.G. 1996. *Effectiveness Demonstration of Fugitive Dust Control Methods for Public Unpaved Roads and Unpaved Shoulders on Paved Roads.* DRI Document No. 685-5200. IF2. August 2, 1996.