APPENDIX 3.3-A, APPENDIX F: POTENTIAL IMPACT FROM INDUCED WINDS

TECHNICAL MEMORANDUM

Potential Impact from Induced Winds for High-Speed Trains

PREPARED FOR: PMT

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COPIES: file

DATE: March 28, 2012

1.0 Background

The operation of a high-speed train (HST) 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 HST system could reach a maximum speed of 220 miles per hour (mph).

This technical memorandum summarizes existing credible scientific evidence related to evaluating potential impacts from induced winds from HSTs on the environment. Specifically, it evaluates the potential for generating fugitive dust emissions and the potential for impacts to honeybees used to pollinate crops. It also includes a discussion of the relevance of incomplete or unavailable information to evaluating potential impacts.

2.0 Induced Wind

The Federal Railroad Administration (FRA) document, *Assessment of Potential Aerodynamic Effects on Personnel and Equipment in Proximity to High-Speed Train Operations* (FRA 1999), based on reviews of both the theoretical and experimental data available at the time, made conclusions on induced winds for trains with speeds of 150 mph or less. 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 HST aerodynamics showed that most research in this area is concerned with determining the dynamic forces on the HST itself (Schetz 2001; Baker 2010) and has been conducted to facilitate the design of HSTs 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 HSTs (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 an HST (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.

During an August 2010 phone call, Professors Sterling and Baker said that due to European HST safety standards, the measurements of induced wind speed done in Europe are at distances of 9.8 feet or less (Sterling and Baker 2010). They said they considered two sets of induced wind profiles from the German

Intercity Connect HST (presented in Figure 18 of their recent paper [Sterling et al. 2008]) to be high-quality data that show the induced velocity as a function of the distance from the train (Sterling and Baker 2010).

Jordan et al., 2010, notes that the induced winds caused by an HST 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).

Understanding that while an exact analytic solution to the induced winds from HSTs 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 CH2M HILL developed a methodology based on papers by Li and the FRA (Li, Renxian 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 HST 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*, 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 Eq. 1 is between 0 feet to 11 feet.

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

Where:

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

The analysis above is only appropriate for distance from the train up to 11 feet. If this equation is used for distance beyond 11 feet, then the results become invalid and another equation is needed. According to *Assessment of Potential Aerodynamic Effects on Personnel and Equipment in Proximity to HST Operations*, a train passing a station platform induces wind in its surroundings that diminishes with distance away from the train (FRA 1999). The paper computed induced wind speeds for two different train-passing speeds (100 mph and 150 mph), based on the high and low induced wind speed curves. The speed of the induced wind can be very high near the passing train but drops off sharply a short distance away. There are sufficient variations in the strength of the aerodynamic forces due to a train's design, such that a streamlined train with a slender nose, traveling at high speeds, creates aerodynamic forces that are no more severe than a train with a bluff nose traveling at slow speeds. If a train proposed for high-speed operation has a streamlined body design with a slender nose at the head and tail ends (such as the California HST traveling at 200 mph), it is possible that its favorable aerodynamic characteristics would offset the higher aerodynamic forces that would otherwise be created by its increase in speed. Therefore, a streamlined HST traveling at 220 mph could have an induced wind speed curve similar to a blunt-nosed train traveling at 150 mph, and the induced wind speed curve equation for a train traveling at 150 mph can be used to estimate wind speeds for an HST traveling at 220 mph by fitting a logarithmic equation to FRA-computed airflow for passing trains. This equation can be used to obtain the following model for distances from 11 feet to 30 feet):

$$u = -3.5515 \times \ln d + 8.8894 \qquad \text{(Eq.2)}$$

Where:

u: the maximum wind velocity around human body near the train (mph).
d: human-train distance (feet).
This equation is only applicable for a train traveling at a speed of 220 mph

Based on the FRA-computed model, induced air flow beyond 30 feet would be significantly less because induced airflow tends to plateau (as shown in Figure 1). Again, a cylinder of approximately 5.7 feet was assumed to represent the human body for this analysis.

Eq. 2 cannot be applied to distances beyond 30 feet because the results become invalid, and literature searches have not shown any quantitative models to estimate induced wind speed past this distance. Therefore, Table 1 only lists the induced airflow as a function of distance from the train from 0 feet to 30 feet.

Table 1
Induced Air Flow from Passing Train Traveling at 220 mph

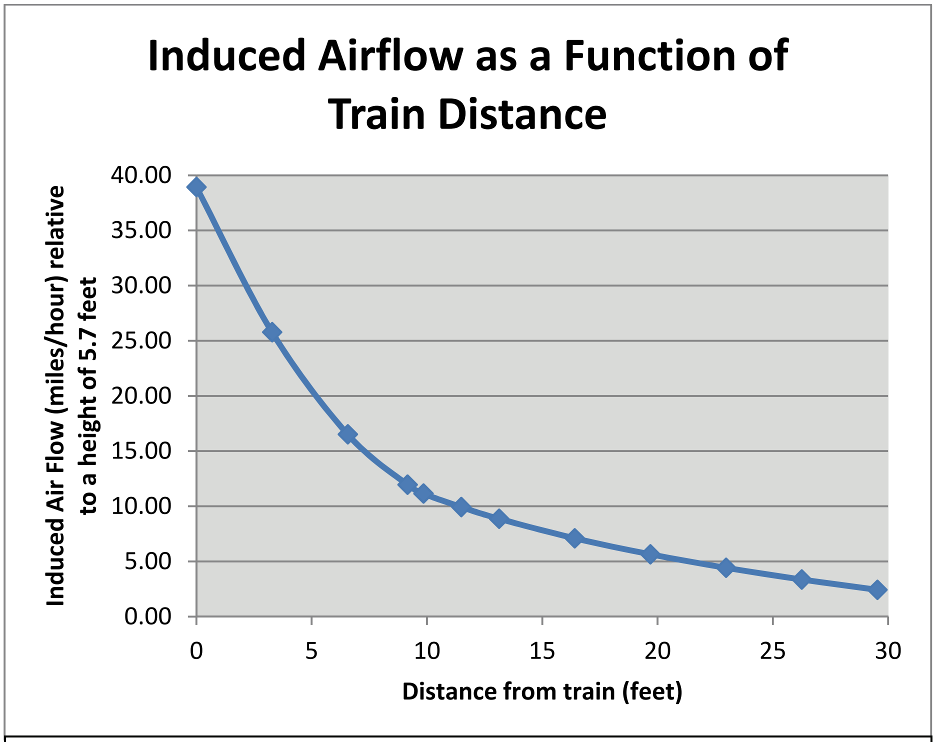
Distance from Train-Body[a] (feet)	Wind Speed u (mph)
0	38.94
3	25.79
7	16.53
9	11.96
10	11.16
11	9.93
13	8.87
16	7.10
20	5.65
23	4.43
26	3.36
30	2.43

[a] The values in Table 1 were developed with 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).

For distance of 11 to 30 feet, the following equation is used to estimate induced air flow: $u = -3.5515 \times \ln d + 8.8894$ (Eq. 2).

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



Note: Figure 1 was created using the methodology listed in Section 2.1, through the use of Eq. 1 and Eq. 2.

Figure 1
Induced Airflow as a Function of Train Distance
for a Train Traveling at 200 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 HST System. As an independent check of the estimates from this approach, the data from the high-quality measurements of the Intercity Connect HST 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. From examining the data given in Figure 18 of that study, it was concluded that these data show that, for trackside measurements, the induced winds are between 5% and 10% of the speed of the train at a distance of 9.8 feet. Using this relationship, for an HST traveling at 220 mph, 5% and 10% of the train speed would be 11 mph (16.1 feet per second) and 22 mph (32.2 feet per second), respectively. These values bound the 16.37 feet per second (11.2 mph) estimate from Eq. 1 in Section 2.1 (shown in Table 1 below). 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 HST.

2.3 Induced Wind Speed and Elevation

While the wind speed generated by a train does vary relative to the 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*

So 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. This means that maximum wind speeds and forces modeled by the equations presented in this memo 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.

So, 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 memo 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 memo.

2.4 Potential Impact of Induced Wind on Honeybees

Concern has been expressed that the wind gusts induced by the proposed HST might affect the bees that pollinate almond trees along the HST alignments. During an August 2010 phone call, Professors Sterling and Baker said they were not aware of any research done on the impact of HSTs on bees or pollination. (Sterling and Baker 2010). Right-of-way width for trains at-grade would be 100 feet and, according to design criteria, the nearest track would be at least 20 feet away from the edge of the HST right-of-way. Consequently, bounding the induced wind speeds at a distance of 20 feet or more was needed to evaluate the potential impact on bees pollinating almond trees.

The methods described in Section 2.0 are expanded upon in the following sections to estimate the wind gusts from a passing HST. These are compared to information about potential induced wind gusts and meteorological data for the Merced Regional Airport / Macready Field (KMCE), the Fresno Yosemite International Airport (KFAT), and the Bakersfield Meadows Field Airport (KBFL).

2.4.1 Meteorological Data

Meteorological data for Merced Regional Airport / Macready Field for the period of record of August 1998 to December 2008 (Western Regional Climate Center 2010a), Fresno Yosemite International Airport for the period of record of July 1996 to December 2008 (Western Regional Climate Center 2010b), and Bakersfield Meadows Field Airport for the period of record July 1996 to December 2008 (Western Regional Climate Center 2010c) were reviewed. The wind data for these three airports are very similar. Wind statistics are organized by month of the year:

- Merced Regional Airport / Macready Field:
  - The daily average wind speed ranges from 4.2 mph for November to 8.2 mph for June.
  - The daily average maximum 2-minute wind speed ranges from 12.1 mph for November to 16.7 mph in May.
  - The daily average peak gust, which is a maximum 5-second average, ranges from 15.0 mph in November to 21.3 mph in May.
  - The maximum daily average wind speed ranges from 10.9 mph for August to 22.1 mph for May.

  - The maximum 2-minute average wind speed range from 24 mph for September to 43 mph for December.
  - The maximum peak gust ranges from 29 mph for September to 51 mph for December.

- Fresno Yosemite International Airport:
  - The daily average wind speed ranges from 4.0 mph for December to 8.5 mph for June.
  - The daily average maximum 2-minute wind speed ranges from 11.5 mph for November to 17.7 mph in May.
  - The daily average peak gust, which is a maximum 5-second average, ranges from 14.2 mph for both November and December to 21.7 mph in May.
  - The maximum daily average wind speed ranges from 12.6 mph for July to 19.3 mph for March.
  - The maximum 2-minute average wind speed range from 25 mph for August to 38 mph for January.
  - The maximum peak gust ranges from 33 mph for both August and September to 46 mph for January.
- Bakersfield Meadows Field Airport (KBFL), CA:
  - The daily average wind speed ranges from 4.3 mph for November to 7.4 mph for June.
  - The daily average maximum 2-minute wind speed ranges from 12.4 mph for November to 17.3 mph in April.
  - The daily average peak gust, which is a maximum 5-second average, ranges from 14.7 mph for November to 21.4 mph in April.
  - The maximum daily average wind speed ranges from 9.4 mph for November to 22.3 mph for January.
  - The maximum 2-minute average wind speed range from 28 mph for July to 49 mph for February.
  - The maximum peak gust ranges from 33 mph for July to 57 mph for February.

2.4.2 Comparison with HST Induced Wind Gusts

Using the relationships from the German Intercity Connect HST data, induced winds from an HST traveling at 220 mph would be expected to range from 11 mph to 22 mph at 9.8 feet from the train. At 50 feet and 100 feet, the induced winds would be significantly less. As shown above in Table 1, at 20 feet the induced wind would be expected to be approximately 6 mph. A 1,400-foot-long train traveling at 220 mph would completely pass by an observer in less than 5 seconds; therefore a comparable wind statistic would be the daily average peak gust, where a peak gust is a maximum 5-second average wind speed. For Merced Regional Airport / Macready Field, Fresno Yosemite International Airport, and KBFL, the daily average peak gusts ranged from 15.0 mph to 21.3 mph, 14.2 mph to 21.7, and 14.7 to 21.4 mph, respectively. These ranges of speed are equivalent to the expected range of speeds of the induced winds at 9.8 feet from the train and two to three times greater than the 6 mph expected at 20 feet. Consequently, at 20 feet, 50 feet, and 100 feet from the train, the magnitude of the speeds of the induced winds would be expected to be less than and indistinguishable from naturally occurring wind gusts. Therefore, no impact on bee pollination from induced winds from the proposed HST would be expected to occur.

3.0 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. Attachment 1, *Wind-Generated Fugitive Dust Emissions from a Passing High-Speed Train* (URS 2010), provides more detail regarding methodology and findings.

3.1 Methodology

To estimate the fugitive dust emission from the particle resuspension, the AP-42 guidance Chapter 13.2.5 Industrial Wind Erosion (EPA 2006) was used to quantify the emission factor for wind-generated fugitive particulates emissions from a passing HST. 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 (PM_{10} and $PM_{2.5}$, respectively) from HST 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 HST 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 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/m2): $$k\sum_{i=1}^{N} P_i \qquad \text{(Eq. 3)}$$

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 HST alignments were provided by the project engineers and are discussed in the *California High-Speed Train Project Merced to Fresno Section Air Quality Technical Report* (Authority and FRA 2012).

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 the Eq. 3 listed above, and the following emission factor (grams/feet^2) as a function of induced wind was derived:

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

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)

3.1.2 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 memo.

3.1.3 Impacted Zone Area

The impacted zone area for the HST 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 Train Project Merced to Fresno Section Air Quality Technical Report* (Authority and FRA 2012)

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 HST activity can be estimated.

Dust emissions generated by the wake at the rear of the train were not added to this calculation 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 in Figure 2, and the emission factor over the impacted zone area is summarized in Table 2.

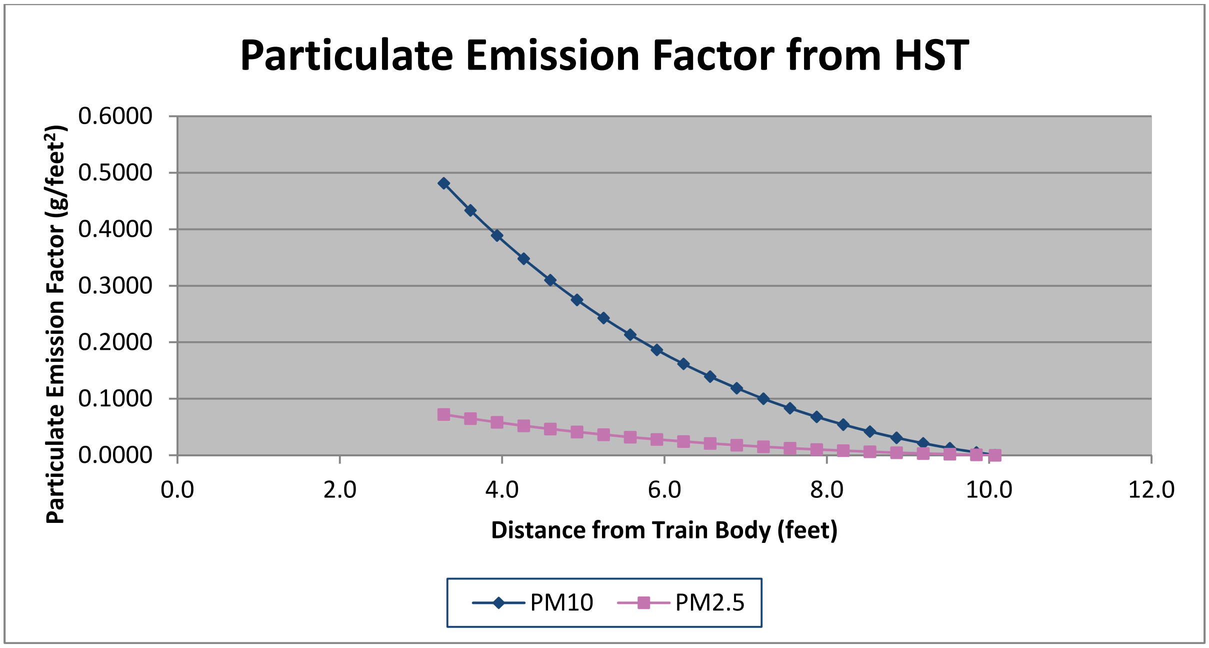


Figure 2
Particulate Emission Factor from Passing Train

Table 2
Emission Factor from Passing Train

Distance from Train-Body (feet)	Emission Factor (g/feet^2)	
	PM$_{10}$	PM$_{2.5}$
3.3	0.48	0.07
3.6	0.43	0.07
3.9	0.39	0.06
4.3	0.35	0.05
4.6	0.31	0.05
4.9	0.28	0.04
5.2	0.24	0.04
5.6	0.21	0.03
5.9	0.19	0.03
6.2	0.16	0.02
6.6	0.14	0.02
6.9	0.12	0.02
7.2	0.10	0.02
7.5	0.08	0.01
7.9	0.07	0.01

Distance from Train-Body (feet)	Emission Factor (g/feet^2)	
	PM_{10}	$PM_{2.5}$
8.2	0.05	0.01
8.5	0.04	0.01
8.9	0.03	0.00
9.2	0.02	0.00
9.5	0.01	0.00
9.8	0.01	0.00
10.1	0.00	0.00

The emission factor for wind-generated particulate emissions from a passing HST moving at 220 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 PM10 and 0.075 for PM 2.5)
- Multiply by the length of at-grade track length (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 HST moving at 220 mph. For at-grade track lengths that range from 50 miles (264,000 feet) to 120 miles (633,600 feet), the PM_{10} fugitive dust ranges from 15.9 tons per year to 38.2 tons per year, and the $PM_{2.5}$ fugitive dust ranges from 2.4 tons per year to 5.7 tons per year. These emissions represent the total fugitive dust that will be suspended within the HST 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 10.1 feet will be insignificant. Therefore, even though the train travels at speeds of 220 mph, it will not suspend herbicides, fungicides, or other harmful residues in the soil outside the HST-impacted zone area. The detailed results of these calculations can be found for various alignments in the *California High-Speed Train Project Merced to Fresno Section Air Quality Technical Report* (Authority and FRA 2012).

4.0 Incomplete and Unavailable Information

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

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

California High-Speed Rail Authority and USDOT Federal Railroad Administration (Authority and FRA). 2012. *Air Quality Technical Report.* Sacramento and Washington, DC: California High-Speed Rail Authority and U.S. Department of Transportation, Federal Railroad Administration. 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, DC. December 1999.

Li, Renxian, Zhao, Jing and Zhang, Shu. 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.

Luft, Arnold. 2010. Email correspondence between Thomas Baily (URS) with Arnold Luft (ARUP), regarding disturbances of right-of-way, dated July 6, 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*. 2008, Volume 222, pages 177–193.

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*. 2010, 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 HSTs. August 23, 2010.

United States Environmental Protection Agency (EPA). 2006. *Industrial Wind Erosion*. AP 42, Fifth Edition, Volume I. Chapter 13.2.5. November 2006.

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

Western Regional Climate Center. 2010a. Climatologically summary for the "Merced Muni/Macready FLD APT (KMCE)," for the period of record August 1998 to December 2008. http://www.wrcc.dri.edu/summary/mce.ca.html. Accessed September 1, 2010.

Western Regional Climate Center. 2010b. Climatologically summary for the "Fresno Yosemite International Airport (KFAT)," for the period of record July 1996 to December 2008. http://www.wrcc.dri.edu/summary/fat.ca.html. Accessed September 1, 2010.

Western Regional Climate Center. 2010c. Climatologically summary for the "Bakersfield Meadows Field Airport (KBFL)," for the period of record July 1996 to December 2008. http://www.wrcc.dri.edu/summary/BFL.CA.HTML. Accessed September 1, 2010.

ATTACHMENT 1

Fugitive Dust Memo

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MEMORANDUM

To: **PMT**
From: Nathalia Prasetyo Jo (URS)
Date: July 12, 2010
Subject: **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 (threshold friction velocity) has been reached, wind erosion occurs as a function of wind power or wind speed.

Trains traveling at high velocity, such as the High-Speed Train, drag the surrounding air along the side of its body, which induces sideways turbulent fluctuations and rear wake. 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.

Methodology

To estimate the fugitive dust emission from the particle resuspension, the AP42 guidance Chapter 13.2.5 Wind Erosion was used to quantify the emission factor for wind-generated fugitive particulates emissions from a passing High-Speed Train. This memo presents the approach used to estimate the annual PM_{10} and $PM_{2.5}$ emissions from the High-Speed Train operation based on the AP42 guidance and current project description (at 15%design).

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 AP42 guidance, the wind erosion emission factor 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).

The influencing factors such as the impacted zone area, wind erosion emission factor, disturbance frequency, erosion potential and induced wind speed profile are discussed in detail in the following subsections.

Impacted Zone Area

The impacted zone area for the High-Speed Train scenario 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 (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. Along the Fresno to Bakersfield alignment, the length of the at-grade track is approximately 43.56 miles (total track length subtracted by the elevated track section length)[1].
The width of the impacted zone is twice the distance from the beginning of the right of way area to the point where the corresponding maximum surface friction velocity generated by the induced turbulence is equal to the threshold friction velocity (assumed 0.19 m/s, based on the lowest value available for disturbed desert soil[2]). In this memo, the width of the impacted zone is referred to in terms of distance from the train body. The doubling of width was to account for the right of way area on the left and right side of the train track.
The boundary for the impacted zone is assumed to start at beginning of the right of way area (approximately one meter from the train body) and end at the distance where the corresponding friction velocity is equal to the threshold friction velocity. The surface area from the train body to the beginning of the right of way area was assumed to consist of non-erodible material because that area is within the embankment and rock ballast area.
To quantify the fugitive dust emissions generated by a High-Speed train passing at the speed of 220 mph, the emission factor needs to account for the induced wind speed profile and the distance within the impacted zone. Further discussion on the determination of the impacted zone boundary is presented in the induced wind speed section.

Wind Erosion Emission Factor
Based on the AP42 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/m2): $k\sum_{i=1}^{N} P_i$ (Eq.1)

Where:
k = particle size multiplier
N = number of disturbances per year
Pi = erosion potential corresponding to the observed (or probable) fastest mile of wind for the ith period between disturbances, g/m^2

As described in Eq.1, the emission factor is a function of the disturbance frequency and erosion potential. The approach and assumptions used to determine the disturbance frequency and erosion potential for the High-Speed Train operation scenario are presented as follows:

Disturbance Frequency
The disturbance is defined as an action that results in the exposure of fresh surface material. The number of disturbances per year during normal High-Speed Train operation is equal to the frequency of right of way access in a year (for maintenance or other purposes). The wind

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[1] The length of at-grade track was estimated based on the Fresno to Bakersfield HST Alignments Preliminary Draft Map, URS, 2010.
[2] Watson, J.G, “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.

generated emission factor is dependent on the disturbance frequency because each time that the right of way surface area is disturbed, its erosion potential is restored.
The right of way surface area is currently expected to be disturbed twice monthly for visual inspection based on the operational and maintenance schedule of the High-Speed Train. Therefore, the erosion potential is assumed to be restored twice a month, which translates to 24 disturbances/year or N=24[3].

Erosion Potential
The erosion potential (P_i) is the finite availability of erodible material (mass/area) on a surface. For the wind erosion emission factor calculation, Pi is defined as the erosion potential corresponding to the observed fastest mile of wind[4] for the ith period between disturbances, and can be calculated as follows:

$$P = 58\,(u^* - u^*_t)^2 + 25\,(u^* - u^*_t) \qquad \text{(Eq.2)}$$
$$P = 0 \text{ for } u^* < u^*_t \qquad \text{(Eq.3)}$$

Where:
u^* = friction velocity (m/s)
u^*_t = threshold friction velocity (m/s). Assumed 0.19 m/s, based on the lowest value available for disturbed desert soil.

Since there was no documentation for the friction velocity from High-Speed Train operation, induced wind velocity was used to estimate the friction velocity on the right of way surface based on the correlation given by Eq.4.

$$u_z = \frac{u^*}{0.4} \ln\left(\frac{z}{z_0}\right) \qquad (z > z_0) \qquad \text{(Eq.4)}$$

Where:
u_z = induced wind speed, m/s
u^* = friction velocity, m/s
z = height above test surface, cm
z_0 = roughness height, cm
0.4 = von Karman's constant, dimensionless

By substituting the friction velocity (u*) from Eq.4 into Eq.2 and the erosion potential (Pi) from Eq. 2 into Eq. 1, the emission factor in Eq.1 can be expressed as a function of induced wind speed as shown in Eq. 5

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[3] Email correspondence between Thomas Baily (URS) with Arnold Luft (ARUP) dated July 6, 2010.
[4] Fastest mile is the fastest one minute observed wind speed taken from a multiple register that contains a time record of the passing of each mile of wind

Emission factor (g/m^2): $$k\sum_{i=1}^{N}\left[58\left(\frac{0.4\,u_z}{\ln\left(\frac{z}{z_0}\right)}-u_t^*\right)^2+25\left(\frac{0.4\,u_z}{\ln\left(\frac{z}{z_0}\right)}-u_t^*\right)\right]_i \qquad \text{(Eq.5)}$$

Where:
k = particle size multiplier (0.5 for PM_{10} and 0.075 for $PM_{2.5}$).
u_z = induced wind speed at a certain height above the surface (m/s). Note that emissions are only calculated in area with $u^* > u^*_t$. Because, when $u^* < u^*_t$, the erosion potential (P) is equal to zero.
u^*_t = threshold friction velocity. Assumed 0.19 m/s, based on the lowest value available for disturbed desert soil.
z = height above the surface (288 cm), based on 1/2 of the train height (1.88 m) and the average embankment height (3ft ~1 meter) with respect to the right of way[5].
z_0 = surface roughness height (cm), assume 0.01 cm for the at grade right of way
0.4 = von Karman’s constant, dimensionless

By substituting the assumptions above and other known parameters into Eq. 5, the equation can be simplified to.

Emission factor (g/m^2): $$k\sum_{i=1}^{N}\left[58\left(0.038955u_z-0.19\right)^2+25\left(0.038955u_z-0.19\right)\right]_i \qquad \text{(Eq.6)}$$

Where:
k = particle size multiplier (0.5 for PM_{10} and 0.075 for $PM_{2.5}$).
u_z = induced wind speed at a certain height above the surface (m/s). Note that emissions are only calculated in area with $u_z > 4.88$ m/s (a substitute for $u^* > u^*_t$). Because, when $u^* < u^*_t$, the erosion potential (P) is equal to zero.

As shown in Eq. 6, the emission factor can be expressed as a function of induced wind speed along the side of the train body. By integrating the emission factor function in Eq.6 across the induced wind speed values within the impacted zone boundary (u_z) area, and multiplying the emission factor by the number of disturbance (24 times per year) and the particle size multiplier (k), the annual fugitive dust emissions from the 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 to avoid double counting. The erodible dust is already suspended in the air when the rear end of the train passes through and therefore additional turbulence or the rear wake will not contribute to more raised dust in the air.

Induced Wind Speed Profile

The width of the impacted zone is twice the distance from the beginning of the right of way to the point where the corresponding maximum surface friction velocity generated by the induced turbulence is equal to the threshold friction velocity. To determine the distance where the corresponding maximum surface friction velocity generated by the induced turbulence is equal to the threshold friction velocity, a wind speed profile analysis is required.
A study on the potential aerodynamic forces created by a passing High-Speed Train on nearby

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[5] Track related measurements are based on Technical Memorandum, Typical Cross Sections for 15% Design TM 1.1.21 Appendix A: Two Track At-Grade Drawing and Project Description Summary (June 28, 2010)

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[6]. Li, et. al. analyzed the maximum wind velocity around a human body for a specific train speed as a function of human-train distance based on different train shape models:

$$u = (1.2319)^{0.072v-4} \times (0.4575d^2 - 3.5496d + 9.1545) \qquad \text{(Eq.7)}$$

Where:
u: the maximum wind velocity around human body near the train (m/s).
d: human-train distance (m).
v: train running speed (m/s).

The range of train speeds specified for Eq. 7 are between 55.56 m/s and 97.22 m/s (between 124 mph and 217 mph) with a human-train distance between 1.0 m and 3.5 m. This raises questions about the validity of this equation to estimate aerodynamic forces from a High Speed train traveling at a speed of 220 mph.

An induced wind speed profile comparison was graphed to determine the relative accuracy of using Eq 7 to estimated aerodynamic forces for train speeds of 220 mp compared to 217 mph (the upper bound of the train speed range for Eq 7). Figure 1 shows that Eq. 7 presents a similar trend when a train speed of 220 mph is used as compared to a train speed of 217 mph. Therefore Eq. 7 can be used to determine the induced wind speed profile as a function of distance from train body for train passing at 220 mph.

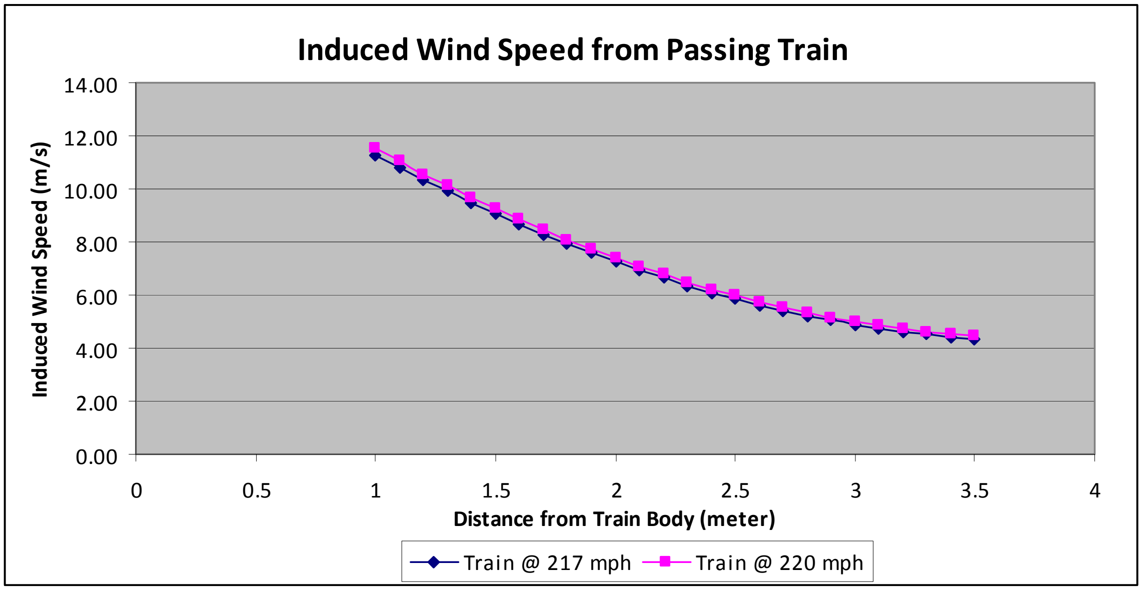

Figure 1. Wind Speed Profile Comparison from Train at 220 mph and 217 mph

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[6] Li, Renxian, et.al, “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, 2008.

Emission Calculation

The emission factor profiles over the distance from the train body are presented in Figure 2 and the emission factor over the impacted zone area is summarized in Table 1.

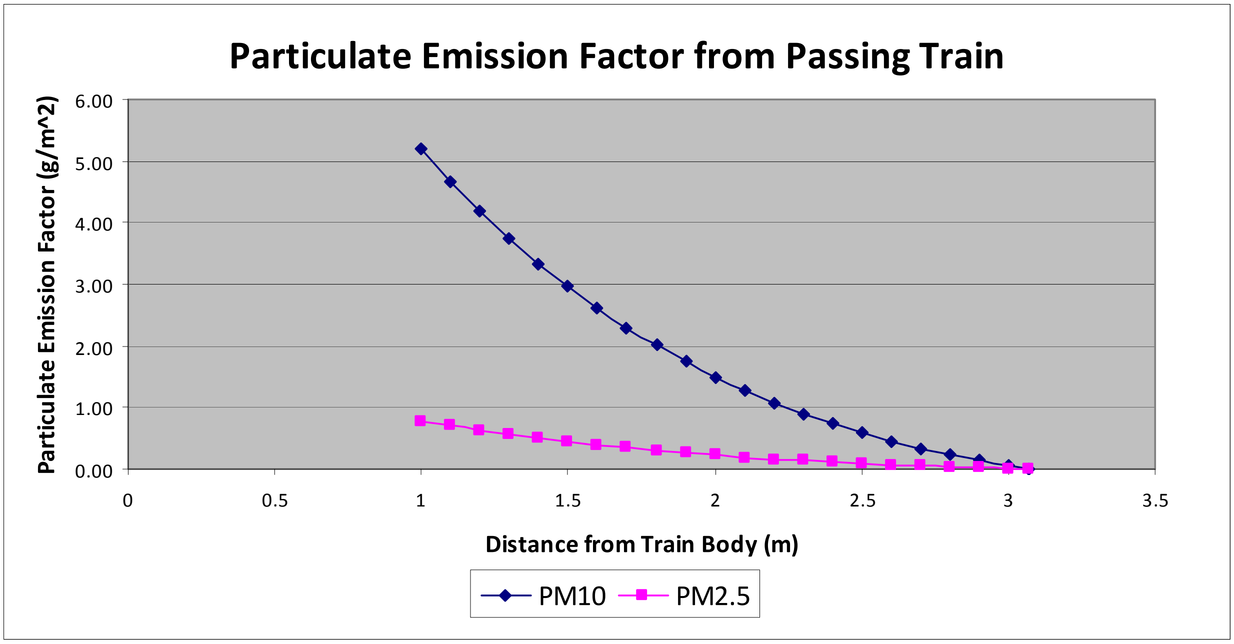

Figure 2. Particulate Emission Factor from Passing Train

Table 1. Emission Factor from Passing Train

Distance from Train-Body	Wind Speed (220 mph Train)	Friction Velocity	Erosion Potential	Emission Factor (g/m^2)	
(m)	u (m/s)	u*(m/s)	P (g/m^2)	PM_{10}	$PM_{2.5}$
1	11.53	0.45	10.37	5.18	0.78
1.1	11.03	0.43	9.33	4.67	0.70
1.2	10.56	0.41	8.38	4.19	0.63
1.3	10.10	0.39	7.49	3.75	0.56
1.4	9.66	0.38	6.68	3.34	0.50
1.5	9.24	0.36	5.92	2.96	0.44
1.6	8.83	0.34	5.23	2.62	0.39
1.7	8.45	0.33	4.60	2.30	0.34
1.8	8.08	0.31	4.02	2.01	0.30
1.9	7.72	0.30	3.48	1.74	0.26
2	7.39	0.29	3.00	1.50	0.22
2.1	7.07	0.28	2.56	1.28	0.19
2.2	6.77	0.26	2.16	1.08	0.16
2.3	6.48	0.25	1.79	0.90	0.13
2.4	6.22	0.24	1.46	0.73	0.11
2.5	5.97	0.23	1.17	0.58	0.09
2.6	5.74	0.22	0.90	0.45	0.07
2.7	5.53	0.22	0.67	0.33	0.05
2.8	5.33	0.21	0.46	0.23	0.03
2.9	5.15	0.20	0.27	0.14	0.02
3	4.99	0.19	0.11	0.05	0.01
3.07	4.88	0.19	0.01	0.00	0.00

As shown in Table 1, the corresponding friction velocity at the distance of 3.07 meters from the train body is equal to the threshold friction velocity of 0.19 m/s. Therefore, emission factor for wind-generated dust emissions should be calculated from the beginning of the right of way (1 meter from the train body) to the distance of 3.07 meters from the train body.

The emission factor for wind-generated particulate emissions from a passing High-Speed Train moving at 220 mph was calculated with the following steps:

- Using Eq. 6 and Eq. 7, integrate the emission factor over the distance of 1 meter to 3.07 meter from the train body.
- Multiply by particle size multiplier, k (0.5 for PM_{10} and 0.075 for $PM_{2.5}$)
- Multiply by 43.56 miles of at grade track length (impacted zone length).
- Multiply by two (to account for the left and right shoulders).
- Multiply by 24 disturbances per year (twice monthly).

Using the trapezoidal rule for numerical integration, the results for emission factor for wind-generated particulate emissions from a passing High-Speed train moving at 220 mph are 26.53 lb PM_{10} /miles of at grade track and 3.98 lb $PM_{2.5}$/ miles of at grade track. Multiplied by the impacted zone length and disturbance frequency, the annual PM_{10} and $PM_{2.5}$ emissions from the High-Speed Train operation for the Fresno-Bakersfield section are 28.97 ton of PM_{10} /year and 4.3 ton of $PM_{2.5}$ /year.

Reference

H. Lee, "Assessment of Potential Aerodynamic Effects on Personnel and Equipment in Proximity to High-Speed Trains Operations", DOT/FRA/ORD-99/11, December 1999.

U.S. Environmental Protection Agency (USEPA), "Compilation of Air Pollutant Emission Factors Chapter 13.2.5", AP-42, 5th ed., Washington, D. C., 2006.

Li, Renxian, et.al, "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, 2008.

Watson, J.G, "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.