Evaluation of Noise Level, Whole-Body Vibration, and Air Quality Inside Cabs of Heavy-Duty Diesel Vehicles

Parked Engine Idling and On-Road Driving

Joshua S. Fu, James A. Calcagno III, Wayne T. Davis, and Albert Alvarez

Heavy-duty diesel vehicles were measured for noise level, whole-body vibration from the driver's seat, and in-cab air quality while the vehicles were parked with engine idling at a rest area and while they were driven. These baseline data will help similar studies determine whether new truck designs have changed these conditions for drivers. Twenty-seven trucks (model years 2006 to 2008) from four manufacturers were tested. Results showed slightly higher noise levels driving on the Interstate versus driving on the state highway. However, overall in-cab noise levels were found to be lower than occupational exposure standards. Evaluation of seating vibration used ISO guidelines. Average vibrations in the *x*-, *y*-, and *z*-axes of the seats were generally found to be well below European Union standard exposures for an 8-h driving day. Inferior road pavement conditions were thought to have contributed to higher vibrations in a few trucks where several instances of the vibrations exceeded the standards. For most trucks, the likely comfort reaction from the vibration magnitude of the driver's seat was "a little uncomfortable." Air quality was determined by measuring in-cab concentrations of carbon monoxide (CO), oxides of nitrogen (NO_X), and particulate matter with less than 2.5 microns aerodynamic diameter ($PM_{2.5}$). Results indicated a tendency of trucks to self-pollute the cabs during periods of extended parked idling. Although overall CO and NO_X concentrations were well below occupational exposure levels, $PM_{2.5}$ concentrations during several parked-idling scenarios were higher than U.S. Environmental Protection Agency limits for ambient monitoring standards. During driving on public roadways, in-cab concentrations were lower than those measured during the extended parked-idling conditions.

The Federal Motor Carrier Safety Administration (FMCSA) promulgates hours-of-service (HOS) regulations that limit daily and weekly hours for which long-haul truck drivers are permitted to operate their vehicles on the public roadways (*1*). Heavy-duty diesel vehicles (HDDVs) that are used for long-distance freight hauling have a sleeping berth behind the driver's seat so the person can rest at travel centers during these federally mandated driver restorative-sleep periods. Driver and public motor safety is the primary concern influencing HOS regulation. Understanding the factors that may contribute to commercial vehicle operator health and performance are important for guiding future regulations. Currently, occupational exposures to noise, vibration, and poor air quality in commercial motor vehicles are not governed by federal regulations.

J. S. Fu, 59 Perkins Hall, and J. A. Calcagno, III, 64B Perkins Hall, Department of Civil and Environmental Engineering, and W. T. Davis, 124 Perkins Hall, College of Engineering, University of Tennessee, 1506 Middle Drive, Knoxville, TN 37996. A. Alvarez, Office of Research and Technology (MC–RTR), Federal Motor Carrier Safety Administration, 1200 New Jersey Avenue SE, Washington, DC 20590. Corresponding author: J. S. Fu, jsfu@utk.edu.

Transportation Research Record: Journal of the Transportation Research Board, No. 2194, Transportation Research Board of the National Academies, Washington, D.C., 2010, pp. 29–36.
DOI: 10.3141/2194-04

BACKGROUND

Noise Level

The sensation stimulated in the organs of hearing caused by a vibratory disturbance in the pressure of air is perceived as sound. Noise is defined as undesirable sound. Sound pressure is measured on a logarithmic scale called the "decibel (dB) scale." Different filters or weightings are also used for measuring noise levels because at different frequencies, the human ear does not sense sound pressure equally. A sound level meter using the A-weighed filter emphasizes the frequencies at which the human ear is more sensitive. The A-weighted sound level measurements (dBA) are typically used in regulation (law) for the protection of workers against occupational noise–induced hearing loss.

Robinson et al. (*2*) determined the in-cab noise level for nine trucks under different highway speed conditions of actual driving and compared these measurements to previous historical values to determine whether truck cab noise has increased or decreased with model-year changes. All trucks in the study had conventional engine-ahead-of-cab design, as opposed to cab-over-engine design; all had standard sleeper berths; truck model years were between 1992 and 1997. The overall broadband sound pressure level (SPL) for the nine trucks was 89.1 dBA across the several different driving conditions. The sleeper-berth mean SPL was 81.6 dBA, and during engine idling, the in-cab SPL level was 68.7 dBA. These overall values were somewhat high but when compared to those of older studies of truck cab noise, the current measurements actually showed a decrease in noise levels.

To evaluate noise level exposure of truck drivers under normal operating conditions, Seshagiri (*3*) measured the equivalent continuous sound level (L_{eq}) under several scenarios of highway driving in Canada that included different terrains and circumstances of windows open or closed and radio on or off. Eight trucking companies voluntarily took part in the study. In more than 90% of the trucks, the engine was located in front of the cab. Results showed that driving with the radio on and the windows closed produced a L_{eq} of 85.5 dBA, and driving with the radio on and the windows open resulted in a L_{eq} of 86.6 dBA. Overall, the results showed a L_{eq} of 90 dBA was exceeded by 10% of the long-haul drivers, and 56% exceeded 85 dBA, with the mean level of exposure at 85 dBA.

For reference purposes, the Occupational Safety and Health Administration (OSHA) permissible exposure limit (PEL) is 90 dBA for an 8-h time-weighted average (TWA) day. In contrast, the National Institute for Occupational Safety and Health (NIOSH) recommends 85 dBA for the TWA. It should be noted that noise levels inside the cab of commercial motor vehicles are not governed by OSHA regulations or NIOSH guidelines.

Whole-Body Vibration

Vibration is mechanical movement that oscillates about a fixed point. By definition, this movement is not constant but alternates between greater or less than some equilibrium position. Whole-body vibration (WBV) results when the whole-body mass of a person is subjected to the mechanical vibration, for example, from a supporting surface such as the seat of a vehicle. Local or segmental vibration is vibration in which only part of the body, for example the hand operating an electric drill, is in direct contact with the vibrating medium and the bulk of the body rests on a stationary surface. For the seated person operating heavy equipment, occupational vibration issues are of concern because of possible health effects to the lumbar region of the spine or from simple personal discomfort and annoyance. In a three-dimensional coordinate system for the human body in a seated position, the direction of the x-axis is the orientation of back-to-front; rotation about the x-axis is called "roll." The direction of the y-axis is the orientation of right-to-left side; rotation about the y-axis is called "pitch." The direction of the z-axis is the orientation of head-to-buttock; rotation about the z-axis is called "yaw."

Evaluations for WBV normally use the ISO guidelines, ISO Document 2631-1 (*4*). The effects of WBV on human health are determined using the frequency-weighted root-mean-square (RMS) acceleration for each axis of translational or rotational vibration on the surface that supports the person. Units of measurement for acceleration are meter per second squared (m/s^2); assessments are made independently along each axis with respect to the highest frequency-weighted RMS acceleration determined in any axis. In addition, vibrations in the horizontal plane are scaled by a correction factor (k) (for seated persons, ($k = 1.4$) because the critical frequencies with respect to possible injury or health are different for the vertical (z) axis and the two horizontal (x and y) axes. Standards for WBV have not been established for industry by OSHA, so for comparison purposes, the European Parliament Directive for Vibration (*5*) will be used for guidance; here the European Commission (EU) recommends 0.5 m/s^2 as the exposure action value (EAV) for an 8-h day and 1.15 m/s^2 as the exposure limit value (ELV). The EAV is the level of daily exposure that, if reached or exceeded, requires specific action to be taken to reduce the risk. The ELV is the level of a daily exposure that must not be exceeded.

The three axes of acceleration, (x, y, and z) can also be combined into a single value called sigma (Σ), where, $\Sigma = (k_x^2x^2 + k_y^2y^2 + k_z^2z^2)^{0.5}$. On its own, Σ is used as relative value for the perception of comfort. For a seated person in ISO 2631, the recommended correction factors are $k_x = k_y = k_y = 1$. Since acceptable values for comfort depend on many factors, which can vary with each application, overall limits are not absolutely defined. However, the following range values, listed in Table 1, are recommended in ISO 2631 to illustrate approximate likely reactions to various magnitudes of overall Σ-values.

TABLE 1 Comfort Reactions to Vibration Environment

Vibration Magnitude (Σ)	Likely Reaction
Less than 0.315 m/s^2	Not uncomfortable
0.315 m/s^2 to 0.63 m/s^2	A little uncomfortable
0.5 m/s^2 to 1 m/s^2	Fairly uncomfortable
0.8 m/s^2 to 1.6 m/s^2	Uncomfortable
1.25 m/s^2 to 2.5 m/s^2	Very uncomfortable
Greater than 2 m/s^2	Extremely uncomfortable

Exposure to WBV in heavy equipment operators and commercial vehicle drivers has been associated with an excess risk for back symptoms and disorders of the lumbar region of the spine (*6–9*). Miyamoto et al. (*10*) investigated lower-back pain (LBP) in professional truck drivers in Japan indirectly using the self-reporting method. The survey found that at least 52.9% of the drivers participating in the questionnaire reported that LBP was related to work. Additionally, most of these drivers claimed that vibration and road shock accounted for their LBP. Bovenzi et al. (*11*) investigated LBP in Italian drivers exposed to WBV. The sample of professional drivers here included drivers of earth-moving machines, fork-lift drivers, general truck drivers, and bus drivers. Questionnaires were again employed; also vibration measurements were made at the driver-seat interface during actual operating conditions on a representative sample of the industrial machines and vehicles used by the drivers. The z-axis (vertical) weighted acceleration was the dominant directional component of vibration measured in most of the machines and vehicles, and the horizontal vibrations were scaled by the correction factor for seated persons (i.e., $k = 1.4$). In the driver group, frequency-weighted, RMS acceleration averaged between 0.28 and 0.61 m/s^2, and the range was 0.1 to 1.18 m/s^2.

Air Quality

Long-haul truck drivers can potentially be exposed to air pollutants within the cab and sleeping berth during conditions of driving and while the vehicle is parked with the engine idling at truck-travel–rest centers. Relationships between diesel vehicle emissions and human health effects have been shown in numerous studies (*12*). The U.S. Environmental Protection Agency (EPA) has also concluded that diesel exhaust is carcinogenic and contributes to other health effects (*13*).

Doraiswamy et al. (*14*) measured air-pollutant concentrations of carbon monoxide (CO), oxides of nitrogen (NO_X), and particulate matter with less than 2.5 microns aerodynamic diameter ($PM_{2.5}$) inside and outside of six HDDVs idling at a commercial truck stop rest area. All trucks had conventional engine-ahead-of-cab design and a standard sleeper berth. Truck model years were between 1996 and 2003. The air samples were taken during several different modes of heating, ventilation, and air-conditioning (HVAC) settings and truck engine–operating conditions. The study showed that average in-cab 1-h concentrations were (*a*) 424–parts per billion by volume (-ppb) CO, 312-ppb NO_X, and 19 μg/m^3 $PM_{2.5}$ for both engine and HVAC in off-mode; (*b*) 820-ppb CO, 1,013-ppb NO_X, and 71 μg/m^3 $PM_{2.5}$ for both engine and HVAC in on-mode with air recirculation; (*c*) 493-ppb CO, 694-ppb NO_X, and 144 μg/m^3 $PM_{2.5}$ for both engine and HVAC in on-mode with fresh air; and (*d*) 780-ppb CO, 531-ppb NO_X and 209 μg/m^3 $PM_{2.5}$ for engine in on-mode and HVAC in off-mode. This suggested that different modes of engine idling and HVAC operation influenced the in-cab air quality. For instance, emissions were lowest when both the truck engine and HVAC were off, and emissions were highest when both the truck engine and HVAC were on with the fresh air condition.

Diesel exhaust exposure was measured by Davis et al. (*15*) at 36 truck freight terminals across the United States. Organic and elemental carbons (OC and EC, respectively) and $PM_{2.5}$ were measured inside the cabs. (To distinguish between OC and EC, analytical chemical methods are required.) Diesel particulate matter is mostly unburned carbon. However, EC or soot is a selective marker of exposure in workplaces where diesel equipment is operated, so it is a good surrogate measure of exposure to this pollutant. OC includes hydrocarbons that can be from unburned fuel, but there are other sources of hydrocarbons besides gasoline and diesel fuel. Both short- and long-distance trips, the smoking status of the driver, and characteristics of the truck were observed. For the long-haul drivers, average EC, OC, and $PM_{2.5}$ concentrations were 1.4 μg/m^3, 21.6 μg/m^3, and 52.6 μg/m^3, respectively. These results suggested that in-cab particle exposures were positively related to driver smoking, background or ambient particle concentrations, truck age, and open windows.

Miller et al. (*16*) conducted a 5-month air-monitoring study along a federal Interstate interchange that was located between several large truck-stop centers where about 20,000 HDDVs travel the Interstate every day, and as many as 400 trucks are idling at night in the several surrounding rest areas. The results showed that there were potential EPA National Ambient Air Quality (NAAQS) exceedances for $PM_{2.5}$ for both the 24-h and annual means and that the idling trucks and interchange ramps are potential hot spots for $PM_{2.5}$. Laden et al. (*17*) also provided insight into mortality patterns that were associated with job-specific exposures in the trucking industry. In this detailed assessment of specific job categories, an excess of mortality due to lung cancer and ischemic heart disease was noted particularly among commercial truck drivers.

The OSHA PEL for CO averaged over an 8-h time period is 50 parts per million (ppm) (*18*). The sum of nitrogen oxide (NO) and NO_2 is the NO_X concentration. By far, the dominant nitrogen compound formed during combustion in spark or compression ignition engines is NO. Also in ambient air, free NO can subsequently oxidize to NO_2. For gases burned at flame temperature, however, chemical equilibrium considerations indicate that NO_2/NO ratios are negligibly small. While experimental data show this is true for spark-ignition engines, in diesel or compression-ignition engines, the NO_2 concentration can be 10% to 30% of the total exhaust NO_X emissions (*19*). Though no occupational standard exists for NO_X, occupational exposures for NO and NO_2 are 25 ppm and 5 ppm (ceiling), respectively. Currently no established occupational exposure limit exists for $PM_{2.5}$, so the EPA NAAQS for $PM_{2.5}$ will be used for comparison purposes (*20*). It must be noted that NAAQSs are outside air-monitoring standards, set to protect general public health, including the health of sensitive populations such as asthmatics, children, and the elderly, and averaging times are usually different from typical occupational or workplace averaging times. In closure, the NAAQS for CO and NO_2 are 35 ppm and 0.053 ppm, respectively.

OBJECTIVE

The purpose of this study was to conduct baseline tests using standardized procedures that can be reproduced in future years to determine how (new) truck designs may have improved the in-cab conditions for drivers. To accomplish the objective, noise level, whole-body vibration from the driver seat, and air quality were determined inside the cab of HDDVs while they were parked with the engine idling at a truck-stop rest area and during actual on-road driving episodes.

EXPERIMENTAL METHOD

Testing

The parked-idling and on-road tests for each truck were conducted over the course of a 2-day period. On the first day of testing, a truck was attached to a utility trailer, driven to a commercial travel center, and then parked in the rest area reserved for extended or overnight truck parking. Each truck was tested at the same travel center, which was located approximately 5 mi west of the city limits of Knoxville, Tennessee, and about 1 mi north of federal Interstate 40. On the second day of testing, the truck with trailer was driven over a prescribed route. The driving course included a mixture of Interstate and rural highway travel. The round trip was approximately 160 mi, of which 75 mi were Interstate travel (I-40) over rolling hills and moderately steep terrain, 50 mi were rural highway travel (US-27 and TN-68) over rolling hills, and 35 mi were Interstate travel (I-75) over relatively flat terrain. For brevity, the US-27 and TN-68 route will just be called “US-27.”

Each truck hauled a 53-ft, fully enclosed, utility trailer that was preloaded with approximately 30,000 lb of palletized topsoil. The same trailer was used for all road tests. A total of 27 trucks were tested; model years were between 2002 and 2008. Four truck manufacturers were represented in the study: Freightliner, International, Kenworth, and Volvo. All trucks had conventional engine-ahead-of-cab design with driver-sleeping berths that are used for long-haul highway driving. The majority of trucks had National seats; several trucks had EzyRider™ seats. No trucks had a closed crankcase ventilation system. All trucks were tested as received or as rented, no trucks were subjected to any special maintenance procedures, and all used locally available standard diesel fuel. Truck model information is included in Table 2.

During the parked-idling test, air sampling occurred according to several predetermined modes of truck engine and in-cab HVAC operation:

1. Engine off–inside air. The truck engine was off; all windows were closed. This condition allowed for the determination of the in-cab air quality while the engine and HVAC systems were both in off mode.

2. Engine on–recirculation air. The truck engine was on with the idling speed adjusted via the cruise control in the range of 900 to 1,000 revolutions per minute (rpm); all windows were closed. The HVAC system was on recirculation mode. In some truck models, this would be the “Max A/C” setting. However, most new model vehicles have a recirculation button on the climate control panel that

TABLE 2 Test Truck Model Information

Truck Manufacturer	VIN	Model Year	Mileage (km)	Engine Make	Engine kW at 1,800 rpm	Engine Displacement	Engine Family Name
Freightliner	1FUJA6CK96LV85582	2006	368,855	Detroit	384	14.0L	5DDXH14.OELY
Freightliner	1FUJA6CK96LV99630	2006	485,462	Detroit	384	14.0L	5DDXH14.OELY
Freightliner	1FUJA6CK97LY17423	2007	306,511	Detroit	384	14.0L	6DDXH14.OELY
Freightliner	1FUJA6CK57LH35085	2007	284,204	Detroit	384	14.0L	6DDXH14.OELY
Freightliner	1FUJA6CK57LH35088	2007	379,834	Detroit	384	14.0L	6DDXH14.OELY
Freightliner	1FUJA6CK37LX35171	2007	465,529	Detroit	384	14.0L	6DDXH14.OELY
Freightliner	1FUJA6CK07PH35539	2007	428,763	Detroit	384	14.0L	6DDXH14.OELY
Freightliner	1FUJA6CK87LY36206	2007	349,109	Detroit	384	14.0L	6DDXH14.OELY
Freightliner	1FUJA6CK97LH78087	2007	153,472	Detroit	384	14.0L	6DDXH14.OELY
International	2HSCNSCR77C350904	2007	329,706	Caterpillar	354	15.2L	6CPXH0928.EBK
International	2HSCNSAR87C374391	2007	370,231	Cummins	336	15.0L	6CEXHO912.XAJ
International	2HSCNSCR57C533363	2007	163,958	Caterpillar	354	15.2L	6CPXH0928.EBK
International	2HSCNSCR37C533460	2007	191,335	Caterpillar	354	15.2L	6CPXH0928.EBK
International	2HSCNSCR17C533439	2007	155,825	Caterpillar	354	15.2L	6CPXH0928.EBK
International	2HSCWAPR68C543354	2007	102,914	Cummins	373	15.0L	7CEXH0912.XAL
Kenworth	1XKADB9X47R190089	2007	325,870	Caterpillar	354	15.2L	6CPXH0928.EBK
Kenworth	1XKADB9X37R190092	2007	239,979	Caterpillar	354	15.2L	6CPXH0928.EBK
Kenworth	1XKADB9X67R190093	2007	200,305	Caterpillar	354	15.2L	6CPXH0928.EBK
Kenworth	1XKADB9X87R190095	2007	175,135	Caterpillar	354	15.2L	6CPXH0928.EBK
Kenworth	1XKADB9X17R190096	2007	216,217	Caterpillar	354	15.2L	6CPXH0928.EBK
Kenworth	1XKADB9X37R190097	2007	239,720	Caterpillar	354	15.2L	6CPXH0928.EBK
Volvo	4V4NC9GH87N455838	2007	319,740	Volvo	347	12.1L	6VTXH12.150S
Volvo	4V4NC9TJ67N461467	2007	367,906	Cummins	354	15.0L	6CEXH0912.XAH
Volvo	4V4NC9GH67N480740	2007	393,592	Volvo	347	12.1L	6VTXH12.150S
Volvo	4V4NC9GH07N482337	2007	451,083	Volvo	347	12.1L	6VTXH12.150S
Volvo	4V4NC9GH08N483909	2008	275,370	Volvo	347	12.1L	6VTXH12.150S
Volvo	4V4NC9GH08N483912	2008	244,443	Volvo	347	12.1L	6VTXH12.150S

dedicates the HVAC system to recirculation of the inside air. The HVAC dash fan switch and the sleeping-berth fan switch were both set at the medium speed settings.

3. Engine on–fresh air. The truck engine was on and set to idle between 900 and 1,000 rpm; all windows were closed. The HVAC system was on. This setting typically allows the (fresh) outside air to be brought into the cab of the truck. The dash fan switch and the sleeping-berth fan switch were both at the medium settings.
4. Engine on–fan off. The truck engine was on and set to idle at between 900 and 1,000 rpm; all windows were closed. However, the HVAC system and both (dash and sleeper) fans were off. This condition allowed for the determination of the in-cab air quality while only the engine idled.
5. Engine off–outside air. The truck engine was off; all windows were open. This permitted outside to enter the truck, and background ambient air concentrations could be established to determine if a relationship existed between outside and inside air.

During the on-road test, the ventilation system was always in Fresh Air mode, and both dash and sleeper-berth fan switches were set to the medium settings. Outside air was not sampled during the on-road test. Additionally, the temperature or climate control setting during all HVAC system operations was adjusted by the occupants at their discretion to maintain the cabin temperature in the comfort region, which was usually between 70°F and 80°F. It should be noted that depending on the truck HVAC configuration, the fresh air or recirculation mode might not use 100% outside air or 100% internal air recirculation. Actually it may involve a mix of both inside and outside air to prevent the buildup of fumes or odors and to prevent oxygen depletion inside the cab.

Sampling Equipment

Noise Level

Noise data were collected using a Cirrus Research 720B sound level meter, which is an integrating, averaging sound level meter. The CR720B makes three sets of measurements known as "Integrators-1, -2, and -3." Integrator-1 provides measurements required by OSHA regulations. Integrator-2 is configured for the OSHA hearing-conservation program. Integrator-3 is configured to give L_{eq} measurements. For the current project, only Integrator-1 and Integrator-3 were selected. The criterion level (CL) is the normalized 8-h average weighted sound level that corresponds to the maximum permitted daily exposure. The CL for Integrator-1 was 90 dB, and the CL for the Integrator-3 was 85 dB. For Integrator-1, 80 dB was used as a threshold in calculating the average weighted sound level. This means that sound levels below the threshold are excluded from all averaging for Integrator-1. Integrator-3 does not use a threshold value. The highest value reached by the sound pressure at any instant during a measurement period is called the "peak value"; it is used with the C-frequency weighting (dBC). The L_{Min} and L_{Max} are the minimum and maximum recorded sound levels, respectively; both use the A-frequency weighting.

Whole-Body Vibration

Several PCB Piezotronic transducer accelerometer pads, Model 356B40, were used to measure WBV from the driver and passenger seats. On the driver seat, one pad was installed on each of the back support and the rump or cushion area of the seat. On the passenger seat, only a single pad was installed on the cushion area of the seat. Eight Piezotronic accelerometers, Model 370D1FD20GA, were also used to measure vibration from the cab and truck body frame. Data from the driver back pad, passenger seat cushion, and the eight external sensors, however, will not be discussed in this report. Two instrument systems were used to acquire and analyze the vibration data: a Larson Davis, human vibration meter (HVM), Model 100; and a Dewetron (DEWE), data acquisition system, Model 5000. The HVM system collected data from the driver seat (cushion) only. The DEWE system collected data from the seats and other sensors located on the truck frame and body of the cab. Occasionally the base RMS method is insufficient for evaluating WBV. In these situations, ISO guidelines recommend other computational methods. In the present report, only data that were collected from the driver seat pad via the HVM system will be discussed using the basic RMS method of analysis. Data collected using the DEWE system and other computational methods will be discussed in later reports.

Air Quality

The in-cab air quality was determined by measuring mass concentrations of CO, NO_X, and $PM_{2.5}$. A Thermo Electron, Model 48C analyzer, which employs infrared adsorption as the detection principle, was used to measure CO concentration. A Teledyne, Model 200E analyzer, which employs chemiluminescence as the detection principle was used to measure NO and NO_2 concentrations. This instrument also reports NO_X concentration. Probes were connected to the input sampling port of the analyzers to bring continuous air into the analyzers during the parked-idling test. During the on-road test, a SKC low-flow portable personal sampling pump, Model 224-PCXR8, was used to collect air samples into 16-L Tedlar bags via the Teflon probe. It should be noted that the bag samples were analyzed later in the laboratory for CO and NO_X concentrations, using the 48C and 200E instruments previously described.

Two instruments were used for measuring $PM_{2.5}$ concentrations: a Thermo Electron, Model DataRam (DRam); and a Climet, optical particle counter (OPC), Model CI-7300. Both instruments use light scattering from particles as the detection principle. The DRam also uses a cyclonic-type 2.5-micron cut-off separator. The OPC samples continuously in six channels ranging from 0.3 microns to greater than 10 microns. Size ranges were 0.3 to 0.5 µm, 0.5 to 0.7 µm, 0.7 to 1.0 µm, 1.0 to 5.0 µm, 5.0 to 10.0 µm, and >10 µm. Using the counts of the number of particles in each size range or channel from the OPC, the PM mass concentration was calculated by a numerical algorithm that converted particle size number into concentration less than or equal to the 2.5 microns of aerodynamic diameter associated with the $PM_{2.5}$. Flow rates for the DRam and OPC were 2 L/min and 28.3 L/min, respectively.

A Teledyne, Model 700, mass flow calibrator was used with EPA protocol calibration gas to calibrate the CO and NO_X analyzers. No certifiable standards exist to calibrate the PM instruments. However, calibration verification was performed on the DRam and OPC, as specified by manufacturer operating instructions. As an additional check of the accuracy of the DRam and the OPC, several collocation experiments were conducted using a Thermo Electron, Model 1400a, tapered element oscillating microbalance (TEOM) located at the Knox Air Pollution Board's ambient monitoring site in Knoxville, Tennessee.

RESULTS AND DISCUSSION

Noise Level

In-cab noise level data were collected and analyzed from only 22 trucks. In general, the measured noise levels were consistently higher during Interstate travel relative to travel on the rural highway. A summary of the overall average noise levels from all trucks is shown in Table 3. The maximum peak value was 138.8 dBC, and the average minimum and maximum values were 65.3 and 92.5 dBA, respectively. The mean TWA for Integrator-1 (30.6 dBA) is lower than the value for Integrator-3 (59.8 dBA). This was because the CL for Integrator-1 was higher than the CL for Integrator-3, and Integrator-1 used a threshold value of 80 dB for calculating the average weighted sound level, which means that levels below this threshold were excluded from averaging for Integrator-1. Even so, noise levels were not above the OSHA (90 dBA) and NIOSH (85 dBA) standards.

Whole-Body Vibration

Data from the HVM were collected and analyzed from only 23 trucks. In general, the ranges of instantaneous frequency-weighted RMS accelerations measured in the three axes were between 0.1 and 0.6 m/s^2 in the x-axis, 0.15 and 0.7 m/s^2 in the y-axis, and 0.15 and 0.8 m/s^2 in the z-axis. Three events occurred where the instantaneous acceleration exceeded 1 m/s^2 during driving over rough road conditions. The TWA equivalent (RMS) accelerations for the three translational axes of vibration and the sigma (comfort) values from the driver seat cushion (only) are listed in Table 4 per roadway. The results indicated that vibration from the seats were generally below the EU exposure action level: 0.5 m/s^2 for an 8-h driving day. However, the comfort index of the seats, in the majority, fell within the

TABLE 3 Overall Average Sound Level Recorded During On-Road Test

				Int-1 (OSHA)		Int-3 (NIOSH)	
Parameter	Peak (dBC)	L_{Min} (dBA)	L_{Max} (dBA)	L_{eq} (dBA)	8-h TWA (dBA)	L_{eq} (dBA)	8-h TWA (dBA)
Min.	111.2	61.3	87.8	35.6	20.2	73.7	57.1
Max.	138.8	69.3	97.5	73.3	45.3	79.5	62.8
Avg.	118.1	65.3	92.5	53.6	30.6	76.5	59.8

TABLE 4 Overall Average Acceleration and Sigma Values per Roadway

Roadway	Parameter (m/s^2)	x-Axis	y-Axis	z-Axis	Σ (comfort)
I-40	Min.	0.20	0.21	0.23	0.33
	Max.	0.35	0.37	0.41	0.51
	Avg.	0.25	0.31	0.31	0.42
I-75	Min.	0.21	0.23	0.26	0.35
	Max.	0.34	0.44	0.41	0.55
	Avg.	0.28	0.32	0.35	0.47
US-27	Min.	0.19	0.20	0.25	0.34
	Max.	0.36	0.45	0.42	0.55
	Avg.	0.28	0.32	0.35	0.47

"little uncomfortable" region, which is one step removed from the best index, which is the "not uncomfortable" region.

Air Quality

Air quality data were collected from a total of 27 trucks. Collocation experiments involving the $PM_{2.5}$ analyzers demonstrate that a linear equation ($R^2 \sim 0.91$, $p < .0001$) was the best-fit line between the OPC and TEOM data, and a two-level polynomial or quadratic equation ($R^2 \sim 0.94$, $p < .0001$) was the best-fit line for the DRam and TEOM data. Thus, the actual $PM_{2.5}$ data from the DRam and OPC were corrected to TEOM values. The R^2 value between the TEOM-corrected OPC and DRam data was approximately 0.86, which was reasonable ($p < .0001$).

Parked-Idling Test

A summary of the overall average 1-h concentrations measured during the parked-idling test is shown in Table 5 for the five Engine–HVAC modes of operation. The zero minimum values listed in the table actually reflect the lower detection limit of the analyzers. Inspection of the overall average data suggests immediately that the different modes of truck engine and HVAC operation have a definite influence on the air quality inside the cab. Highest average CO (585 ppb) and NO_X (643 ppb) concentrations occurred during engine on (or idling) and with the HVAC system in recirculation air mode; highest average $PM_{2.5}$ concentrations (51 μg/m^3 OPC and 22 μg/m^3 DRam) occurred during engine on and with the HVAC system in fresh air mode. For the most part, concentrations of all pollutants were lowest when both the truck engine and HVAC were off. Even when the HVAC system was off and the truck engine was on, the in-cab concentrations were still generally higher than both the inside and outside background concentrations that were measured during the engine off conditions. Overall it appeared that extended parked engine idling at the truck stop rest areas has the potential to be self-polluting with respect to the in-cab air quality for the occupants.

Nonetheless, the in-cab CO concentrations were low relative to the OSHA PEL of 50 ppm (0.5 ppb) and should not pose a health problem for the occupants of the trucks. The NO_X concentrations were also relatively low, and it was improbable that the OSHA TWA value of 25 ppm (25,000 ppb) for NO or the 5 ppm (5,000 ppb) ceiling for NO_2 were exceeded since average NO_X concentrations were around 0.5 ppm (500 ppb) and usually only between 70% and 80% of the NO_X were NO concentration. However, the $PM_{2.5}$ concentrations were relatively high for most of the trucks that were tested, especially during the three engine-on conditions. Concentrations were also moderately high outside the trucks. The average $PM_{2.5}$ concentrations for several of the engine-on conditions were higher than the EPA NAAQS annual average (15 μg/m^3) and the 24-h standard (35 μg/m^3). It must be noted that these EPA standards are ambient (outside) monitoring standards requiring 3-year averaging times and were used here because there are no occupational standards for $PM_{2.5}$. Both analyzers also recorded very high maximum $PM_{2.5}$ concentrations. Overall the $PM_{2.5}$ concentrations as measured by the OPC were about 2.5 times larger than the $PM_{2.5}$ values reported by the DRam for the same group of trucks. The correlation coefficient or the R-value between the OPC and the DRam using the 1-h average $PM_{2.5}$ data was approximately 0.81 ($p < .0001$).

On-Road Test

A summary of the 15-min concentrations is shown in Table 6 for the three roadways. Review of the overall average data shows that the

TABLE 5 Overall Average Concentrations for Engine: HVAC Modes of Operation

Pollutant	Parameter	Engine Off– Inside Air	Engine Off– Outside Air	Engine On– Fan Off	Engine On– Fresh Air	Engine On– Recirculation Air
CO (ppb)	Min.	0	0	26	14	0
	Max.	975	1,041	2,514	1,502	3,287
	Avg.	396	295	508	472	585
NO_X (ppb)	Min.	0	1.2	31	75	14
	Max.	553	479	6,254	2,518	7,266
	Avg.	120	119	624	466	643
$PM_{2.5}$ OPC (μg/m^3)	Min.	4	7	15	12	6
	Max.	52	111	120	132	90
	Avg.	14	27	48	51	28
$PM_{2.5}$ DRam (μg/m^3)	Min.	4	4	4	4	4
	Max.	38	58	132	115	34
	Avg.	7	13	19	22	9

TABLE 6 Overall Average In-Cab Concentrations During Driving

Pollutant	Parameter	Roadway I-40	I-75	US-27
CO (ppb)	Min.	48	0	0
	Max.	2,340	1,208	854
	Avg.	412	347	281
NO_X (ppb)	Min.	17	3	11
	Max.	301	559	128
	Avg.	110	95	40
$PM_{2.5}$ OPC (mg/m^3)	Min.	4	4	4
	Max.	16	12	14
	Avg.	8	7	7
$PM_{2.5}$ DRam (mg/m^3)	Min.	4	4	4
	Max.	143	168	177
	Avg.	12	13	12

in-cab concentrations were very low for all measured pollutants. Overall average CO, NO_X, and $PM_{2.5}$ concentrations were around 350 ppb, 80 ppb, and 10 μg/m^3, respectively. In particular for the gaseous pollutants, the concentrations were somewhat higher during driving on the Interstates than during driving on the rural highways, and the concentrations on I-40 were somewhat higher than concentrations measured on I-75.

In general, the $PM_{2.5}$ concentrations were relatively flat across all the trucks that were tested. The *R*-value between the OPC and the DRam using the average 15-min $PM_{2.5}$ data was approximately 0.65 ($p < .0001$), which was lower than the *R*-value between the DRam and OPC for the park-idling test. The DRam recorded several unusually high $PM_{2.5}$ concentrations as shown by the maximum values that the OPC did not record. At this juncture, it is strongly felt that these high values from the DRam were outliers that were caused by the vibrating environment of the truck. For example, severe jarring of the truck occurred when the wheels encountered disruptions in the surface of the roadway. Apparently the $PM_{2.5}$ separator vibrated to such an extent that most of the particles passed through the separator, so that it was unable to cut the size at 2.5 microns, resulting in an overestimation of $PM_{2.5}$.

CONCLUSIONS

Neither the OSHA nor the NIOSH equivalent 8-h TWA standards were exceeded by any test truck. Higher noise averages were generally observed while the trucks were driven on the federal Interstate relative to the state highway. It is believed that noise from tires, engine rpm, and wind impacting the cab at higher road speed contributed to the elevated noise levels measured during Interstate travel because there are higher speed limits on the Interstate.

The vibrations from the driver seat were generally well below the EU standard for an 8-h driving day exposure level. Several isolated incidents occurred where the exposure limit value was exceeded, but for the most part, these happened while the trucks were driven on poorer road pavement conditions. Generally, the federal Interstate roads are maintained in a better condition than most state rural highways; however, huge variability exists between roadway maintenance from region to region even on the Interstate.

Overall CO, NO_X, and $PM_{2.5}$ concentrations were relatively low inside the cab when both the engine and HVAC were in off modes. Highest CO and NO_X concentrations occurred during modes of engine on and HVAC in recirculation; high $PM_{2.5}$ concentrations occurred during modes of engine on and HVAC in fresh air and modes of engine on and fan off. These results tend to demonstrate that long-haul trucks have a tendency to self-pollute the cab during periods of (extended) parked-idling conditions. It is believed that this problem and the close proximity of many trucks idling at the same time in the truck-stop rest areas create conditions for diesel exhaust to enter the cab via the HVAC system or naturally from air infiltration around window and door seals and from other areas. Measured concentrations of CO and NO_X for all of the engine–HVAC modes of operation, nonetheless, were well below the OSHA 8-h TWA and should not pose health problems for drivers sleeping in the cabs during rest periods. However, measured concentrations of $PM_{2.5}$, which is known to cause certain respiratory and health problems, were around the limits set by the EPA for the NAAQS for the 24-h and annual averages. These results were in line with those of similar studies that had measured in-cab concentrations during parked-engine-idling conditions at another truck-stop rest area and ambient air monitoring along an Interstate interchange.

During driving on the road, the CO, NO_X, and $PM_{2.5}$ concentrations were relatively low inside the cab, suggesting that there was much less of a chance for the trucks to be self-polluting the cabin area. However, the in-cab concentrations were usually higher while driving on the federal Interstates relative to driving on the state highways, even though the overall concentrations were low. This is believed to be because the vehicle densities on the Interstate system are higher, and because the pollutants enter the vehicle via the HVAC system. These results suggest that the highway environment, rather than the truck itself, is the cause of the air pollution exposure for the truck driver while driving. Given this fact, possible in-cab driver exposures may also increase when trucks are driven through dense urban or metropolitan areas where air pollutants from high density traffic and other sources in the ambient air are also at elevated levels.

ACKNOWLEDGMENTS

This study was funded by the Federal Motor Carrier Safety Administration for improving heavy-duty diesel truck ergonomics to reduce fatigue and improve driver health and performance. The authors thank Martin Walker for support and directions.

REFERENCES

1. *Hours-of-Service of Drivers.* 49 CFR, Part 395. Federal Motor Carrier Safety Administration, U.S. Department of Transportation, 2007.
2. Robinson, G. S., J. G. Casali, and S. E. Lee. *Role of Driver Hearing in Commercial Motor Vehicle Operation: An Evaluation of the FHWA Hearing Requirement.* FHWA Contract No. DTFH61-C-00172. Office of Motor Carrier Research and Standards, Washington, D.C., 1997.
3. Seshagiri, B. Occupational Noise Exposure of Operators of Heavy Trucks. *American Industrial Hygiene Association Journal,* Vol. 59, No. 3, 1998, pp. 205–213.
4. International Organization for Standardization. *Mechanical Vibration and Shock- Evaluation of Human Exposure to Whole-Body Vibration: Part 1. General Requirements.* Ref Document 2631-1. ISO, Geneva, Switzerland, 1997.
5. European Commission. *Directive 2002/44/EC of the European Parliament and of the Council of 25 June 2002 on the Minimum Health and Safety*

Requirements Regarding the Exposure of Workers to the Risks arising from Physical Agents (Vibration): Article 16(1) of Directive 89/291/EEC. Official Journal of the European Communities, 2002, p. L177.
6. Dupuis, H., and G. Zerlett. *The Effects of Whole-Body Vibration.* New York, Springer-Verlag, 1986.
7. Bongers, P. M., and H. C. Boshuizen. *Back Disorders and Whole-Body Vibration at Work.* Academsch Proefschrift, Universiteit van Amsterdam, Netherlands, 1990.
8. Griffin, M. J. *Handbook of Human Vibration.* Academic Press, London, 1990.
9. Seidel, H. Selected Health Risks Caused by Long-Term Whole-Body Vibration. *American Journal of Industrial Medicine,* Vol. 23, 4, 1993, pp. 589–604.
10. Miyamoto, M., Y. Shirai, Y. Nakayama, Y. Gembun, and K. Kaneda. An Epidemiologic Study of Occupational Low Back Pain in Truck Drivers. *Journal of Nippon Medical School,* Vol. 67, No. 3, 2000, 186–190.
11. Bovenzi, M., F. Rui, C. Negro, F. D'Agostin, G. Angotzi, S. Bianchi, L. Bramanti, G. Festa, S. Gatti, I. Pinto, L. Rondina, and N. Stacchini. An Epidemiological Study of Low Back Pain in Professional Drivers. *Journal of Sound and Vibration,* Vol. 298, 3, 2006, 514–539.
12. *Diesel Emissions and Lung Cancer: Epidemiology and Quantitative Risk Assessment: A Special Report of the Institute's Diesel Epidemiology Expert Panel.* Health Effects Institute, Flagship Press, North Andover, Mass., 1999.
13. *Health Assessment Document for Diesel Engine Exhaust.* Publication No. EPA/600/8-90/057F. National Center for Environmental Assessment, Office of Research and Development, U.S. Environmental Protection Agency, Washington, D.C., 2002.
14. Doraiswamy, P., W. T. Davis, T. L. Miller, N. Lam, and P. Bubbosh. Air Quality Measurements Inside Diesel Truck Cabs During Long-Term Idling. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1987,* Transportation Research Board of the National Academies, Washington, D.C., 2006, pp. 82–91.
15. Davis, M. E., T. J. Smith, F. Laden, J. E. Hart, A. P. Blicharz, P. Reaser, and E. Garshick. Driver Exposure to Combustion Particles in the U.S. Trucking Industry. *Journal of Occupational and Environmental Hygiene,* Vol. 4, 11, 2007, pp. 848–854.
16. Miller, T. L., J. S. Fu, B. Hromis, J. M. E. Storey, and J. E. Parks II. Diesel Truck Idling Emissions: Measurements at PM2.5 Hot Spot. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2011,* Transportation Research Board of the National Academies, Washington, D.C., 2007, pp. 49–56.
17. Laden, F., J. E. Hart, T. J. Smith, M. E. Davis, and E. Garshick. Cause-Specific Mortality in the Unionized U.S. Trucking Industry. *Environmental Health Perspectives,* Vol. 115, No. 8, 2007, pp. 1192–1196.
18. *Air Contaminants.* 29 CFR, Part 1910.1000, Occupational Safety and Health Administration, U.S. Department of Labor, 2007.
19. Heywood, J. B. *Internal Combustion Engine Fundamentals.* McGraw-Hill, New York, 1988.
20. *National Primary and Secondary Ambient Air Quality Standards.* 40 CFR, Part 50.13, U.S. Environmental Protection Agency, 2007.

The Truck and Bus Safety Committee peer-reviewed this paper.