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The Effects of Altitude on Heavy-Duty Diesel Truck On-Road Emissions

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On-road measurements of carbon monoxide, hydrocarbons, and nitric oxide from 5772 heavy-duty diesel trucks at five locations in the United States and Europe show slightly increasing emissions with increasing altitude.The result for nitric oxide showed a statistically significant increase of 4.1 ± 1 gNO/kg of fuel consumed/km increase in altitude. The increases for CO and HC were also statistically significant.

Introduction

Since the late 1960s in the United States, attention to vehicle emissions has largely been focused on the regulation and control of exhaust emissions from light-duty gasoline powered vehicles. This focus has been because of health concerns that related to the direct emissions of carbon monoxide (CO) and unburned hydrocarbons (HC). As our understanding of ozone formation and transport has advanced, many areas of the country have become more interested in reducing oxides of nitrogen (NO_x) emissions (*1*). In addition, particulate emissions have gained notoriety as a reported public health risk (*2*).

These and other factors have brought new attention to diesel truck emissions. Because of the design of the compression ignition engine, diesel vehicles as a rule emit low levels of CO and HC, but larger amounts of NO_x and particulates, while being extremely fuel efficient. California has estimated that mobile compression ignition engine sources contribute 27% of the total NO_x emissions and 74% of the particulate emissions while accounting for only 4−6% of the total on-road registered vehicles (*3*−*5*).

A recent review by Yanowitz et al. (*6*) describes the knowledge base of heavy-duty diesel emissions which has been collected since the early 1970s. These data are largely made up of carefully controlled engine and chassis dynamometer measurements of which an unrepresentatively large fraction are urban transit buses. In addition, fleet average emissions from several tunnel studies and a listing of published remote sensing measurements are reported and compared.

There is little reported in the literature of the effects of altitude on compression ignition engine emissions. Human et al. and Chaffin and Ullman developed a method to simulate changes in altitude by reducing the pressure to both the intake and the exhaust of an engine on a dynamometer (*7*, *8*). Both studies reported emissions increases in CO, HC, CO_2, and particulate matter with increasing altitude but no significant change in NO_x emissions. Similar results were obtained by Lizhong et al. using a similar approach (*9*). Graboski and McCormick reported on measurements made at 1609 m and sea level on three engines that CO and particulate matter emissions increased with increasing altitude but not NO_x emissions (*10*).

Experimental Section

We report in this paper remote sensing measurements of in-use heavy-duty diesel trucks collected between 1997 and 1999 at five different locations and elevations in the United States and Europe. These locations include Anaheim, CA (elevation 104 m), San Marcos, TX (elevation 198 m), Golden, CO (elevation 1695 m), Dumont, CO (elevation 2530 m), and on the Gotthard route near the village of Wassen in the Canton of Uri, Switzerland (elevation 884 m). Temperature and humidity at the time of measurement also varies and is noted in Table 1.

The remote sensing instrumentation and measurement technique (FEAT, Fuel Efficient Automobile Test) for light-duty vehicles has been discussed in a number of publications (*11*−*14*). Double-blind studies have shown the CO measurements to be correct to within ±5% and within ±15% for HC (*15*, *16*). On-road fleet average emissions for CO, HC, and NO by model year have been shown to correlate extremely well ($r^2 > 0.96$) with fleet IM240 dynamometer measurements (*17*). Light-duty vehicles have low level exhaust pipes and as such the remote sensing equipment is normally used at ground level with a sensing beam height of 30 cm. Successful on-road emissions measurements of trucks in the U.S. and Europe require hardware and software changes from the light-duty setup.

In the U.S., almost all heavy-duty trucks have elevated exhaust stacks with heights of approximately 4 m. This requires the sensing beam to be 4−4.5 m off the ground to sample truck exhaust. For the U.S. studies we used scaffolding to raise the source and detector to the necessary height and incorporated an external triggering device. Either an ultrasonic position sensor (Ultra-Beam SUA925QD, Banner Engineering Corp. Minneapolis, MN) or a retroreflective infrared position sensor (Maxi-Beam RSBLV, Banner Engineering Corp. Minneapolis, MN) was used to start the measurement (see Figure 1). The scaffolding was stabilized with the addition of guy wires and ground anchors to limit tower vibrations. Research personnel were only on the towers during setup and alignment and not during the measurements. The external position sensor was necessary because with the equipment elevated on the scaffolding the normal trigger (blocking and unblocking the sensing beam) never occurs. We also extended the exhaust data collection time from 0.5 s to 1.0 s to allow for some imprecision in the start sequence. At all of the sites, calibrations were carried out according to standard operating procedures using a certified 4 gas mixture (CO, propane, CO_2, and NO) in nitrogen.

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TABLE 1. Measurement Site Statistics, Characteristics, Environmental Data, and NO Humidity Correction Factors

site collection dates	number of measurements	estimated speeds (km/h)	altitude (m) grade	mean temp and dew point (°C)	mean pressure (kPa)	C_f^a
Anaheim, California	3348	20−35	104			
Aug. 25, 1997	345		+4%	31.2/14.4	100.8	0.99
Aug. 26, 1997	575			31.2/13.9	100.8	0.99
Aug. 27, 1997	931			30/13.9	100.8	0.99
Aug. 28, 1997	702			29.3/13.9	100.8	0.99
Aug. 29, 1997	795			31.2/15	100.7	1.00
San Marcos, TX	322	20−40	198			
Aug. 6, 1998	322		+0.3%	28.9/23.3	99.2	1.16
Wassen, Switzerland	1720	50−60	884			
June 9, 1998	931		+4.4%	13.5/ 5.9	89.7	0.93
June 10, 1998	521			13.5/9.9	89.0	0.96
June 12, 1998	268			5/0	89.6	0.91
Golden, CO	188	5−25	1695			
May 13, 1999	62		+0.7%	20.6/8.3	81.8	0.96
May 14, 1999	126			26.1/8.3	82.0	0.96
Dumont, CO	194	20−40	2530			
May 17, 1999	194		+2.5%	11.1/−6.7	75.4	0.90

[a] This is the NO humidity correction factor by which all NO emissions are multiplied before reporting herein.

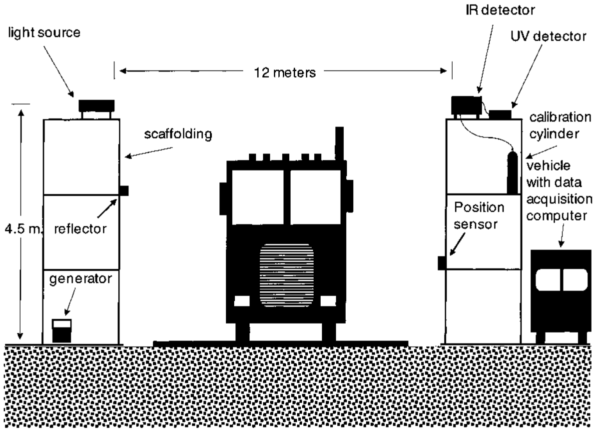

FIGURE 1. Measurements of elevated exhaust stacks, such as heavy-duty trucks in the U.S., were made using scaffolding as shown. The reflector was only used in conjunction with the retroreflective position sensor.

Two different techniques were used to measure NO emissions during the five studies. The study carried out at the weigh station in Anaheim, CA utilized our first generation nondispersive UV detector to measure NO emissions. This instrument was fully described by Zhang et al. (*18*) and suffered from a lower than desired NO sensitivity (noise on individual readings of ± 3.6 gNO/kg) and interference from exhaust hydrocarbons, which was important for gasoline powered vehicles (*14*). However, fleet average readings were robust, and the HC interference is not relevant because of the very low HC emissions from heavy-duty diesel trucks.

The remaining four studies used our second generation NO detector which utilized a dispersive UV grating monochromator. A complete description of this instrument, which includes a side-by-side intercomparison with the first generation unit, has been provided by Popp et al. (*14*). This instrument features an order of magnitude improvement in sensitivity for NO and the elimination of the interference from exhaust hydrocarbons. As discussed elsewhere (*13*) ambient CO_2 is automatically eliminated by analysis of air in front of as well as during the exhaust plume exposure.

Three of the four U.S. sites (Anaheim, San Marcos, and Dumont) were exit ramps from weigh stations. The Anaheim site was located on northbound 91 south of Corona, CA, and measurements were collected between 7 a.m. and 1 p.m. August 25−29, 1997. The entrance to the station divided the trucks into two lanes, one for loaded trucks and one for unloaded. Actual weights are not available, but the lane status of the trucks is recorded in the database. The measurements were made downstream of the scales as the trucks exited the weigh station and proceeded uphill to merge back into the flow of traffic. On August 25, 26, and 29 the registration status of the tractors was noted as having a California license plate or not having a California license plate. In addition some speed and acceleration data were also collected.

The San Marcos site was a weigh station on the northbound side of interstate 35, 2.5 miles north of San Marcos, TX. Measurements were made approximately 100 m beyond the scales between 6 p.m. and 10 p.m. August 6, 1998 at the exit to the scales.

The Golden site was an exit from a large corporate distribution center. The trucks would arrive with a load to drop off and leave with a new load without any engine down time. The remote sensing scaffolding was approximately 25 m beyond the exit gate where all trucks were accelerating after a stop. Data were collected on May 13 and 14, 1999 between the hours of 9 a.m. and 5 p.m.

Dumont is located on interstate 70 on the eastern slope of the continental divide 45 miles west of Denver. We collected data at the uphill exit from the eastbound weigh station approximately 100 m beyond the scales between 9 a.m. and 3 p.m. on May 17, 1999.

The European study took place on the European highway A1, a major north south highway which crosses the Alps in Switzerland. A repavement project just south of Wassen in the Canton of Uri had temporarily restricted the two southbound lanes to a single lane. Data were collected between 8 a.m. and 5 p.m. June 9, 10, and 12, 1998. The remote sensing equipment was located in the last 100 m of the southbound road works just before the single lane traffic was allowed to return to two lanes. At Erstfeld, which is just north of the village of Wassen, all of the trucks were required to stop for a weight inspection. Video information from the June 9 measurements was used in combination with the inspection data to assign vehicle make and country of registration for 806 trucks and weights for 387. This is the only location were vehicle data is available.

European trucks almost exclusively (the exceptions are construction equipment such as dump trucks) have ground level exhaust systems which enabled the FEAT system to be set up as for light-duty vehicles, although several modifications to the software were required. The original FEAT software triggered a 0.5 s data scan when the IR source was

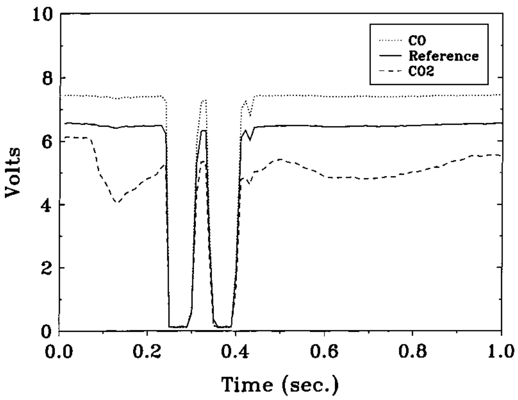

FIGURE 2. Heavy-duty trucks in Europe have low level exhausts, and the FEAT can be used in its standard configuration. The figure is a 1-s voltage vs time graph of data from under a heavy-duty truck collected at 100 Hz with the modified software. HC and NO data obtained are not shown.

fully blocked and subsequently restored as determined by the instrument's reference channel. With the instrument's beam height set around 30 cm above the road surface this normally results in a single beam block for the typical passenger car. In the event that the beam is interrupted during the half-second data scan the computer halts the measurement process and upon the second beam unblock commences a new 0.5 s data scan. For European trucks this stop/restart mechanism was disabled in such a way that after the data scan started it continued uninterrupted for 1 s of data collection. Any obstructions encountered during the data scan, such as additional wheels or trailer undercarriages, would be removed with postprocessing, and the remaining clear airway could be used to analyze the exhaust emissions from the truck. Since this roadway had a mix of heavy- and light-duty vehicles, the program was also modified to allow the operator to manually initiate measurements on heavy-duty vehicles only. This was largely successful; however, a few light-duty measurements remain in the database.

Figure 2 shows a 1 s voltage scan taken underneath a tractor-trailer combination. The data scan was initiated after the drive wheels of the tractor cleared the beam and continued for 0.6 s after the two trailer wheels had passed the beam. A large portion of exhaust is seen in the CO_2 voltage decrease at 0.1 s after the drive wheels, and a second wave of diluting exhaust spreads from 0.5 to 0.9 s. The reference channel provides an unequivocal record of physical blockages of the sensing beam (the two wheels and bumper) and provided the key information for postprocessing the data. It was not always possible to measure every truck. Car transports in particular have such a low slung trailer carriage that few if any clear airways existed to monitor the exhaust.

Results

Table 1 provides a number of important details for the five locations from which data were collected. The measured ratios of CO/CO_2, HC/CO_2, and NO/CO_2 are recorded from which grams of pollutant per kilogram of fuel burned can be calculated. All of the reported emission values for hydrocarbons are reported in propane equivalents. Typically diesel truck emissions for oxide of nitrogen emissions are reported as NO_x ($NO + NO_2$). Because our instruments do not measure NO_2 all values reported are the mass of NO emissions only and have not been corrected or scaled to account for any additional NO_2 emissions. The grams of pollutant/kilogram of fuel calculations assume a carbon weight percent for the fuel of 87%. In addition, local temperature, dew point, and atmospheric pressure were collected from local monitoring sites to adjust our gNO/kg of fuel values on a daily basis using the humidity correction equation specified in the U.S. Code of Federal Regulations (*19*). These correction factors are identified as C_f in Table 1. All of the reported NO values in this paper have been multiplied by these correction factors. Each location's measured ratio and g/kg data and any supporting data which were collected have been saved to FoxPro databases and are available from our website at www.feat.biochem.du.edu (the NO data in the database are not corrected for humidity).

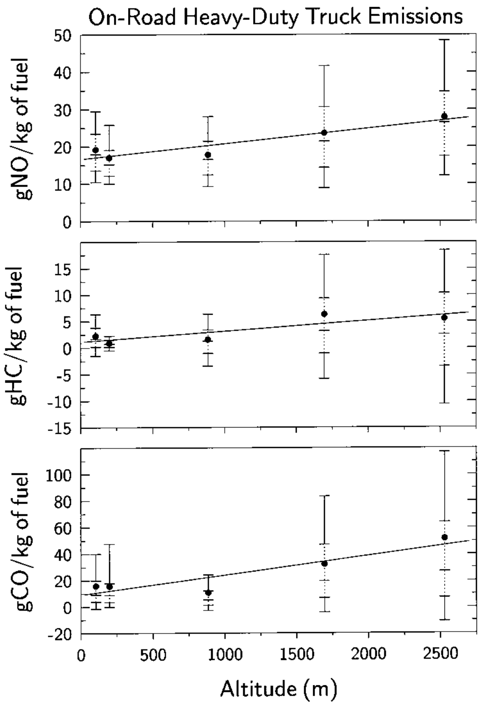

FIGURE 3. Plots of gNO (humidity corrected), gHC, and gCO emissions/kg of fuel consumed versus altitude for the five sites listed in Table 1. Horizontal lines are plotted at each altitude for the 10th, 25th, 50th, 75th, and 90th percentiles with the solid points representing the mean values. The slopes and intercepts for the regressions are 4.1 ± 1 gNO/kg of fuel/km and 16.6 ± 1.4 gNO/kg of fuel, 2 ± 0.7 gHC/kg of fuel/km and 1.2 ± 1 gHC/kg of fuel, and 14.8 ± 4 gCO/kg of fuel/km and 9.2 ± 5.6 gCO/kg of fuel, respectively. HC emissions are reported as propane equivalents and the NO emissions are reported as NO not NO_2.

Figure 3 is a plot versus altitude of grams of pollutant/kilogram of fuel used for each of the five locations listed in Table 1. Horizontal lines are plotted for the 10th, 25th, 50th, 75th, and 90th percentiles with the solid points representing the mean values. The line plotted is an unweighted regression of the means for each species. The NO regression has a slope of 4.1 ± 1 gNO/kg of fuel/km ($F = 18.5$, $p < 0.02$), an intercept of 16.6 ± 1.4 gNO/kg of fuel, and an r^2 of 0.86. The regression for HC has a slope of 2 ± 0.7 gHC/kg of fuel/km ($F = 7.7$, $p < 0.34$), an intercept of 1.2 ± 1 gHC/kg of fuel, and an r^2 of 0.72. The CO regression has a slope of 14.8 ± 4 gCO/kg of fuel/km ($F = 13.8$, $p < 0.2$), an intercept of 9.2 ± 5.6 gCO/kg of fuel, and an r^2 of 0.82. The positive slopes found for each of the pollutants were found to be statistically valid at the 95% confidence level when the distributions from the end points (Anaheim, CA and Dumont, CO) are tested against the null hypothesis using a computational resampling method (*20*). This type of analysis has been shown (*20*) to be robust in the face of different population distributions in the data.

Table 2 displays data from Anaheim, CA showing emission rates as a function of vehicle type (transfer trucks and nontransfer trucks), loaded or empty lane, and in-state or out-of-state plated registration. Transfer trucks have been

TABLE 2. California Mean Emissions Data by Lane, Vehicle Type, and Registration

characteristic	mean gCO/kg (number)	mean gHC/kg[a] (number)	mean gNO/kg[b] (number)
loaded lane	16.9 (1390)	2.0 (1346)	17.4 (1246)
empty lane	15.4 (2269)	2.4 (2223)	20.3 (2102)
nontransfer trucks	15.8 (2427)	2.0 (2350)	18.0 (2168)
transfer trucks	16.2 (1232)	2.8 (1219)	21.4 (1180)
California plated[c]	15.9 (1636)	2.2 (1576)	19.4 (1466)
no California plates[c]	14.7 (306)	1.5 (293)	16.0 (249)

[a] HC emissions are reported as propane equivalents. [b] NO emissions are reported as NO not NO_2. [c] Data collected on 8/25, 8/26, and 8/29 only. California plated trucks displayed at least a California license plate on the tractor.

defined here as locally operated single or multitrailered construction trucks involved in hauling dirt, rock, or paving material, and at this site most were unloaded at the time of measurement.

Discussion

This collection of data sets is the first attempt to quantify emissions changes with altitude from on-road compression ignition vehicles. The collection has diverse characteristics common to on-road fleets with an added attribute of a non-U.S. fleet.

Remote sensing data sets are traditionally very large with many thousands of measurements. In contrast, three of these data sets are smaller with each having less than 350 measurements. NO emissions from heavy-duty diesel vehicles are unlike gasoline vehicle emissions in that they are nearly normally distributed not gamma distributed (*21, 22*). Because of this fact, smaller data sets can be acquired for NO on heavy-duty vehicles and still have the ability to produce meaningful averages. This is not the case for CO and HC emissions from heavy-duty vehicles. They are gamma distributed just as light-duty vehicles, and we believe that many of our sample sets may be too small to fully describe the distributions at those sites.

The most comparable data sets to compare our on-road NO emissions with are several tunnel studies conducted during the 1990s (*23, 24*) and remote sensing data collected by Jimenez et al. (*25*); however, these data sets have all been collected at higher speed steady-state interstate driving. The available tunnel NO_2 results range from 34.5 ± 1.2 to 48.8 ± 10.6 g/kg (*6*), and Jimenez et al. have reported an NO_2 value of 45 ± 2 g/kg (*25*). NO_2 emissions collected from chassis dynamometer work on class 8a and 8b trucks ranges from 27.6 ± 1.4 to 36.1 ± 1.8 g/kg (*6*). Our results, converted to NO_2 and assuming 92% of emissions are NO (*25*), range from 28.2 ± 0.4 to 46.1 ± 1 g/kg in reasonable agreement with the literature values.

A simplistic look at combustion chemistry would lead one to conclude that our observations and the literature are consistent in finding that at higher elevations lower air-to-fuel ratios result in increases in tailpipe CO, HC, CO_2, and particulates. It would follow then that NO_x emissions should also increase as the air-to-fuel ratio moves toward stoichiometry (increasing power) and up the NO_x emissions curve (*26*). For example, the transfer trucks observed in California exhibit this correlation that when CO and HC emissions increase NO emissions increase as well (see Table 2). However, modern diesel engines are complex, and NO formation depends on air/fuel ratio, injection delay, cylinder pressure, turbine intercooler temperature, and other computer controlled subtleties. It is not clear to us how the interaction of these factors may have led to observed increases in NO emissions from the on-road fleet while the reported laboratory measurements do not.

There are several important differences that are contained within these five data sets. There are different engine manufacturers and emission regulations for the United States and Europe. Each location presented different environmental and driving conditions in addition to the changes in altitude.

Engine load is one important contributor in cylinder NO formation and might explain some of the differences found at the various sites. However, fleet average emissions measured in the Fort McHenry tunnel on I-90 in Baltimore showed only a 10% drop in NO_x emissions per kg of fuel when the trucks were measured in the downhill portion (−3.3% grade) versus the uphill (+3.6% grade) section at highway speeds (*23*). The NO differences between loaded and unloaded trucks measured in California was 14% (see Table 2). The speed and acceleration of the trucks was not physically restricted at any of the sites. Scaffolding alongside a weigh station exit ramp will create a lot of curiosity though which will influence driving patterns. We suspect that drivers on average slow their rate of acceleration and thus slightly lower their engine load which should not result in a large change in NO emissions. Many of the measurements made at the four U.S. sites were collected during high periods of gear shifting and therefore variable engine loads. However, few if any idle measurements were made since our instruments successful measurement rate correlates with the exhaust plume strength which drops considerably when the shifts are first initiated. The San Marcos site experienced the highest temperature and humidities and as a result most likely had the largest additional air conditioning loads.

The Swiss data are consistently below the regression line for each of the three measured species in Figure 3. We believe that this is most likely due to fleet and load differences when compared to the U.S. sites. European heavy-duty trucks are generally smaller and haul lighter loads than their counterparts in the U.S. Four and a half percent of the measured traffic identified by type and weight at Erstfeld on June 9 weighed less than 3.5 tonne, while the average was 19.3 tonne. In addition the largest trucks on this route have a maximum rated weight of 45 tonne but are limited by Swiss law to 29 tonne. Lighter loads were partially offset by the grade and higher speeds at the Swiss site; however, a large number of the trucks we measured experienced lighter loads overall. The combination of smaller and lighter trucks, when compared to the U.S. fleets, is most likely the cause of the lower observed emissions which are comparable to the reductions in NO_x observed in the downhill section of the Fort McHenry tunnel.

During the course of these measurements three different calibration cylinders were used to calibrate two different instruments. Golden and Dumont relied on a cylinder purchased from Praxair (Los Angeles, CA), while the San Marcos and Anaheim work used a similar blend purchased from Scott Specialty Gases (Plumsteadville, PA). Both of these mixtures had stated accuracies of ±2%, and their contents were consistent with each other and their labeling when intercompared in the lab. The work in Switzerland used a similar mixture (Carbagas, Switzerland). Since our instrument is really just a comparator, comparing the ratios found in the calibration bottle with the ratios found in the vehicle exhaust, the differences we have observed are directly tied to the accuracy of the calibration gas, and it is important to rule out any large discrepancies which it might introduce. The use of similar blends, which were shown in a lab setting to be consistent with each other, at opposite ends of the altitude scale suggest that any differences caused by calibration inaccuracies of the instrument are small.

In light-duty vehicle emission studies, the age of the fleet is the single most important parameter in determining fleet emission levels. To date no one has published any in-use emission trends by model year for heavy-duty trucks. In their review of emission trends Yanowitz et al. (*6*) showed very little change in NO_x emissions for new vehicles over the last 25 years. This still leaves uncertain the important question as to how the fleet emissions deteriorate with time. Only for the Swiss data set do we have additional data on truck weight, make, and type of combination. It is not completely clear how useful just knowing the model year of a heavy-duty truck might be. Many chassis manufacturers use different engines from different engine manufacturers for the same chassis within the same model year. An added complication is that heavy-duty trucks are expected to replace/overhaul their engines several times before the truck is retired. It is very likely that the ages of the fleet discussed here are different from site to site. From observation we would think that the Anaheim, CA site would have the oldest fleet due to a large number of local transfer trucks and a lower number of national long-haul trucks. Table 2 shows that the out of state plated tractors, which we believe would be on average newer models because of their long haul nature, did have statistically significantly lower emissions for HC and NO than the California registered trucks. The lack of in-use data about fleet NO deterioration and our lack of fleet age information leaves this as a potential contributor to the change in NO emissions shown in Figure 3.

The last item we wish to discuss is the ability of electronic engine management systems on U.S. trucks to operate the engine with different engine maps: one map for certification testing and the other for noncertification operating condition (*27*). This capability started appearing in heavy-duty trucks in the late 1980s until a 1998 agreement between engine manufacturers and the U.S. EPA to stop its use (*27*). The noncertification map has been shown to produce large increases in the NO_x emissions from the trucks (*24, 28*). It is believed that most of the algorithms allowed the truck to be commanded into a fuel saving mode after some predetermined amount of steady-state driving which indicated that the engine was not undergoing certification testing (*25*). Other “defeat” algorithms are possible. The effect is that despite new regulations to lower NO_x emissions from heavy-duty trucks in-use emissions have most likely increased (*24*). Only the Swiss measurements were made during steady state conditions, and we believe that the observed increases for CO, HC, and NO with altitude are not a result of dual engine map operation. However, since only the individual engine manufacturers fully understand the conditions that trigger the use of these strategies, it is possible that some of the increases we have observed are a result of a higher percentage of trucks operating with the noncertification engine map at the time/location that we measured them.

Acknowledgments

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