Journal of the Air & Waste Management Association
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/uawm20

Effects of Engine Speed and Accessory Load on Idling Emissions from Heavy-Duty Diesel Truck Engines

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Published online: 27 Dec 2011.

To cite this article: Christie-Joy Brodrick , Harry A. Dwyer , Mohammad Farshchi , D. Bruce Harris & Foy G. King Jr. (2002) Effects of Engine Speed and Accessory Load on Idling Emissions from Heavy-Duty Diesel Truck Engines, Journal of the Air & Waste Management Association, 52:9, 1026-1031, DOI: 10.1080/10473289.2002.10470838

To link to this article: http://dx.doi.org/10.1080/10473289.2002.10470838

TECHNICAL PAPER

ISSN 1047-3289 *J. Air & Waste Manage. Assoc.* **52**:1026-1031

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ABSTRACT

A nontrivial portion of heavy-duty vehicle emissions of NO_x and particulate matter (PM) occurs during idling. Regulators and the environmental community are interested in curtailing truck idling emissions, but current emissions models do not characterize them accurately, and little quantitative data exist to evaluate the relative effectiveness of various policies. The objectives of this study were to quantify the effect of accessory loading and engine speed on idling emissions from a properly functioning, modern, heavy-duty diesel truck and to compare these results with data from earlier model year vehicles. It was found that emissions during idling varied greatly as a function of engine model year, engine speed, and accessory load conditions. For the 1999 model year Class 8 truck tested, raising the engine speed from 600 to 1050 rpm and turning on the air conditioning resulted in a 2.5-fold increase in NO_x emissions in grams per hour, a 2-fold increase in CO_2 emissions, and a 5-fold increase in CO emissions while idling. On a grams per gallon fuel basis, NO_x emissions while idling were approximately twice as high as those at 55 mph. The CO_2 emissions at the two conditions were closer. The NO_x emissions from the 1999 truck while idling with air conditioning running were slightly more than those of two 1990 model year trucks under equivalent conditions, and the hydrocarbon (HC) and CO emissions were significantly lower. It was found that the NO_x emissions used in the California Air Resources Board's (CARB) EMFAC2000 and the U.S. Environmental Protection Agency's (EPA) MOBILE5b emissions inventory models were lower than those measured in all of the idling conditions tested on the 1999 truck.

IMPLICATIONS

Research has shown that fuel consumption during truck idling varies as a function of engine model year, accessory loading, and engine speed. It is logical that emissions change along with fuel economy. This paper presents data on the effect of engine model year, accessory loading, and engine speed on emissions during heavy-duty diesel truck idling. NO_x, CO, CO_2, and HC emissions were measured by EPA on four different vehicles, with the most extensive testing being conducted on a vehicle with a 1999 model year engine. The results are compared with idling emissions factors obtained from CARB's EMFAC2000 and EPA's MOBILE5b emissions inventory models. The methodology of measuring idling emissions as a function of multiple factors can be employed to obtain improved emissions factors for the idling portions of the emissions inventory models.

INTRODUCTION

Heavy-duty diesel trucks produce relatively high amounts of NO_x and particulate matter (PM) compared with light-duty vehicles. For the ~458,000 line-haul trucks in the United States, which may idle overnight,[1] limited evidence suggests the amount of these emissions that occur during idling may be significant.[2] Idling is also fuel-inefficient. It was found that during idling, the engine is only 3–11% efficient compared with the greater than 30% efficiency achieved in highway operation. Idling fuel consumption is estimated to be between 838 million and 2 billion gallons annually.[1,3] In addition to excess air pollutants and fuel consumption, heavy-duty truck idling causes engine wear, noise, and vibrations. The impacts of tractor vibration and noise are difficult to quantify but are special concerns because of their potential impact on driver sleeping and fatigue.

Truck drivers idle their engines to power sleeper-compartment heaters and air conditioners, to power "hotel" accessories (televisions, refrigerators, computers, tools, and fleet operations systems) during nondriving operations, to avoid start-up problems in cold weather, to maintain air system pressure, and simply as general practice during many delivery operations. Auxiliary power units and other options to reduce idling have received little market acceptance, with a market penetration of ~5% according to industry estimates.[4] As a result, heavy-duty line-haul trucks in the United States continue to idle.

Little data exist about the amount of truck idling. One study used a 6 hr/day idling time as a baseline case and a range of 3.3 to 16.5 hr/day depending on the season and operations.[1] Some fleets reported vehicles idling up to 10 hr/day, or greater than 50% of the total engine run time. This is consistent with fleet interview data collected by Stodolsky et al.[1]

In most states, trucks and buses that are idling can be ticketed under state nuisance laws, but this has been infrequent.[5] In response to health concerns about diesel particulates, there has been a recent surge of interest in curtailing idling emissions. Regulators are pursuing a variety of strategies to curtail idling. For 2001, the California Air Resource Board's (CARB) Low Emissions Incentive Program (Carl Moyer) added a monetary incentive for the purchase of an auxiliary power unit that would be used in lieu of idling.[6] In December 2000, the Texas Natural Resources Conservation Council approved a ban on truck idling in the eight-county Houston area as part of their clean-air attainment plan.[7] To determine the effectiveness of idling-reduction policies, such as incentives and bans, it will be necessary to estimate the emissions reductions associated with the decreased idling.

Very little quantitative data exist on the emissions and fuel consumption characteristics of truck idling.[1,8] In fact, in 2000, CARB's Mobile Source Emissions Model EMFAC2000 incorporated truck idling emissions as a factor for the first time, but the data are based on limited testing, and the emissions values derived were applied to all vehicles, regardless of age.[9]

McCormick et al.[8] provide a more comprehensive study of idle emissions from 24 heavy-duty diesel vehicles (12 buses and 12 trucks) of various model years. The data were measured on a chassis dynamometer at high altitude. The 12 diesel trucks, which ranged from 1989 to 1999 model years, averaged 71.0 g/hr CO, 85.0 g/hr NO_x, and 10.2 g/hr total hydrocarbons (THCs). Fuel economy and CO_2 emissions were not reported; however, PM was measured and averaged 1.8 g/hr for the 12 trucks. The effect of altitude on emissions is uncertain.[8] All emissions were measured with the trucks idling under standard, factory-specified idling speed, and the use of accessories was not reported.

Research has shown that fuel consumption during truck idling varies as a function of engine model year, accessory loading, and engine speed. It follows that emissions also would be affected by these factors. Engine model year is a large factor because emissions standards and engine design differ. Limited evidence, provided by the present study, suggests that idling emissions from some electronically controlled engines may be affected by idle duration and vehicle operation prior to idling. Regardless of engine design, older engines are more likely to have increased emissions because of deterioration, poor maintenance, and tampering.

Accessory loading and engine speed affect the torque-speed region in which the engine operates, and this in turn affects the emissions and fuel consumption. The actual accessories and their power requirements determine accessory loading. These loads vary from large power demand by air-conditioning compressors to small power demands from hotel accessories such as televisions. Truckers often increase the idle speed from its default setting to prevent battery drain and to improve accessory performance. The extent to which truckers increase engine idling speed is not documented, but truck manufacturers and fleet owners indicate it is a common practice. In fact, some trucks are equipped with physical and electronic throttle controls that allow engine speed to be set during idle.

To the best of our knowledge, no data have been published on truck idling emissions as a function of engine model year, accessory loading, and engine speed. The U.S. Department of Energy (DOE) publishes a table that estimates fuel consumption as a function of brake horsepower (bhp) demand of accessories and engine speed for the general truck population. The numbers suggested by the DOE are shown in Table 1.[10] The fuel consumption ranges from 0.6 gal/hr for a truck idling at 800 rpm with no accessories to 2.25 gal/hr for a truck idling at 1200 rpm with 30 bhp of accessories. The objectives of this study were to quantify the effect of accessory loading and engine speed on idling emissions from a properly functioning, modern, heavy-duty diesel truck and to compare these results with data from earlier model year vehicles.

METHODOLOGY

The U.S. Environmental Protection Agency's (EPA) emissions measurement trailer was used to measure NO_x, HC,

Table 1. Fuel consumption (gal/hr) as a function of accessory horsepower demand and engine speed.[10]

	bhp of Accessories				
rpm	0	5	10	20	30
800	0.6	0.7	1.0	1.4	1.7
1000	0.75	1.0	1.2	1.55	2.0
1200	1.0	1.2	1.5	1.8	2.25

CO, and CO_2 emissions under a variety of accessory loadings and engine speed combinations. The Emissions Characterization and Prevention Branch developed EPA's mobile facility in 1994 for the purpose of quantifying gaseous emissions as a function of truck operating parameters. The accessory loadings and engine speeds were selected based on discussions with trucking companies. The truck tested was a 1999 Freightliner Century Class truck with 450-hp engine. Emissions data also are presented from less extensive idling testing conducted by EPA on two 1990 and one 1989 vintage tractors. The emissions estimates then are compared with emissions rates from EPA's emissions model (MOBILE5b) and CARB's emissions model (EMFAC2000). Five idling tests (modes) were run: (1) at standard idle (600 rpm) after cruising at 55 mph for 10 min, (2) at standard idle after running a 10-min transient cycle, (3) at standard idle with the air conditioner in use after running a 10-min transient cycle, (4) at high idle (1050 rpm) with the air conditioner running after a 10-min transient cycle, and (5) at high idle with the air conditioner running for 5 hr. For comparison purposes, two tests were conducted with the vehicle cruising at 55 mph with and without the air conditioner running.

RESULTS

Reduction in Air Pollutants and Greenhouse Gases

Emissions test results are presented in Table 2. For each test, a minimum of three repetitions was conducted. The average and standard deviation (SD) are presented. Examination of the EPA data reveals that, as expected, increases in engine loading and accessory loading had significant effects. Comparison of modes 2 and 4 indicates that raising the engine speed from 600 to 1050 rpm and turning on the air conditioning resulted in an increase in NO_x emissions of ~2.5 times and a large increase in CO emissions. HC emissions increases were unavailable because of analyzer failure. With engine speed maintained at 600 rpm, when the air conditioner was activated (comparing modes 2 and 3), HC and CO emissions decreased slightly, but NO_x emission increased by 58%. The large increase in HC and CO emissions during high engine speed and long idling with accessories (comparing modes 3 and 5) warrants further study of this condition, which is typical of the type of idling that would be replaced by auxiliary power units.

Emissions while cruising at 55 mph are provided for comparison. High idling with air conditioning (mode 4) produces NO_x emissions of ~33% of the emissions at 55-mph cruise with air conditioning (mode 7). Because of equipment failure, only one of the repetitions was valid for both of the 1050-rpm conditions.

Continuous Emissions Patterns

Average emissions levels provide an incomplete picture of idling emissions. Close examination of the continuous emissions data reveals that emissions while idling are not steady. Thus, simple averages may be misleading. Figures 1–3 are examples of the emissions patterns observed over time under three of the test modes.

Figure 1 is an example of the patterns observed for idling after steady-state freeway driving at 55 mph. The emissions pattern illustrated is for idling at 600 rpm with no accessory load. The figure illustrates that the idling emissions begin at ~100 g/hr following freeway driving. After several minutes, the idling emissions crept up and continued to creep up throughout the idling testing. This indicates that the length of idling time over which emissions are measured may affect NO_x emissions levels. The observed pattern could partially explain the difference in emissions seen in replications of modes 1 and 2 tests. The longer replications of these tests had higher average emissions than the shorter replications of the same test. This was because the longer tests had more data subsequent to the increase in emissions. The longest idling data collection without accessories was ~10 min, so it is not known what the NO_x emissions pattern would have been after 10 min.

Figure 2 illustrates the trend in idling emissions following lower-speed transient modes typical of city driving. As with Figure 1, the emissions shown here are for a

Table 2. Emissions test results from EPA on-road testing.

	HC		CO		NO_x		CO_2		Fuel Economy	
	g/hr	SD	g/hr	SD	g/hr	SD	g/hr	SD	gal/hr	SD
Mode 1: Idling after Cruising	1.8	0.3	14.6	2.3	103	14	4034	224	0.36	0.03
Mode 2: Idling after Transient Cycle	2.9	1.0	15.9	2.0	105	5	4472	342	0.39	0.04
Mode 3: Idling at 600 rpm with A/C	1.4	0.2	15.3	0.6	166	5	4976	73	0.52	0.04
Mode 4: Idling at 1050 rpm with A/C	[a]	[a]	86.0	NA[b]	254	NA	9441	NA	0.88	NA
Mode 5: Long Idling at 1050 rpm with A/C	86.4	NA	189.7	NA	225	NA	9743	NA	0.93	NA
Mode 6: Cruise at 55 mph, no A/C	5.6	0.2	65.1	1.2	713	41	60,592	1777	5.92	0.14
Mode 7: Cruise at 55 mph, with A/C	3.9	0.3	57.4	0.9	777	51	60,320	4072	6.88	1.40

[a]Not available: instrument failure; [b]Not applicable: only one valid test because of equipment failure.

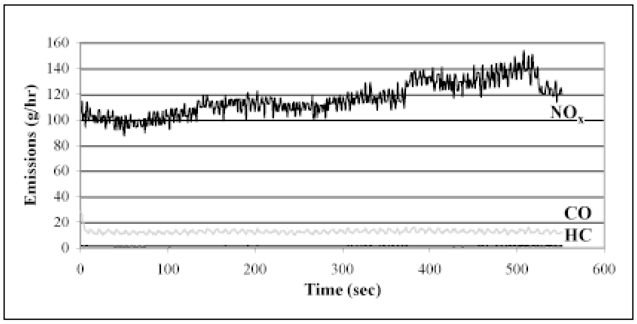

Figure 1. Idling emissions vs. time for a 1999 model year, 450-hp engine operating at 600 rpm with no accessories following cruising at 55 mph.

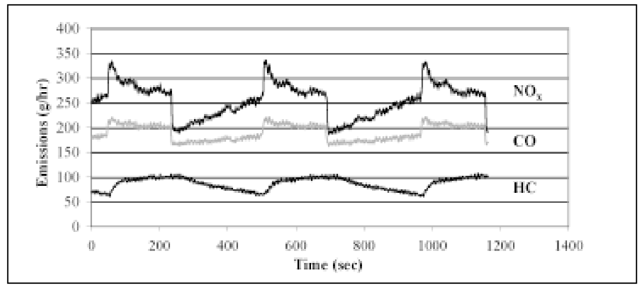

Figure 3. Idling emissions vs. time for a 1999 model year, 450-hp engine operating at 1050 rpm with air conditioning running during a long idling period.

typical idling test at 600 rpm without accessories. In Figure 2, the emissions immediately following the transient modes were 75 g/hr. The emissions remained at 75 g/hr for several minutes. Then, a sudden jump in emissions was observed. This is in sharp contrast to Figure 1, in which emissions began at a higher level and crept upward. The reason for the jump is unclear. It is not believed that any accessories, such as air compressors, cycled on to load the engine.

Figure 3 shows yet another pattern. This figure is an excerpt from a 5-hr overnight idling test with air conditioning running and the engine speed at 1050 rpm. For this long idling test with accessories, a distinctive pattern was observed. This was likely caused by the air compressor periodically loading the engine. The overall emissions level clearly is higher than in the emissions tests at 600 rpm with no accessories.

Comparison to Previous Findings

From 1996 to 1998, EPA conducted idling tests of three older heavy-duty diesel trucks: a 1989 Ford CL-9000 with a mechanical Cummins NTC-315 engine, a 1990 Freightliner with an electronic Caterpillar 3176 engine, and a 1990 Kenworth with a Detroit Diesel Series 60 electronic engine. The emissions test results are presented in this paper for reference. The 1990 Freightliner and 1990 Kenworth tests were run at standard idling with air conditioning, and the Ford was run without air conditioning. The emissions test results for these trucks, as well as the 1999 Freightliner, are shown in Table 3. For the 1989 truck, the results represent the average of eight 4-min idling tests after transient driving with no accessory load. For the 1990 trucks, EPA conducted 12 4-min tests after transient driving with an accessory load. The emissions from the 1999 Freightliner Century Class with a 1999 engine is provided in the last row for reference. The data for the 1999 Freightliner are the average of three idling tests at 600 rpm with the air conditioning running.

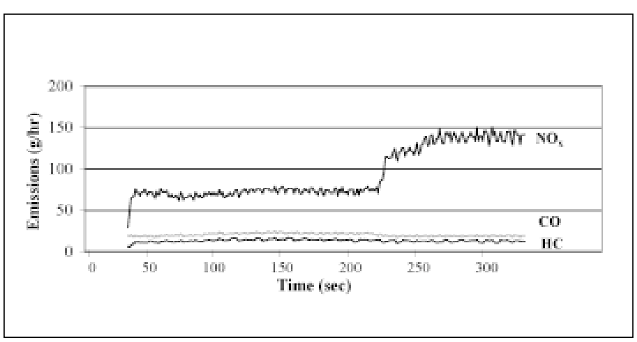

Figure 2. Idling emissions vs. time for a 1999 model year, 450-hp engine operating at 600 rpm with no accessories following transient, city operation.

In Table 3, the NO_x emissions from the 1999 Freightliner truck at standard idling with air conditioning are slightly more than those of the 1990 Freightliner and Kenworth trucks. HC emissions from the 1999 Freightliner are significantly lower, as are CO emissions. Fuel economy was not measured for the 1989 and 1990 model year vehicles.

Comparison of Findings to Those in Emissions Models

Using EPA's emissions measurements as a baseline, we compared the emissions factors used in EPA's and CARB's emissions models. Emissions estimates from EPA's MOBILE5b model vary based on environmental factors, such as temperature and pressure, as well as truck fleet characteristics, such as truck model year. Assuming an ambient temperature of 75 °F and the 1998 U.S. fleet characteristics in MOBILE5b, average idling emissions for the U.S. fleet were 55.0 g/hr of NO_x, 94.2 g/hr of CO, and 12.5 g/hr of HC.[11] The average NO_x emissions of 55 g/hr are ~30% of the emissions measured for the 1999 Freightliner at low idle with the air conditioning running, but they are consistent with emissions measured on the 1989 Ford without air conditioning running. In contrast, the HC and CO emissions measured were much lower than predicted by MOBILE5b.

CARB's model, EMFAC2000, incorporates idling factors for the first time.[12] They were derived from testing on

Table 3. Emissions test results from EPA testing of older tractors compared with the emissions results from the 1999 Freightliner.

	HC		CO		NO_x		CO_2	
	g/hr	SD	g/hr	SD	g/hr	SD	g/hr	SD
1989 Ford	12.4	1.0	21.6	2.3	65.7	6.8	NA	NA
1990 Freightliner	2.6	0.4	44.6	41.1	149.3	22.3	NA	NA
1990 Kenworth	4.9	1.3	79.3	24.8	134.6	36.2	NA	NA
1999 Freightliner	1.4	0.2	15.3	0.6	166	5	4976	73

a set of heavy-duty diesel vehicles tested by West Virginia University. CARB did not observe differences in emissions factors between model year, so the same emissions factors were used for all model years.[9] Idling emissions for the U.S. fleet were 80.7 g/hr of NO_x, 26.3 g/hr of CO, and 3.48 g/hr of HC.[9] These are much lower than the idling emissions first proposed.[12] As with MOBILE5b, the NO_x emissions factors used in CARB's model (80.7 g/hr) are lower than measured on the 1999 Freightliner (103–254 g/hr NO_x, depending on engine speed and accessory load). The EMFAC2000 NO_x emissions factor is slightly higher than our lowest emissions measurement of 65 g/hr NO_x, which was from the 1989 truck at 600-rpm idle. HC and CO emissions factors were higher but more consistent with our results for the 1999 tractor at low idle than were the MOBILE5b factors.

CARB is currently cosponsoring the Coordinating Research Council E-55/E-59, which includes collection of idling data. EPA is sponsoring similar work. It is suggested that these idling data be collected for a variety of model years and engine sizes with the vehicles running under a variety of realistic accessory loads and engine speeds.

Fuel Economy Results

Fuel consumption was calculated and found to be reasonably consistent with that recorded by the engine computer. The fuel consumption for the 1999 tractor was lower than the fuel consumption estimates generated by the DOE (see Table 1). Based on Table 1, fuel economy for the 1050-rpm condition with the air conditioner in use would have been expected to be 1.0 gal/hr, assuming an air conditioner load of 5 hp. The fuel economy was between 0.88 and 0.93 gal/hr. Some difference is expected because the DOE estimates were based on data from 1986, 1995, and 1996.

Emissions on a fuel basis (g/gal) are presented in Table 4. The low fuel consumption during idling at 600 rpm resulted in very high emissions during this condition. A second trend is that the emissions difference between idling and highway operation was much smaller than seen when emissions were compared on a grams-per-hour basis. The NO_x emissions in grams per gallon while idling were at least twice as high as emissions when the truck traveled at 55 mph in highway operation. The CO_2 emissions in the two conditions were similar.

Table 4. Emissions test results from EPA on-road testing on a fuel basis.

	HC g/gal	CO g/gal	NO_x g/gal	CO_2 g/gal
Mode 1: Idling after Cruising	5.0	41	292	11,369
Mode 2: Idling after Transient Cycle	7.4	40	267	11,336
Mode 3: Idling at 600 rpm with A/C	2.9	31	335	10,037
Mode 4: Idling at 1050 rpm with A/C	[a]	98	287	10,678
Mode 5: Long Idling at 1050 rpm with A/C	92.9	204	242	10,476
Mode 6: Cruise at 55 mph, No A/C	1.0	11	120	10,232
Mode 7: Cruise at 55 mph, with A/C	0.6	9	116	8975

[a]Not available: instrument failure.

CONCLUSIONS

- Emissions and fuel consumption during truck idling vary based on engine model year, accessory loading, and engine speed.
- Limited evidence also suggests that emissions while idling may be affected by idling duration and vehicle operation prior to idling.
- Depending on accessory load and engine speed, idling emissions from the 1999 truck tested ranged between 1.4 and 86.4 g/hr HC, 14.6 and 189.7 g/hr CO, 103 and 254 g/hr NO_x, and 4034 and 9743 g/hr CO_2. There is significant uncertainty in the highest emissions levels, which were obtained from the high idle with accesories condition.
- Emissions of NO_x, HC, and CO_2 while idling can be minimized by using the lowest engine speed with the smallest accessory load.
- At engine speeds of 1050 rpm with air conditioning, idling produces NO_x emissions (g/hr) of ~33% of the emissions generated while cruising at 55 mph with air conditioning.
- Cycling of the accessory loads, such as compressors, results in fluctuations in emissions levels over time. This contributes to the variation in emissions between test replications.

ACKNOWLEDGMENTS

We would like to thank Edward Brown and Matt Clayton of ARCADIS Geraghty and Miller for their data collection and processing assistance. We would like to thank Jenny Tang, Nicolas Lutsey, and Renee Pearl of ITS-Davis for their valuable contributions. We would also like to thank

Archana Agrawal and Hector Maldonado of California Air Resources Board for their review of this paper. Funding for this work was provided in part by the University of California Transportation Research Center, the National Science Foundation IGERT Program, and the Dwight D. Eisenhower Fellowship Program.

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