91-88.14

Uncertainty in The Emission Inventory For Heavy-Duty Diesel-Powered Trucks

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AIR & WASTE MANAGEMENT
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SINCE 1907

For Presentation at the
84th Annual Meeting & Exhibition
Vancouver, British Columbia
June 16 - 21, 1991

EXECUTIVE SUMMARY

Emissions from motor vehicles are a function of how, and under what conditions, the vehicles are operated. In general, mobile source emission inventories are developed by defining vehicle activities (through vehicle activity models), and coupling the activities with activity-specific emission rates (appropriately corrected for environmental conditions and trip characteristics). The emissions from individual vehicle activities are summed to determine the total emission inventory.

We find that the estimated emissions for heavy-duty diesel trucks are highly uncertain due principally to the following: 1) test methods used to determine emission rates are somewhat imprecise and inaccurate, 2) the activity-specific emission rates employed are not representative of actual vehicle activity, 3) highly questionable activity-specific emission rate correction factors are employed, 4) the application of "typical" or "average" emission factors to specific vehicle activity does not represent the diversity of vehicle activity, 5) emission rates are based upon a non-statistically-representative numbers of vehicles, 6) vehicle activity parameters are highly aggregated, 7) the actual vehicle activities being monitored are not representative of emission producing activities, 8) questionable surrogate indicators are used to estimate actual activity parameters (e.g. traffic counts used to estimate vmt are suspect), and 9) a number of critical vehicle activities are omitted from the models.

Policy analysts are faced with evaluating emission control measures for which the existing models are the only analytical tools available. However, the modeling results are highly uncertain because the models were only designed to roughly estimate a "bulk" emission inventory, and were never designed to evaluate policy issues in the manner that they are often employed. Significant modeling and data collection improvements are needed for analyzing changes in vehicle activity and activity-specific emission rates.

BACKGROUND

This paper is a summary of a research report prepared by the authors, entitled: Uncertainty in the Emission inventory for Heavy-Duty Diesel-Powered Trucks. The report focuses on the sources of uncertainty in emission factors and activity estimates used by regulatory agencies to estimate the emission contribution of heavy-duty diesel trucks to the total emission inventory. The final report, with additional detail findings and addendums, is available through the Institute of Transportation Studies, Department of Civil Engineering, University of California, Davis.

Almost all of the discussion in this paper regarding uncertainty in the heavy-duty diesel-powered truck emission inventory is applicable to the heavy-duty gasoline-powered truck emission inventory. In fact, many of the uncertainty issues raised in this paper are even applicable to the light-duty vehicle emission inventory (although light-duty problems are generally less pervasive). For the most part, heavy-duty diesel and gasoline emission inventories are more uncertain than light duty vehicle emission inventories due to limited heavy-duty vehicle laboratory testing and scant knowledge about heavy-duty vehicle activity patterns.

INTRODUCTION

Currently, all of the major urban areas in California are in violation of one or more of the National Ambient Air Quality Standards for ozone, carbon monoxide, and particulate matter (CARB, 1989a; CARB, 1990a). The evaporation and combustion of motor vehicle fuels contributes significantly to high levels of pollution that can harm human health and economic productivity.

On-road heavy-duty diesel-powered vehicles are major contributors of emissions, especially oxides of nitrogen and oxides of sulfur. Approximately 16.7% of the oxides of nitrogen, 11.6% of the oxides of sulfur, 1.9% of the reactive organic gas, 1.8% of the PM_{10}, and 1.3% of the carbon monoxide emissions in California are from heavy-duty diesel-powered trucks (CARB, 1990b).[1] Emissions of NOx, as a precursor to the formation of photochemical smog, and the emissions of particulate matter, primarily as a nuisance pollutant,[2] are the major concerns from heavy-duty diesels in most heavily urbanized areas.

Emission Trends and Regulatory Direction

Emissions from the overall mobile source category have been decreasing during the past ten years, as a result of stringent light-duty vehicle exhaust emission standards. However, California's population of has been growing at a rate of about 2% per year (CCSCE; 1989), and the use of vehicles per capita is increasing even faster than population. To service the increasing needs of a growing population, truck activity has also been increasing rapidly. The California Department of Transportation (Caltrans) truck travel survey indicates that truck-miles-traveled for 5+ axle heavy-duty trucks has increased

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[1] It should be noted that heavy-duty gasoline trucks are responsible for significantly higher contributions of reactive organic gases and carbon monoxide than are diesel vehicles.

[2] PM_{10} is also under investigation as a toxic air contaminant.

by 4.9% between 1985 and 1986 and 10.5% between 1986 and 1987 (Caltrans, 1988).

The emissions of ozone precursors from heavy-duty diesel truck operations are forecast by the CARB emission inventory staff to continue to increase through the year 2000. The emission increase takes into account, as best as can be modeled, the heavy-duty diesel emission control strategies that have already been implemented. This emission increase is largely due to projected growth in heavy-duty truck travel and, to some extent, due to a projected increase in congestion.

Heavy-Duty Diesel Emission Modeling and Policy Concerns

Accurate methods are needed to estimate heavy-duty diesel emissions, and to estimate the quantity of emission reductions from proposed emission control strategies. In evaluating potential of emission control measures, specific emission reduction effects must be determined (CARB, 1989b). Without accurate emission estimation methods, the technical and economic feasibility of proposed transportation control strategies and fuel requirements cannot be accurately evaluated.

Regulators and the regulated community are now evaluating potential emission control strategies, such as: reformulated diesel, alternative fuels, AM/PM truck operating restrictions, off-peak shipping and receiving, freight distribution centers, truck idling restrictions, speed limit enforcement (as an emission control), and truck-accident mitigation (to improve traffic flow) (AB2595 TAC, 1990; Nelson, et al., 1991).

Although the contribution of heavy-duty diesel vehicles to the total mobile source emission inventory appears large, the problem is that much of the mobile source emission data and methodologies are suspect. To determine which control measures should be implemented, a fundamental question must be answered: are the existing heavy-duty diesel vehicle emission inventory methods adequate to estimate the emission reductions from proposed transportation control measures or fuel requirements?

THE EMISSION INVENTORY PROCESS

The emission inventory is an estimate of the total anthropogenic emissions released into the atmosphere from stationary, area, and mobile sources of pollution within an air basin. Mobile source emissions are calculated by estimating individual vehicle activities, and coupling the activities with activity-specific emission rates.

Vehicle Activity

From an emission modeling standpoint, "vehicle activity" can be loosely defined as any discrete vehicle attribute or use that results in emissions. In general, regulatory agencies currently define vehicle activity in terms of four parameters: number of vehicles, number of trips, vehicle miles traveled, and hours of idling.

The heavy-duty truck activity estimation methodology differs significantly from that of light-duty vehicles. The essential difference between heavy-duty and light-duty vehicle methodologies is that heavy-duty truck activity is estimated through surrogate indicators (such as traffic counts) while light-duty vehicle activity is estimated through local travel demand models.[3]

Activity-Specific Emission Rates

An activity-specific emission rate is the mass of pollutants emitted during a particular vehicle activity. For example, emission rates can be determined for such activities as an engine start or one mile of travel (and would be expressed in units of grams per start, and grams per mile, respectively).

Emissions result from the following general vehicle activities: vehicle miles traveled (running emissions), engine starts (cold or hot start incremental emissions), engine cool-down (hot soak incremental emissions, gasoline engines only), diurnal and multi-day diurnal evaporation (gasoline engines only), and running evaporative losses (gasoline engines only).

Of the four activities currently applicable to heavy-duty diesel trucks (running emissions, hot starts, cold starts, and engine idling) only vehicle miles traveled is used in estimating the emission inventory.

Vehicle emission rates are determined through laboratory testing, using the methods and procedures established by the EPA and the CARB. Emission rates for each vehicle and engine are dependent upon vehicle characteristics (size, weight, etc.), engine design, and emission control technologies applied by the manufacturer to the vehicle. The emission factors from subsets of vehicle types are aggregated into average vehicle class emission factors for local areas, using vehicle registration data.

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[3] Urban Transportation Planning System (UTPS) models for light duty vehicles are developed using origin-destination surveys. The models provide trip generation (based upon land-use and socioeconomic characteristics), trip distribution, mode choice, and route assignment. However, UTPS models do not include heavy-duty truck activity.

Emission Rate Correction Factors

The magnitudes of vehicle activity emission rates are influenced by the operating environment of the vehicle. In particular, engine start mode (hot and cold), vehicle speed, and operating temperature affect vehicle emission rates.

Baseline emission rates (determined through standard test procedures) are adjusted, through the use of laboratory determined correction factors, so that they may be applied to specific operating conditions. For example, baseline emission rates must be corrected for average trip speed, and expected compliance with inspection and maintenance requirements.

By applying correction factors to the baseline rates, a multi-dimensional emission rate matrix is prepared (CARB, 1986 and 1988). Thus, emission rates associated with specific vehicle operation and environmental conditions are stored in the matrix.

Emission Rate Matrix Schematic

The information provided in this section of the report can be summarized in a schematic diagram. Figure 1 illustrates the components of activity-specific emission rate tables that are coupled with applicable vehicle activities (boxes). Omitted emission rates (and activities) are represented by dashed boxes.[4] Correction and conversion factors are indicated with ellipses. This figure may be compared to the analogous figure for light-duty vehicles (Figure 2).

HEAVY-DUTY TRUCK ACTIVITY

Number and Classification of Vehicles

In 1987, more than 150,000 California-based heavy-duty diesel and gasoline trucks, and more than 150,000 additional out-of-state-based trucks were operating in California (Sydec, 1987a,b).

The following vehicle classes, based upon gross vehicle weight rating[5] (GVWR) are employed by the California Air Resources board for on-road motor vehicles: light-duty

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[4] In a few cases, idling is included in the emission inventory (e.g. at airports).

[5] The differences in the definitions of "heavy-duty truck" between various regulatory agencies can be significant, depending upon whether weight is measured as gross vehicle weight, gross vehicle weight rating, or unladen weight. These differences create data discrepancies and uncertainty in measurement of number and types of diesel vehicles. For more information, see Nelson, et al., 1991.

FIGURE 1
CARB's
EMISSION FACTOR MODEL
HEAVY-DUTY VEHICLES

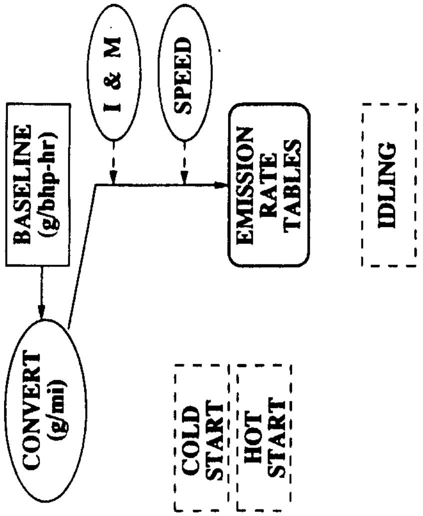
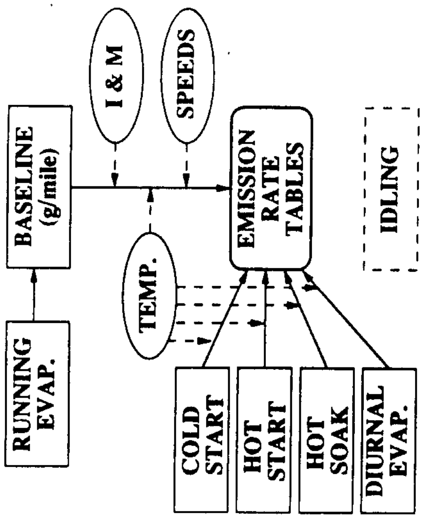


FIGURE 2
CARB's
EMISSION FACTOR MODEL
LIGHT-DUTY VEHICLES



automobiles, light-duty trucks (0 - 6000 lb GVWR), medium-duty trucks (6000 - 8500 lb GVWR), heavy-duty trucks (8500+ lb GVWR), urban buses, and motorcycles.

Vehicle classes are further segregated into vehicle technology categories, by fuel type and emission control technology. In addition, the USEPA has defined three general classifications of heavy-duty truck engines: light heavy-duty, medium heavy-duty, and heavy heavy-duty. However, there are currently no activity or emission factor estimates that are disaggregated by engine classification.

Vehicle Registration

Regional emission models generally rely upon vehicle registration data for estimating mobile source contributions. However, emission estimation methodologies cannot account for the use of vehicles in one county that are registered in another county. Because this issue is especially significant for trucks, due to significant numbers of out-of-state vehicles, the use of registration data is problematic.

The registration mix contributes indirectly, because the emission rate for the "average vehicle" in the vehicle class is used in emission inventory calculation and can introduce aggregation bias.

The California registration mix for heavy-duty vehicle technology type is based upon the 1975 Polk truck data for Diamond-Reo, Kenworth, Mack, Peterbuilt, and White manufacturers (CARB, 1986 and 1988). The VMT fractions were derived from the 1972 Census of Transportation and Truck Use Survey (CARB, 1986).

The vehicle registration mix only includes subdivisions for heavy-duty gasoline engines, gasoline engines with catalytic controls, and diesel engines. No information regarding the engine size or payload of the vehicle is employed, because there are no emission factors available that reflect these variables.

Number of Trips

The number of motor vehicle trips directly affects the magnitude of incremental emissions that occur from cold and hot starts.[6] Before engines reach efficient operating temperatures (i.e. "warm-up"), combustion efficiency is somewhat lower that in normal operations and emissions are higher.

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[6] When the engine is shut down, fuel in gasoline fueled systems can evaporate, resulting in what are called hot soak emissions. For diesel engines, hot soak emissions are assumed to be insignificant due to low fuel volatility and physical fuel injection characteristics. Thus, there is no need to include hot soak emissions in the emission inventory.

Cold start and hot start incremental emission rates have not been measured in the laboratory for heavy-duty diesel or gasoline trucks, and are assumed to be an integral component of baseline running emission rates (discussed later). Because emission factors for these incremental activities do not exist, the number of trips is not considered in emission inventory preparation, heavy-duty vehicle trips are currently not modeled, and incremental emissions associated with tripends are not quantified. In California, the CARB and EPA methodologies for heavy-duty trucks essentially assume that "trucks never stop."

Vehicle Miles Traveled

As would be expected, a significant portion of the emissions resulting from a vehicle trip are directly dependent upon the number of vehicle miles traveled. For light duty vehicles, the percentage of the emission contribution from VMT depends upon the length of the trip. The incremental cold and hot start emissions are much more significant for shorter trips. Hence, it might be expected that if cold and hot start emission factors existed for heavy-duty vehicles that they would also be less significant than VMT related emissions for longer trips.

The Caltrans cost allocation study, prepared by Sydec Inc., estimated the annual truck VMT (Fiscal Year 1986-87) to be approximately 13.9 billion miles. The Caltrans Truck Miles Traveled report estimated approximately 12 billion truck miles were traveled during that same period (Caltrans, 1988). The EMFAC7D/BURDEN7A model, used by the California Air Resources Board (CARB) to estimate motor vehicle emissions, indicated that 15.5 billion heavy-duty truck miles were travelled in 1986-87 (average of the 1986 and 1987 estimates).

Until 1985, the CARB calculated the heavy-duty vehicle fleet VMT by multiplying vehicle registration data by an assumed annual VMT per vehicle. However, there was a much greater potential error associated with using that method, because most diesel heavy-duty vehicles operate outside of their registered county.

Currently, the CARB estimate for heavy-duty diesel truck VMT is based upon the report Assessment of Heavy-Duty Gasoline and Diesel Vehicles in California: Population and Use Patterns, prepared by Pacific Environmental Services (PES) for the CARB in 1985 (Horie and Rapoport, 1985). The PES study provided estimates of heavy-duty truck VMT based upon VMT data generated by the Caltrans' Truck Program and Highway Performance Monitoring System as well as a limited survey of truck operators. The VMT estimates were based on Caltrans traffic counts, a PES survey of 21 city and county roads, a PES telephone survey of 233 fleets, the 1976 Interstate Commerce survey, and a 1971 UC Berkeley Institute of Transportation and Transportation Engineering (ITTE) survey.

In preparing the total VMT figures, PES added travel estimates for non-state-highway roads (major and minor collector streets), based upon Highway Performance Monitoring System (HPMS) data, bringing the total VMT per day estimates up from 24.950 million miles per day to 36.029 million miles per day. Thus, approximately 31% of the estimated VMT is believed to accumulate on non-state-highway roads.

Unfortunately, local roadway estimates are based upon limited survey data provided by local municipalities and their accuracy is somewhat suspect. There are a number of reasons for concern with accuracy and reliability of HPMS data. For example, reported data must be used without knowing if the local agencies followed all HPMS guidelines and without knowing what actual axle correction algorithms were used to convert total vehicle axle counts into heavy-duty VMT estimates (Hu, et al., 1989).

Since the 1984 PES projections were obtained, the CARB has abandoned their original methodology, but has not adopted the proposed PES methodology. Instead, the CARB elected to apply annual growth factors to the 1984 PES projected VMT to estimate the VMT for each of the following years. However, it is not clear how the CARB growth projections have affected the accuracy of the VMT estimates since 1984.

Because Caltrans surrogate data were coupled with limited supplemental interviews (without origin destination logs being obtained), it is not really clear how accurate the PES estimates were. Unfortunately, all of the existing estimates are based upon different surrogate indicators and calculation methodologies, making them difficult to compare.

There is still a greater question that must be answered: are we modeling the activities that should be tied directly to vehicle emissions? As will be discussed later, it may be more appropriate to model VMT activity at specific speeds and acceleration activity, rather than aggregate VMT at average operating speeds.

Hours of Engine Idling

Even when an engine is not pulling a load, a running engine continues to emit air contaminants. The non-engine-loaded operation is known as vehicle idle (e.g. sitting at a stoplight). Heavy-duty diesel engines are frequently idled for extended periods in lieu of turning the engine off. Idling may be the result of severe congestion, traffic signalization, pick-up and delivery of goods, and the provision of necessary services (e.g. electrical power needs).

Separate testing has been conducted by the USEPA and average idling emission rates are quantified in the Compilation of Air Pollutant Emission Factors (USEPA, 1985), based upon limited

engine tests. However, idling emissions are generally not included in the emission inventory because idling activity has never been quantified.

HEAVY-DUTY DIESEL TRUCK EMISSION RATES

The current emission modeling methodology requires that vehicle activities be linked to appropriate activity-specific emission rates. Plus, correction factors to adjust the emission rates for specific operating conditions, are developed.

Baseline Running Emission Rates for VMT

Baseline mobile source emission factors for each vehicle class, as mentioned previously, are determined by testing numerous vehicles in the vehicle class and preparing composite, or average, emission factors for each model year. The emission rates from each vehicle are dependent upon such attributes as: fuel type, engine class, vehicle size, emission control technologies, and vehicle age or accumulated mileage.

The running vehicle emission factor for any light-duty vehicle is established by the light-duty Federal Test Procedure (FTP) on a chassis dynamometer. A chassis dynamometer allows the entire vehicle to be operated on the test equipment. Thus, the vehicle emissions are collected while the drive shaft and wheels are actually rotating. The light-duty vehicle FTP has an average speed of 19.6 miles per hour and is composed of a set pattern of stops, starts, accelerations, decelerations, and constant speed cruises. Numerous tests are run to determine the average emissions within each specific vehicle class. Thousands of light duty vehicles have been tested by the USEPA, CARB, and other groups in their ongoing testing programs.

Baseline in-use vehicle emission rates for heavy-duty diesel and gasoline vehicles are also determined through laboratory testing, using the methods and procedures developed for the certification of new engines by the Environmental Protection Agency and California Air Resources Board. Heavy-duty vehicle emission testing differs significantly from the testing of light-duty vehicles. The primary difference is that heavy-duty vehicle emission testing is conducted on an engine dynamometer, rather than a chassis dynamometer, and conversion factors are used to prepare gram/mile emission rates. The heavy-duty Federal Test Procedure (40 CFR 86) is based upon the application of varying brake-horsepower loads to the engine.

As with light-duty emission rate results, uncertainty exists from the outset as a function of the precision and accuracy associated with the individual sampling and test methods. For example, with NOx emission testing under the FTP, the results of repeated EPA Federal Test Procedure runs on the same heavy-duty engine can vary by about 5-10% within the same lab and by about 5-25% from laboratory to laboratory (USEPA, 1984). This range is not atypical of many environmental analysis techniques. However, with hydrocarbon and particulate matter emission testing, the results between laboratories range by as much as a factor of two (NRC, 1981).

The heavy-duty FTP tests are run in both hot start and cold start modes, and the test results were weighted 1/7 cold starts and 6/7 hot starts. These splits were apparently designed to reflect the start-mode distribution thought to occur in the field. However, the hot start and cold start mode emission weighting, used to adjust the test results, are not likely to represent actual vehicle operations.

The heavy-duty engine testing procedure employs an estimated cycle speed of 19.45 miles per hour and an approximate trip length of 6.4 miles (USEPA, 1985). Note that the speed and distance must be estimated because the test procedure applies a load to the engine, rather than testing an actual vehicle on a chassis dynamometer. The engine cycle includes 36% idle operation (USEPA, 1985).

To develop the emission factors that are currently in use, a one-time heavy-duty engine testing program was conducted in 1983/84 as a cooperative effort between the USEPA and the Engine Manufacturing Association (EMA)(Platte, 1989). Engine emission rates were determined as a function of the average brake-horsepower load applied to the engine during the transient cycle test (grams/brake-horsepower-hour) under the heavy-duty FTP, and were converted to grams/mile emission factors using a USEPA model (Machiele, 1988).

In the 1983/84 tests, the USEPA and EMA tested 30 in-use heavy-duty diesel engines (USEPA, 1984). The final in-use heavy-duty diesel engine emission factors are based upon the test results for 22 (9 medium heavy-duty diesel and 13 heavy heavy-duty diesel engines) of the 30 engines tested. Thus, the emission factor data is based upon very limited testing data.

The 22 engines were accepted "as is," removed from the chassis of their respective vehicles, and tested on engine dynamometers by the U.S. Environmental Protection Agency using the new-engine transient test cycle. To simulate actual operating conditions, these engines were not tuned-up before testing. Each engine was run through the transient cycle from one to four times to generate an average emission factor for each of the four pollutants measured (HC, CO, NOx, and Particulate). Emissions were analyzed in accordance with the federal test procedures outlined in the Code of Federal Regulations (40 CFR 86).

Using the torque and RPM feedback in the test procedure, applied brake-horsepower is integrated with respect to time for the hot and cold cycles. This produces a brake-horsepower-hour value that is used in calculating brake specific emissions (40CFR86.1327-84 and 40CFR86.1342-84).

The range of test results for the 22 engines are provided in Tables 1 and 2. As can be noted in the tables, the range of results from the heavy-duty federal test procedure for similar sized engines is large. It should be noted that the engines tested had accumulated varied miles traveled (29,000 to 410,000 miles). However, it is unclear if the vehicle mileage accumulated was representative of the in-use vehicle fleet. Based upon the limited number of samples, and the number of variables involved, it would be inappropriate to use the test results to establish statistical relationships between engine size, accumulated mile traveled, and emission rates.

Table 1
Transient Cycle Emission Test Results for
Nine Medium Heavy-Duty Diesel Engines
(165 HP to 210 HP Rating)

Pollutant	Range of Emissions (g/bhp-hr)	
	Low	High
HC[7]	0.72	1.38
CO	2.30	10.37
NOx	5.71	9.95[8]
Particulate	0.62	0.89

Table 2
Transient Cycle Emission Test Results for
Fourteen Heavy Heavy-Duty Diesel Engines
(230 HP to 435 HP Rating)

Pollutant	Range of Emissions (g/bhp-hr)	
	Low	High
HC[7]	0.37	1.35
CO	1.55	13.53
NOx	6.65	9.61
Particulate	0.58	2.14

(Source: USEPA, 1984)

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[7] Including methane.

[8] In addition, one of the engines rated at 175 HP was listed by EPA as potentially over-fueled and mistimed. This engine was characterized by a NOx emission rate was 18.9 g/bhp-hr.

The baseline emission rates for heavy-duty diesel vehicles appear to be fraught with uncertainty. The one time testing program yielded emission rates for a very limited number of vehicles and the supplemental data gathered from manufacturers may or may not be representative of the 150,000 vehicle in-use fleet. Furthermore, emission rates are generated as a function of the average brake-horsepower torque load applied to the engine during the transient cycle test (grams/brake-horsepower-hour), and may not be representative of in-use emissions.

In 1988, based upon the results of a Radian Corporation study entitled Heavy Duty Diesel Vehicle Inspection and Maintenance Study (Radian, 1988), the CARB modified the USEPA emission factors to reflect inspection and maintenance practices in California. The Radian emission factors were adopted directly by the California Air Resources Board, replacing the federal emission factors. The differences between the baseline emission factors used by the CARB and USEPA are significant, but are still highly uncertain.[9]

USEPA Conversion Factors

The emission rates determined from the federal transient test procedure (grams per brake-horsepower-hour) are not useful for the purposes of preparing an emission inventory. To couple the emission factor with vehicle activity, specifically vehicle miles traveled, the EPA developed a conversion factor so that g/BHP-hr emission rates could be converted to g/mi emission rates (Machiele, 1988). The conversion factors are based upon the premise that brake-specific fuel consumption (BSFC) data (pounds of fuel/BHP-hr) gathered during transient cycle testing can be coupled with assumed fuel density (pounds/gallon) and fuel economy data (miles/gallon) for the engine class and used to prepare a conversion factor (BHP-hr/mi).

The brake-specific fuel consumption and fuel economy data vary with gross vehicle weight and fuel type (Machiele, 1988). The BSFC data were collected during the testing of the same 22 1979/80 model year engines by the USEPA in 1984. These data were supplemented with new vehicle BSFC specifications (manufacturers were contacted in 1987 and requested to supply BSFC data for their 1987 engines).

It is not clear if the BSFC data used to convert g/bhp-hr emission rates to g/mile emission rates are representative of engines that are operating in the vehicle fleet. Given that the BSFC data from the in-use 1984 engine tests varied from 0.398 lb/BHP-hr to 0.504 lb/BHP-hr, some uncertainty is necessarily associated with the use of the average BSFC factors.

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[9] The inspection and maintenance corrections are discussed in more detail in the full report by the authors.

Fuel economy (mi/gallon) data were based upon the nationwide 1982 Truck Inventory and Use Survey (TIUS) data (Machiele, 1988). Fuel economy is primarily dependent upon the engine characteristics and an increase in fuel economy should be automatically compensated by a decrease in BSFC in the conversion factor. However, fuel economy is also dependent upon the operating environment (traffic conditions, speed, and driver behavior) and vehicle load. Because no better data were available to disaggregate fuel economy data, the EPA chose to use the TIUS fuel economy data under the assumption that the average values would likely be representative of urban fuel economy (i.e. assuming that the effects of partial load and operation in an urban setting are offsetting).

Engine related fuel economy improvements were assumed to be offset by a corresponding decrease in brake-specific fuel consumption (Machiele, 1988). However, these projections do not account for changes in engine and drivetrain technology and computer control that may have affected the fundamental relationship between engine output (brake-horsepower) and fuel efficiency.

The USEPA prepared adjustments to the non-engine-related fuel economy for future vehicle model years based upon projected effects of such factors as: decreased drag coefficient, use of advanced radial tires, weight reduction, new drivetrain lubricants, etc. (Machiele, 1988). Deregulation of the trucking industry, i.e. pricing and market entry, may have accelerated fuel economy improvements as cost reduction measures.

The conversion factors used to change g/bhp-hr emission rates to g/mile emission rates used in emission inventory preparation appear to be a weak link in the chain. The BSFC and fuel economy data are aggregated for the fleet and may not represent in-use vehicle characteristics. Given the wide variability of the test results and the limited number of engines tested, it is likely that the conversion factors need substantial improvement.

Specific problems with the conversion factor estimates add uncertainty to the g/mi emission rates: 1) there is uncertainty at the outset associated with the use of the measured BSFC rates from the 1984 tests (measurement uncertainty, plus the question of whether the data are representative of the truck fleet), 2) there is uncertainty in the average fuel efficiency factors, 3) the data do not account for potential changes with time and new engine technology (e.g improved injection technology) in the BSFC/emission rate ratios, and 4) future non-engine related fuel economy improvement projections are highly speculative and uncertainty appears in both the magnitude of the effects and the percent penetration of the improvements into the truck fleet.

Speed Correction Factors

The emissions of hydrocarbons (HC) and carbon monoxide (CO) from motor vehicles (both gasoline and diesel) decrease as average vehicle speed increases (CARB, 1986; CARB, 1988). The emissions of oxides of nitrogen (NOx) from motor vehicles tend to increase as vehicle speed increases (CARB, 1986; CARB, 1988).[10]

The EMFAC7E emission factor program includes a speed correction algorithm for heavy-duty diesel trucks. The algorithm is applied to 13 speed groups (from 5-65 mph in 5 mph increments). EMFAC generates speed correction factors only for speeds below 65 mph, all higher speeds are assumed to occur at 65 mph. Thus, heavy-duty diesel truck emission rate uncertainty is more pronounced for high speed operations.

Speed correction factors for light-duty vehicles are based upon multiple cycle tests. Each of the cycle tests has a different average operating speed. The speed correction factor algorithm is a regression formula derived from the plot of measured emissions versus the average speed of the test cycles (USEPA, 1988).

The speed factor (SF) regression formula used by both the USEPA and the CARB for heavy-duty diesel emission inventory preparation (USEPA, 1985; CARB, 1986) is:

SF(S) = EXP(A + B*S + C*S**2)

Where S is the vehicle speed, and the empirical constants (A, B, and C) are pollutant dependent and assumed to be constant for all model years, and truck and engine sizes. Note that the derivation of the speed correction factor is based upon highly aggregated data. The speed correction factor is applied to the baseline emission rate to generate average speed emission rates.

It is unclear how USEPA staff developed the speed correction factors, given the limited data that were collected during the USEPA/EMA testing program. The USEPA staff members that developed the speed correction factors for Mobile 1 (the Mobile 4 predecessor) are no longer employed by the USEPA (Platte, 1989).

Laboratory data used by USEPA to develop the speed correction factors were likely the results from the sampling of the 22 diesel and 18 gasoline engines in early 1980 (Platte, 1989). The speed correction factors were updated in 1984 by recognizing that the emission standards for heavy-duty diesel vehicles had been modified; no additional engine tests were conducted (Platte, 1989).

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[10] NOx emission rates decrease until the average speed reaches about 30 mph, then increase as speed increases.

During the 1983/84 USEPA/EMA engine testing battery, the USEPA ran the 22 heavy-duty diesel truck engines through two test cycles. The first cycle, as described previously, was the federal test procedure consisting of transient mode testing. The second cycle was the 13-mode steady test cycle[11] used prior to 1984 to certify heavy-duty diesel engines. Each of the test cycles provided one integrated bag sample for analyses from each engine. The average "equivalent operating speed" of the engines, based upon the BSFC correction factors, for the transient FTP is different than for the thirteen mode test (based upon differences in applied loads and time increments). Significant differences in measured emission rates (grams/bhp-hr) result, especially for hydrocarbons and particulate matter, under the steady-state mode and transient mode tests (USEPA, 1984; NRC, 1981).

If the speed correction factors were developed in a manner similar to those for light duty vehicles, a significant problem exists. The speed correction factors would have to have been based upon two data points for each engine (one for the transient test and one for the 13-mode steady-state test, converted to grams per mile). Thus, not only would the same problems noted for light duty vehicles exist (i.e the application of average cycle correction factors to actual in-use traffic speeds), but additional uncertainty based upon data deficiencies plays a role.

The problem that is encountered in using the aggregated speed-emission relationships found in laboratory testing is that they do not relate to actual driving conditions. The speed correction factor for 50 mph, does not yield the emissions that would occur at 50 mph, but the emissions that would occur at an average speed of 50 mph if the vehicle was operated in an identical manner to the certification procedure (i.e. the same number of stops and starts and the same acceleration rates).

Even if the speed correction factors yielded instantaneous steady-state speed emission rates, vehicle speed distributions vary from road-type to road-type and from area to area. As would be expected, if speed correction factors are to be applied to the baseline emission rates for VMT, speed distributions on the roadway links must be known. In this manner, proper speed correction factors could be applied to specific portions of the vehicle miles traveled on each link.

The CARB does not estimate speed distributions on individual road links to prepare emission estimates. Instead, a bulk estimate of VMT is disaggregated into estimated speed groups based upon "engineering judgement." For areas other than the South Coast Air Basin, staff of the CARB and Caltrans used Highway Performance Management System (HPMS) data to estimate speed average speeds distributions of vehicle traffic on different roadway types.

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[11] Five power modes (each at two speeds) and three idle modes (40CFR86.334-79).

Cold and Hot Starts

The incremental cold start emissions for light-duty diesel trucks are significantly lower than for light-duty gasoline powered trucks (1/3 for NOx, 1/12 for HC, and 1/26 for CO), but they are still a necessary component of the emission inventory (CARB, 1986).

One mitigating aspect is that the certification procedure used to develop the in-use baseline emission rates is conducted in both cold and hot modes and the sample results are weighted 1/7 cold and 6/7 hot to simulate vehicle start conditions. However, three questions arise: 1) were the small number of engines tested representative, 2) is the cold/hot start ratio appropriate, and 3) is it appropriate to include these incremental emissions in an aggregated VMT emission rate?

Cold and hot start emission rates for heavy-duty diesel trucks warrant further investigation and are likely to be a high priority for future research efforts.

Acceleration

Power enrichment (acceleration) is believed to be a discrete vehicle activity resulting in incremental emissions for light-duty vehicles (Groblicki, 1990; Calspan Corp, 1973; Kunselman, et al., 1974; CARB, 1991). Recent General Motors and California Air Resources Board studies have indicated that power enrichments (high power demand and acceleration rates) in light-duty gasoline vehicles may contribute high incremental emissions, even with today's modern emission controls (Groblicki, 1990; CARB, 1991). Acceleration emissions may be significant at freeway onramps, signalized intersections, etc. This may be especially true for heavy-duty diesel trucks, because of their heavy operating loads and power requirements to achieve merging speeds.

The current modeling efforts (baseline rates and speed correction factors) do not account for increased emissions that may occur during acceleration and deceleration. Because the EMFAC emission factors for average cycle speeds do not adequately account for acceleration, it does not seem logical to apply the existing emission factors to fine tuned acceleration-related analyses such as signal timing emission reduction estimates.

Fuel Properties

With respect to fuel specifications, the effects of fuel composition on pollutant emissions is likely to be important. Recent results of the Auto/Oil Air Quality Improvement Research Program appear to indicate that the gasoline certification fuel, used for testing in the dynamometer research, appears to be much less polluting than the average gasoline fuel currently purchased by the public (Auto/Oil AQIRP, 1990). Southwest Research Institute performed limited heavy-duty diesel engine testing that indicated diesel fuel composition has an effect upon emission rates (Dietzman, et al., 1980). However, the effects of current diesel fuel compositions purchased by the public on in-use emission rates is relatively unresearched.

As new diesel fuel requirements are implemented in California (or areas of California), the variation in fuel used will affect the emission inventory. Emission factors will likely need to be developed for different fuels that may be available in various areas of the state. Fuel parameters for heavy-duty diesel trucks may be important in developing future emission estimates.

SUMMARY OF UNCERTAINTY

Numerous assumptions and generalizations are made when generating a bulk emission inventory. Unfortunately, due to the large numbers of assumptions made and the relative uncertainty associated with each step of the emission inventory preparation process, a large amount of uncertainty exists in the heavy-duty diesel truck emission inventory methodologies.

Uncertainty is pervasive in all three emission calculation factors: vehicle activity, activity-specific emission rates (including the conversion factors), and correction factors.

There are major problems with the vehicle activity parameters used in modeling heavy-duty diesel truck emission: 1) uncertainty is associated with the use of any surrogate indicator to estimate actual activity parameters, and getting to the right answer (i.e. the actual vehicle miles traveled by various sectors within the trucking industry) is not possible given current levels of knowledge; 2) the activity that is used in modeling methodologies are highly aggregated; 3) highly aggregated estimates for VMT and average speed assumptions are currently used; 4) heavy-duty truck activities are not estimated by UTPS-type models and, even if they were included, UTPS models would not estimate the activities that should be linked to activity-specific emission rates (acceleration and vehicle miles traveled at constant speed cruise); and 5) some vehicle activities, specifically idling and engine starts, are currently omitted from the models.

We are dealing with a number of "levels" of uncertainty in the use of the existing activity-specific emission factors to estimate the heavy-duty diesel truck emissions inventory: 1) precision and accuracy of the test methods; 2) testing of a non-statistically representative numbers of vehicles; 3) highly questionable emission rate conversion factors; 4) use of "average speed" emission factors and the application of speed correction factors to activity data; 5) "on-road" representativeness of existing activity-specific emission rates; and 6) fuel composition effects.

Uncertainty is multiplicative in the methodologies used to develop the emission inventory. That is, uncertainty in vehicle activity is multiplied by the uncertainty in the activity-specific emission rates, corrected by uncertain correction factors. However, a simple statistical formula representing suspected ranges of uncertainty cannot be applied to the estimates to determine what the net uncertainty is. There are simply too many unanswered questions regarding the fundamental emission relationships and the basic applicability and usefulness of much of the data collected.

CONCLUSIONS AND RECOMMENDATIONS

The use of current emission models for predicting the results of transportation control measure and alternative fuel control strategy implementation will be fraught with uncertainty. This is not to say that relative comparisons cannot be performed using the existing models. However, when such comparisons are made, one should not assume that the results are precise nor highly accurate. It does not, however, seem appropriate to rely heavily upon cost-effectiveness estimates that are based upon modeled emission effects. Furthermore, the comparison of mobile source and stationary source control strategy cost-effectiveness seems inherently improper based upon the relative uncertainties associated with estimates.

The picture is not so bleak, however, that regulators, industry, and the general public should become disillusioned with the regulatory process. The problems with emission reduction estimation techniques can be corrected through research. Yet, we should not necessarily let our inability to accurately predict the actual consequences of emission control strategies prevent us from making progress toward attainment. Instead, we must recognize the limitations with our models and take the emission reduction uncertainty into account when determining which control strategies should be implemented.

Regulatory agencies must use models to evaluate the potential effects of emission control strategies. Yet, uncertainty will exist in any models used to estimate vehicle emissions, even if significantly improved. The important question to be answered is whether all avoidable uncertainty has been eliminated from the analytical methods.

Although the USEPA and CARB have attempted to ensure that the best available data are employed and that research projects designed to improve the methodologies are undertaken, additional research is necessary to characterize the emissions from the heavy-duty diesel fleet. Improvements to methodologies are inevitable, as the CARB and regulated industry come to grips with emission inventory uncertainty.

The California Air Resources Board's Haagen-Schmidt Laboratory in El Monte, California, has entering into a co-funded project with the Southern California Rapid Transit District to construct a heavy-duty vehicle chassis dynamometer (Carlock, 1990). The new chassis dynamometer will be capable of monitoring modal[12] emissions (second-by-second motor vehicle emission rates under specific idling acceleration and constant speed operating conditions) for buses as well as heavy-duty gasoline and diesel powered trucks. Using the data collected, the CARB research team will endeavor to establish modal emission rates that might be linked with specific emission-related activity data (idling, steady-state speed, and acceleration/deceleration). Thus, both correction factors and conversion formulas may potentially be eliminated from the methodologies. The dynamometer will be used initially to examine bus emissions, and should be used to examine heavy-duty truck emissions in late 1991. Two full time staff positions have been allocated by the State to the heavy-duty dynamometer project (Carlock, 1990).

The proposed CARB research program (CARB, 1990c) over the next few years should resolve a large amount of the uncertainty in the mobile source emission inventory, by addressing the inadequacy of the existing emission rates. The CARB studies have the potential to provide new activity-specific emission factors for heavy-duty diesel and gasoline vehicles, reducing emission factor and correction factor uncertainties. However, activity-specific emission factors must be coupled with appropriate emission-related vehicle activities. It is not enough to develop new emission factors without improving activity estimation methodologies. Parallel research efforts should focus on methods to estimate disaggregate vehicle activity estimates that may be linked to the new activity-specific emission rates; idling, engine start, steady-state speed, and acceleration activities.

The Institute of Transportation Studies has recently prepared a research plan designed to reduce the uncertainty in the heavy-duty diesel truck emission inventory (Guensler, et al., 1991). The research plan supports a disaggregate modeling framework that will better resolve the emission impact of the heavy-duty diesel truck fleet. This long range research plan takes a parallel approach toward improving the emission

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[12] "Modal" is a term that is used in a number of different ways by engineers and regulatory agency staff. For mechanical engineers, modal serves as a reference to specific engine operating parameters. In previous emission testing, modal testing has often referred to the transient test cycle (FTP). The latest use of the term "modal emission testing" is essentially a hybrid of these. Modal testing will be the evaluation of emission rates for specific engine operating parameters.

inventory, with research into modal emission rates on one hand and research into modal activity estimates on the other. Further, the proposed activity plan includes the investigation of both advanced activity monitoring and modeling techniques for the goods movement industry. The research plan is staged, such that incremental emission rate research results can be used to focus activity research efforts and vice versa.

It is easy to point fingers at the uncertainty in existing methodologies, but solving the emission inventory problems for heavy-duty diesel and gasoline vehicles is not going to be easy. Experiments that resolve modal emission effects will consume significant laboratory resources, and the development of goods movement models will be data and resource intensive. However, if we really want to approach the implementation of emission control measures in a calculated and logical fashion, this research and development is crucial. To understand the complex relationships that determine emissions, a serious and cooperative commitment on the part of government agencies, the goods movement industry, and the research community will be required.

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NOTE TO EDITORS