CHAPTER 10

Air Quality Impacts

Clearing the air, literally or metaphorically, does tons of good to all.

—*Anonymous*

INTRODUCTION

An *air pollutant* is a gas, liquid droplet, or solid particle which, if dispersed in the air with sufficient concentration, poses a hazard to flora, fauna, property, and climate. Air pollution, a visible environmental side effect of transportation, has become a public health concern for millions of urban residents worldwide (TRB, 1997). Transportation or "mobile" sources of air pollution, particularly motor vehicles, are a primary source of local carbon monoxide problems and are considered the main cause of excess regional photochemical oxidant concentrations. Transportation vehicles typically emit carbon monoxide, nitrogen oxides, small particulate matter, and other toxic substances that can cause health problems when inhaled. Air pollution also has adverse effects on forests, lakes, and rivers. The contribution of transportation vehicle use to global warming remains a cause for much concern as anthropogenic impacts on the upper atmosphere become increasingly evident. Airports, for instance, are a major source of local violations of ambient carbon monoxide standards and contribute to regional photochemical oxidant problems. In the current era, rail travel is increasingly being powered by electricity and is therefore typically not associated with significant air pollution, except in cases where the source of rail energy generation is associated with significant pollution, such as coal-based electrical power generation.

In this chapter we discuss the transportation sources and adverse impacts of air pollution and factors that affect pollutant emissions and concentrations. We also describe how to estimate pollutant emissions and concentrations using various models and present a general methodology to estimate the air quality impacts of transportation projects. In addition, possible measures to mitigate air pollution impacts, and air quality legislation, are discussed.

10.1 AIR POLLUTION SOURCES AND TRENDS

10.1.1 Pollutant Types, Sources, and Trends

Primary air pollutants are those emitted directly into the atmosphere and include carbon monoxide, hydrocarbons, sulfur oxides, nitrogen oxides, and particulate matter. *Secondary air pollutants* such as ozone and acidic depositions, are those formed in the atmosphere as a result of physical and chemical processes (such as hydrolysis, oxidation, and photochemistry) on primary pollutants. *Greenhouse gases*, such as carbon dioxide, are also direct emissions although not as yet included in USEPA list primary air pollutants.

Natural sources of air pollution include forest fires and volcanoes; *anthropogenic sources* include power generation, fuel use, slash-and-burn agricultural practices, and transportation. Table 10.1 describes the types, sources, effects, and scales of transportation pollutants.

Total air pollution increased from 1960 to 1970 but decreased thereafter despite a great increase in vehicular travel (Figure 10.1). Emissions of volatile organic compounds and particulate matter have declined steadily over the years, while there has been only a slight increase in sulfur dioxide emissions. Also, lead emissions have dropped sharply following the development of lead-free gasoline. The drop in pollutant emissions over the years is often attributed to governmental intervention through the establishment of increasingly restrictive federal emission standards. For example, between 1980 and 1995, the allowable level of carbon monoxide emissions from a passenger car was reduced from 7.0 to 3.4 g/mi.

In the last decade, transportation contributed about 83% of the carbon monoxide (CO), 45% of the volatile organic compounds (VOCs), and 53% of the nitrogen oxide (NO_x) emissions in the United States (USEPA, 2005). Tailpipe emission rates have declined significantly over the past few decades. However, the actual reductions may be smaller because the standard tests do not reflect real driving conditions; and vehicles producing harmful emissions are typically not measured in these tests (BTS, 1997; Homburger et al., 2001). Also, increased vehicle mileage has offset much of the reduction in per-mile emissions, so vehicle emissions continue to be a major

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Table 10.1 Air Pollutants from Transportation Sources

Pollutant	Description	Source	Effects	Scale
Carbon monoxide (CO)	Colorless and odorless toxic gas formed by incomplete combustion of fossil fuels. The most plentiful of mobile-source air pollutants.	Vehicle and aircraft engines	Human health (undermines oxygen-carrying ability of blood), climate change.	Very local
Fine particulates (PM_{10}; $PM_{2.5}$)	Inhalable solid particles emitted by mobile sources: droplets of unburned carbon, bits of rubber, metal, material from brake pads, lead particles, etc.	Diesel engines and other sources	Human health (causes respiratory problems), aesthetics.	Local and regional
Nitrogen oxides (NO_x)	Primarily, NO and NO_2, caused by oxidation of atmospheric nitrogen. Some are toxic, all contribute to ozone formation.	Engine	Helps formation of corrosive acids that damage materials; kills plant foliage, impairs respiratory system; absorbs light and reduces visibility; contributes to ozone formation.	Regional
Volatile organic compounds	Includes hydrocarbons (HC) such as methane (CH_4). Emitted from unburned fuel from fuel tanks and vehicle exhausts. Smog is a haze of photochemical oxidants caused by the action of solar ultraviolet radiation on HC and NO_x.	Fuel production and engines	Human health, ozone precursor.	Regional
Lead	Formed by burning leaded fuel.	Fuel production and engines	Affects circulation, reproductive, nervous, and kidney systems; suspected of causing hyperactivity and lowered the learning ability in children.	Regional
Airborne toxins (e.g., benzene)	Pollutants that are carcinogenic or have effects on human reproductive or developmental systems.	Fuel production and engines	Human health risks.	Very local
Ozone (O_3)	Highly reactive photochemical oxidizer formed in atmosphere through reactions involving NO_x, VOCs, and sunlight.	NO_x and volatile organic compounds	Human health (respiratory), plants, aesthetics; ground-level O_3 is a primary component of smog, which impairs visibility.	Regional

Table 10.1 (*continued*)

Pollutant	Description	Source	Effects	Scale
Sulfur oxides (SO_x)	Formed by burning of sulfur-containing fossil fuels and oxidation of sulfur; SO_2 is a colorless water-soluble pungent and irritating gas.	Diesel engines	Human health risks, causes acid rain that harms plants and property; lung irritant; causes acid rain.	Regional
Carbon dioxide (CO_2)	By-product of combustion.	Fuel production and engines	Climate change.	Global
Chlorofluorocarbons (CFCs)	Nontoxic, nonflammable chemicals containing atoms of carbon, chlorine, and fluorine. Classified as halocarbons, a class of compounds that contain atoms of carbon and halogen atoms.	Air conditioners manufactured before the 1980s	Climate change (depletion of outer ozone layer).	Global
Road dust	Dust particles created by vehicle movement.	Vehicle use	Human health, aesthetics.	Local

Source: Carpenter (1994), Faiz et al. (1996), USEPA (1999), Holmen and Niemeier (2003).

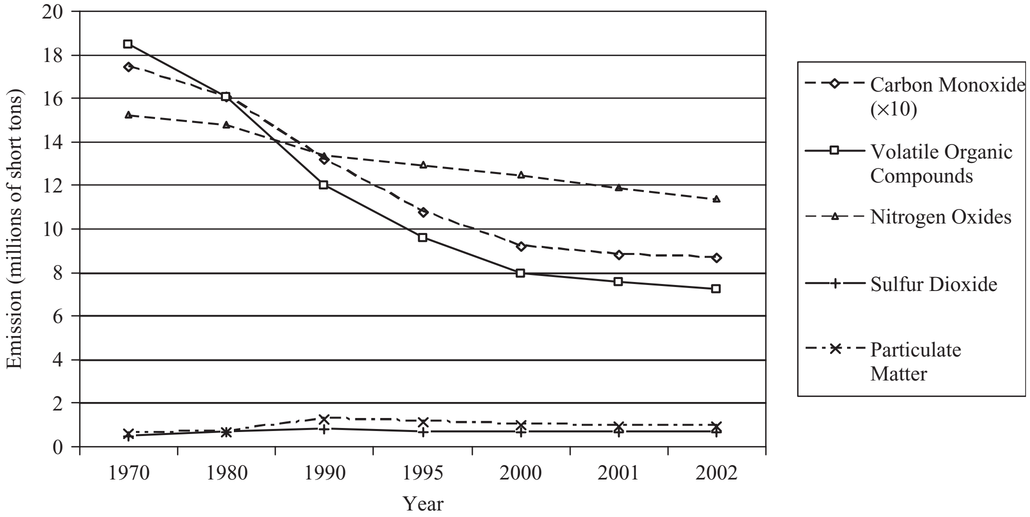


Figure 10.1 Trends in pollutant emissions from transportation sources, 1970–2002. (From USEPA, 2005.)

problem. The overall level of emissions depends heavily on traffic flow characteristics, such as the average flow speed, the frequency and intensity of vehicle acceleration and deceleration, the number of stops, and the vehicle operating mode.

Although highways continue to be the major contributor of transportation air pollution, contributions from other modes should not be underestimated. More than 120 million people live in areas with unhealthy air due to high levels of smog, and most of the busiest airports in the United States are located in, and contribute pollution to, urban areas where air quality is already a problem. Furthermore, it is anticipated that the relative contribution of airport activities to overall emissions will increase over time. Airport emissions are becoming the largest *point sources* in many urban areas, emitting as much NO_x as a large power plant. Sources of air pollution at airports are aircraft (main engines, auxiliary power units), ground service equipment (aircraft tugs, baggage tractors, etc.), and ground access vehicles at airports.

10.1.2 Categories of Air Pollution

There are generally two categories of air pollutants: criteria air pollutants and greenhouse gases.

(*a*) *Criteria Air Pollutants* This category consists of carbon monoxide (CO), nitrogen oxide (NO_x), volatile organic compounds (VOCs), particulate matter of size 10 μm or less, particulate matter of size 2.5 μm or less, sulfur dioxide (SO_2), and ammonia (NH_3). Gasoline-powered light vehicles continue to be the source of most carbon monoxide emissions from highway vehicles. In the United States, heavy diesel-powered vehicles account for 46% of NO_x emissions from highway vehicles, and light gasoline vehicles are responsible for about 48%. With regard to volatile organic compounds, the transportation sector accounted for just over 54% of total emissions in 2002, and gasoline-powered vehicles were responsible for 91% of highway vehicle VOC emissions. In 2002, the transportation sector also accounted for just over 54% of particulate matter emissions of size 10 μm or less. Most of these were from gasoline vehicles. A similar distribution was seen for particulate matter of smaller size (2.5 μm or less). With regard to lead, the transportation sector (highway vehicles in particular) has long been identified as a dominant source of lead emissions, but its share has dwindled over the years from 82% in 1970 to about 13% in 1999. This is due largely to a 1978 regulatory action calling for reduced lead content of gasoline fuels. Only a small share of transportation lead emissions is now attributed to highway fuel use (USEPA, 2005). In some developing countries, however, lead continues to be a major air pollutant from transportation sources.

(*b*) *Greenhouse Gases* The atmosphere serves as a blanket for retaining and redistributing heat to maintain Earth's mean surface temperature at levels that are conducive for life. This role is played by certain gases in the atmosphere known as *greenhouse gases*, which include carbon dioxide (CO_2), methane (CH_4) nitrous oxides, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride. These gases, released by anthropogenic sources, have reached levels that threaten to expand the natural layer of greenhouse gases, thus leading to greater retention of radiation energy, accelerated global warming, and consequent damage to the global ecology and development of extreme weather patterns. Transportation sources are significant in this regard: Most CO_2 emissions are from petroleum fuels, particularly motor gasoline, and CO_2 accounts for 80% of the total greenhouse gas emissions.

10.2 ESTIMATING POLLUTANT EMISSIONS

10.2.1 Some Definitions

- *Emission*. This is the discharge of pollutants into the atmosphere. The overall magnitude of emissions depends on the number of emitting sources, the diversity of source types, the nature and scale of activity at the polluting source, and the emission characteristics. For instance, more pollutants are emitted by motor vehicles at higher altitudes, due to inefficient combustion caused by air thinness.
- *Mobile emission*. A mobile source of air pollution is one that is capable of moving from one place to another under its own power, such as a motorized vehicle. Emissions from mobile sources are described as mobile emissions. The total air quality in an area is measured in terms of the ambient concentration of pollutants that are emitted by mobile and stationary sources.
- *Emission factors*. An *emission factor* is an average estimate of the rate at which a pollutant is released into the atmosphere as a result of some activity (such as motor vehicle operation) in terms of activity level such as VMT (vehicle-miles of travel) or VHT (vehicle-hours traveled) for motor vehicles.

10.2.2 Factors Affecting Pollutant Emissions from Motor Vehicles

The major factors that affect the level of vehicle emissions can generally be classified as follows: travel-related, driver-related, highway-related, vehicle-related, fuel type, and environmental (Figure 10.2). An NCHRP study (Report 394) provides information on the sensitivity of vehicle emissions in response to changes in these factors (Chatterjee et al., 1997). We discuss the factors below.

(*a*) *Travel-Related Factors* Travel-related factors include vehicle engine operating modes, speeds, and accelerations and decelerations. Three *operating modes* are typically considered in estimating exhaust emissions: cold start, hot start, and hot stabilized period. Emission rates differ significantly across these modes. The EPA defines a *cold-start* as any start of a vehicle engine occurring 4 hours or later following the end of the preceding trip for non-catalyst-equipped vehicles, and 1 hour or later following the end of the preceding trip for catalyst-equipped

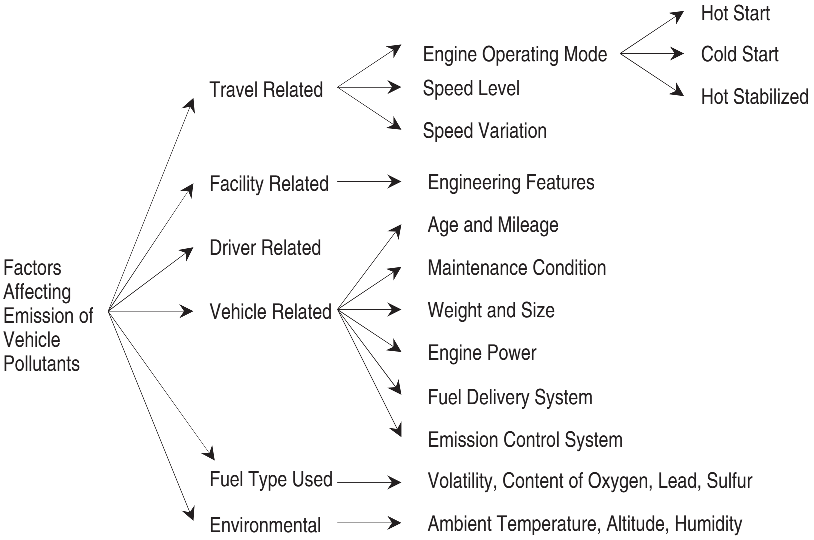


Figure 10.2 Factors affecting vehicle emissions.

vehicles. *Hot starts* are those that occur less than 4 hours after the end of the preceding trips for non-catalyst-equipped vehicles, and less than 1 hour after the end of the preceding trip for catalyst-equipped vehicles. The time between the start and the end of a trip is called the *hot-stabilized period*. Emission rates of HC and CO are higher during cold starts than during hot starts and are lowest during hot-stabilized operation. The difference in vehicle emission rates between operating modes are due to their different air-to-fuel ratios and catalytic conversion rates. In the cold-start mode of vehicle engine operation, the catalytic emission control system is not fully functional and the low air-to-fuel ratio leads to the high HC and CO emissions. The emission of NO_x is, however, low during cold-start modes.

The type, speed, and acceleration of a vehicle and the load on its engine have significant impacts on the level of emissions. HC and CO emissions are highest at low speeds. Figure 10.3 shows the effect of speed on CO and NO_x emissions by vehicle type and fuel type. It is seen, for example, that for most vehicle types, CO and NO_x emissions generally are high at low speeds, decrease with increasing speed to their minimum rates, and then stay flat or increase slightly depending on the vehicle or fuel type, or the pollutant in question. The smoothness and consistency of vehicle speed, traffic conditions, and driving behavior can influence emissions. Sharp acceleration at a high speed and heavy load on an engine require more fuel to feed the engine, thus generating more HC and CO emissions but cause little change in NO_x emissions.

(*b*) *Facility-Related Factors* Certain facility designs can encourage transportation vehicles to operate at low-emitting speeds or modes. For highway transportation, examples include low grade, existence of ramps and signals, acceleration and deceleration lanes, and channelization. It has been shown, for example, that traffic signal coordination can result in up to a 50% reduction in emissions under certain circumstances (Rakha et al., 1999).

(*c*) *Driver-Related Factors* Driver behavior varies significantly by person and by traffic condition, and can influence emission rates. For example, aggressive drivers typically exert more frequent and severe accelerations and decelerations than do their less aggressive counterparts. Such abrupt changes in velocity impose heavy loads on the engine and thus result in higher levels of emissions.

(*d*) *Vehicle-Related and Other Factors* Vehicle emissions are influenced by vehicle age, mileage, condition, weight, size, and engine power. Older model vehicles typically emit more pollutants than do newer ones and heavier and larger vehicles emit more pollutants than are emitted by lighter and smaller vehicles (Ding, 2000). Fuel type also affects emission levels significantly. Furthermore, there is a difference in the combustion processes of the two major engine types that translate into different pollutant emissions rates. Table 10.2 shows pollutant emissions by highway vehicle type and transit mode under average operating conditions.

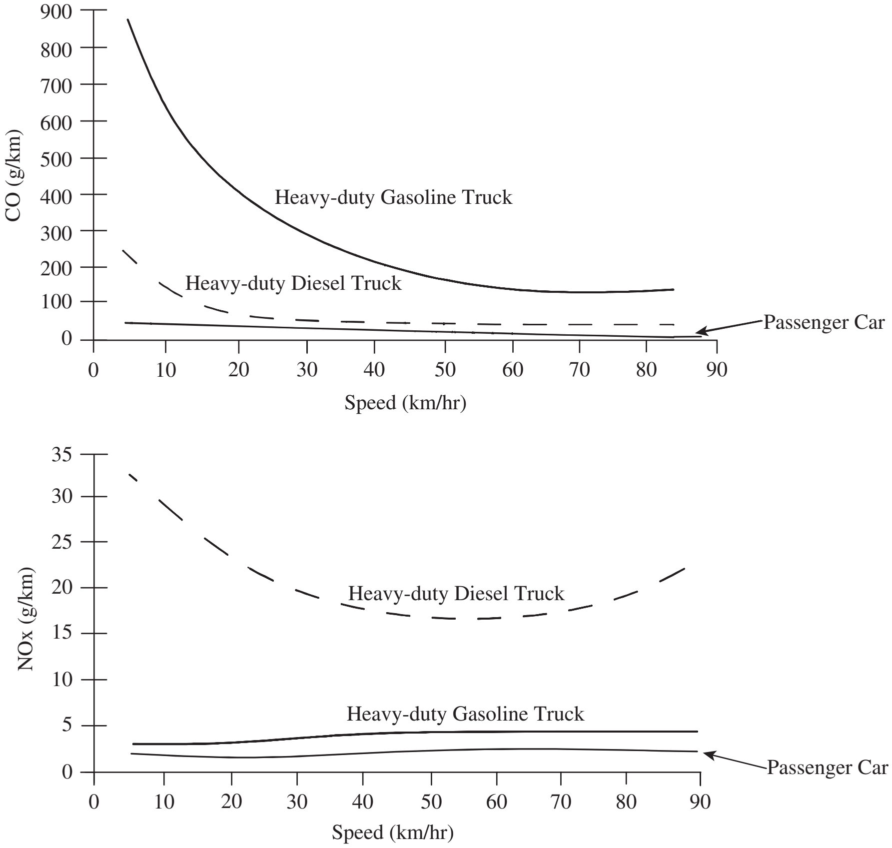


Figure 10.3 Variation in CO and NO_x emission rates by speed, vehicle, and fuel type. (From Faiz et al., 1996.).

(*e*) *Environmental Factors* At low temperatures, more time is required to warm up the engine and the emission control system, thus increasing the level of cold-start emissions. At higher temperatures, on the other hand, combustive emissions are low, but evaporative emissions are high, due to the increased fuel evaporation rate.

10.2.3 Approaches for Estimating Pollutant Emissions from Highways

In evaluating the impact of transportation improvements on air quality, the first step is to estimate the change in emissions as a result of changes in the average speed of vehicles, increases in motor vehicle trips, and increases in VMT due to these improvements. The second step is to determine the resulting change in pollutant concentrations due to the change in emissions. For highway transportation, emission models can be grouped as follows: speed-based, modal, microscopic, and fuel-based models (Ding, 2000).

(*a*) *MOBILE 6.0 Mobile Source Emission Factor Model* The EPA MOBILE6 is a speed-based model that estimates highway transportation emission factors in gms/vehicle-mile for three pollutants: hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen (NO_x), for gasoline- and diesel-fueled highway motor vehicles and certain specialized vehicles, such as natural gas–fueled or electric vehicles. MOBILE6 estimates the emission factors for 28 individual vehicle types under various conditions, such as ambient temperature, travel speed, operating mode, fuel volatility, and mileage accrual rates, and considers four vehicle roadway facilities: freeways, arterial and collectors, local roadways, and freeway ramps (USEPA, 2002). The fleet average emission factor (EF) for a vehicle class, calendar year, pollutant, and emission-producing process is given as follows (Koupal and Glover, 1999):

$$\mathrm{EF}_{ijk} = \sum_{m=1}^{n}[\mathrm{FVMT}_{im}(E_{ijkm}C_{ijkm})] \tag{10.1}$$

Table 10.2(a) Pollution Emissions by Mode (g/VMT)

	VOC	CO	NO_x	CO_2
Automobile	1.88	19.36	1.41	415.49
SUVs, light truck	2.51	25.29	1.84	521.63
Bus	2.3	11.6	11.9	2386.9
Diesel-powered rail	9.2	47.6	48.8	9771.0

Source: TCRP (2003).

Table 10.2(b) Pollutant Emissions by Truck Type (g/VMT)[a]

Truck Type	Road Class	VOC	CO	NO_x	PM-10	PM-10 Exhaust Only
Single-unit gasoline truck	Local	7.06	144.07	5.94	0.13	0.11
	Arterial	2.29	59.87	7.18	0.13	0.11
	Urban freeway	1.31	51.39	8.12	0.13	0.11
	Rural freeway	1.31	75.87	8.84	0.13	0.11
Single-unit diesel truck	Local	1.18	6.86	14.95	0.42	0.38
	Arterial	0.59	2.86	15.34	0.42	0.38
	Urban freeway	0.42	2.21	22.69	0.42	0.38
	Rural freeway	0.41	2.8	30.39	0.42	0.38
Combination-unit diesel truck	Local	1.22	7.64	16.07	0.41	0.37
	Arterial	0.61	3.18	17.02	0.41	0.37
	Urban freeway	0.43	2.48	25.65	0.41	0.37

Source: http://www.fhwa.dot.gov/ENVIRonment/freightaq/appendixb.htm.

[a] Emission estimates may differ somewhat from EPA National Emission Inventory (NEI) heavy-duty truck estimates, due to differences in aggregation methods for vehicle class and speed.

where EF_{ijk} is the fleet-average emission factor for calendar year i, pollutant type j, and emission-producing process k (e.g., exhaust, evaporative); $FVMT_{im}$ the fractional VMT attributed to model year m for calendar year i ($n = 28$ in MOBILE6); E_{ijkm} the basic emission rate for calendar year i, pollutant j, process k, and model year m; and C_{ijkm} the correction factor (e.g., for temperature, speed) for calendar year i, pollutant j, process k, and model year m.

The MOBILE6 model produces separate emission factors for the start- and running-modes. The running-mode emission factors are based only on hot-stabilized operating conditions; the start emissions represent the additional emissions that result from a vehicle start. The model provides daily and hourly emission factors for each hour of day. In addition, it incorporates enhancements such as update of fuel effects on emissions, use of diurnal evaporative emissions based on real-time diurnal testing, update of hot-soak evaporative emission factors, update of heavy-duty engine emission conversion factors, update of fleet characterization data, and a provision for distinct emission factor calculations for a wider range of vehicle categories. To facilitate implementation, a software package has been developed for the MOBILE6 model (see Section 10.2.5).

(*b*) *Emission Models Based on Vehicle Operating Modes* The term *engine operating mode* refers to engine temperature (hot start, cold start, etc.), while *vehicle operating mode* refers to speed change (or lack thereof), such as cruise, acceleration, deceleration, and idling. Barth et al. (1996) and An et al. (1997) developed modal emission models for light-duty cars and trucks. These models predict the engine power, engine speed, air-to-fuel ratio, fuel use, engine-out emissions, and catalyst pass fraction and finally estimate tailpipe emissions and fuel consumption. The vehicle power demand is modeled as a function of the operating variables (i.e., vehicle acceleration and speed), specific vehicle parameters (e.g., vehicle mass, transmission efficiency, effects of accessories), and road conditions. The fuel use rate is a function of the power demand, engine speed, and air/fuel ratio, and the engine-generated emissions are estimated using the fuel rate and other factors, as follows:

$$E = \mathrm{FR} \times g \times \mathrm{CPF} \tag{10.2}$$

where E is the tailpipe emission in g/s, FR the fuel-use rate in g/s, g the grams of engine-out emissions per gram of fuel consumed, and CPF the catalyst pass fraction (the ratio of tailpipe emissions to engine-out emissions).

Another modal emission model is MEASURE (Mobile Emissions Assessment System for Urban and Regional Evaluation) (Guenslar et al., 1998). The emission rates estimated by MEASURE are dependent on both vehicle mode variables (vehicle speed, acceleration profile, idle times, and power demand) and vehicle technology variables (fuel metering system, catalytic converter type, availability of supplemental air injection, and transmission speed). Also, the models estimate the emission rates for each pollutant type.

(*c*) *Microscopic Emission Models* Microscopic emission models are used in traffic operations software packages to estimate emissions at highway segments, interchanges, and intersections. The emission rates are estimated incrementally as a function of the instantaneous vehicle fuel consumption, speed, acceleration, and engine power. The Transportation Analysis and Simulation System (TRANSIMS), for example, does this by multiplying the fractional power change at a given time and the emission difference for the given speed and power, and then adding the result to the emissions at constant power. The Traffic Simulation and Dynamic Assignment Model (INTEGRATION) accounts for vehicle stops and accelerations and decelerations at freeways and arterials and estimates emissions by computing fuel consumption for each vehicle on a second-by-second basis for three operation modes (constant-speed cruise, velocity change, and idling) as a function of travel speed (USEPA, 1998). Vehicle emissions are then estimated as a function of fuel consumption, ambient air temperature, and the extent to which a particular vehicle's catalytic converter has already been warmed up during an earlier portion of the trip (Rouphail et al., 2001). INTEGRATION also has the ability to capture congestion effects on emissions (Sinha et al., 1998). FHWA's TRAF-NETSIM tracks the movements of individual vehicles on a second-by-second basis at single intersections and at freeway segments and ramps, and estimates hot-stabilized emissions of CO, HC, and NO_x as a function of vehicle travel speed and acceleration.

(*d*) *Fuel-Based Emission Models* Fuel-based models estimate vehicle emissions on the basis of fuel consumed as vehicles operate in various operating modes. An example is the SYNCHRO traffic model, which first predicts fuel consumption as a function of vehicle-miles, total delay in vehicle-hours/hour, and total stops in stops/hour. Then, to estimate vehicle emissions, the fuel consumption is multiplied by an adjustment factor based on the emission type (Rouphail et al., 2001).

(*e*) *Greenhouse Gas Emission Models* CO_2, one of the biggest by-products of engine combustion (USEPA, 2006), is a significant greenhouse gas. For every gallon of motor fuel burned, approximately 20 pounds of CO_2 are emitted into the atmosphere. The USEPA has developed a score-based model for estimating the amount of this greenhouse gas. The score is determined on the basis of a vehicle's fuel economy and fuel type, because each type of fuel contains a different amount of carbon per gallon. The scale used ranges from 0 (maximum CO_2 emission) to 10 (least CO_2 emission), and the average score for model year 2005 was 5. Table 10.3 shows the score that corresponds to fuel efficiency rates (mpg) and fuel type. The fuel efficiency rate is a combination of rates from city and highway driving condition as follows:

$$\begin{aligned}&\text{Combined fuel economy(mpg)}\\&\quad = 1/(0.55/\text{city mpg} + 0.45/\text{highway mpg}).\end{aligned}$$

10.2.4 Procedure for Estimating Highway Pollutant Emissions

A transportation agency may seek to evaluate either (1) the existing air quality *situation* at a given time (with no intent of any transportation intervention) or (2) the estimated air quality (using models) or actual air quality (using field measurements) after a planned or past transportation intervention. Air quality is typically measured in terms of emissions and/or resulting concentrations of selected air pollutants. Transportation interventions first lead to changes in traffic flow patterns (operating speeds, speed change frequencies, traffic composition); in the medium term, such interventions cause changes in travel demand patterns (trip purposes, route, frequency, mode, etc.); and in the long term, they lead to changes in land-use patterns (locations of residences and businesses). The short-term effects lead to changes in emission rates,

Table 10.3 Greenhouse Gas Score Model

Fuel Type and Fuel Economy[a]					CO_2 Emissions (pounds/mile)	Greenhouse Gas Score
Gasoline	Diesel	E85	LPG	CNG		
44 and higher	50 and higher	31 and higher	28 and higher	33 and higher	Less than 0.45	10
36 to 43	41 to 39	26 to 30	23 to 27	27 to 32	0.45 to 0.54	9
30 to 35	35 to 40	22 to 25	20 to 22	23 to 26	0.55 to 0.45	8
26 to 29	30 to 34	19 to 21	17 to 19	20 to 22	0.65 to 0.74	7
23 to 25	27 to 29	17 to 18	15 to 16	18 to 19	0.75 to 0.84	6
21 to 22	24 to 26	15 to 16	14	16 to 17	0.85 to 0.94	5
19 to 20	22 to 23	14	13	14 to 15	0.95 to 1.04	4
17 to 18	20 to 21	13	12	13	1.05 to 1.14	3
16	18 to 19	12	11	12	1.15 to 1.24	2
15	17	11	10	11	1.25 to 1.34	1
14 and lower	16 and lower	10 and lower	9 and lower	10 and lower	1.35 and higher	0

Source: USEPA (2006).

[a] E85 = 85% ethanol and 15% gasoline, LPG = liquefied petroleum gas, CNG = compressed natural gas.

while the medium- and long-term effects lead to changes in travel amounts (vehicle-miles of travel); thus, the short-, medium-, and long-term effects all lead to a change in overall emissions. For example, a lane-widening project may reduce congestion and improve traffic flow by reducing speed-change cycles (subsequently, reducing pollution) in the short term but may attract induced demand in the long run thus increasing pollution. Also, transportation interventions such as ramp metering and HOV lanes may have adverse air quality effects in the short term (due to queuing and congestion in certain areas) but beneficial air quality impacts in the long term due to overall decreased travel delay. Figure 10.4 illustrates the sequence of impacts of transportation intervention on air quality. The stages discussed in step 1 are for the intervention scenario, while the stages in step 2 are for the no-intervention scenario (base case), which is the do-nothing situation at the current time or at a future time.

Step 1: Determine the Transportation Intervention This may be a policy change or physical enhancement, such as improvements in alignment design, traffic management, or transit operations.

Step 1.1: Identify the Short-Term Effect Most transportation interventions typically lead to changes in operational characteristics, often in the form of increased vehicle operating speeds and fewer speed-change (acceleration and deceleration) events. These operational changes that happen in the short term, also termed *first-order effects* (Dowling et al., 2005), have two impacts: (a) changes in the emission rates of vehicles using the facility, and (b) changes in travel demand patterns.

Step 1.2: Identify the Operational Changes The operational changes that affect travel demand patterns in the medium term (8 to 14 months of the intervention) are typically referred to as *second-order effects* (Dowling et al., 2005). The higher speeds (and hence lower travel times) due to the intervention may induce travelers to undertake more frequent trips, change their current mode to one that benefits most from the intervention, or change their trip schedules. Second-order effects may result in new travel amounts and frequencies (and ultimately, increased total emissions even if emission rates decrease or remain the same).

Step 1.3: Identify the Locational Shifts of Residences and Businesses Operational improvements and changes in demand patterns may lead in the long term to changes in home and business location patterns. Improved traffic flow and reduced congestion tend to attract new businesses and residences or retain existing ones. These can be considered as *third-order effects* (Dowling et al., 2005).

Step 1.4: Establish the New Travel Amounts and Frequencies In investigating the air quality impacts of

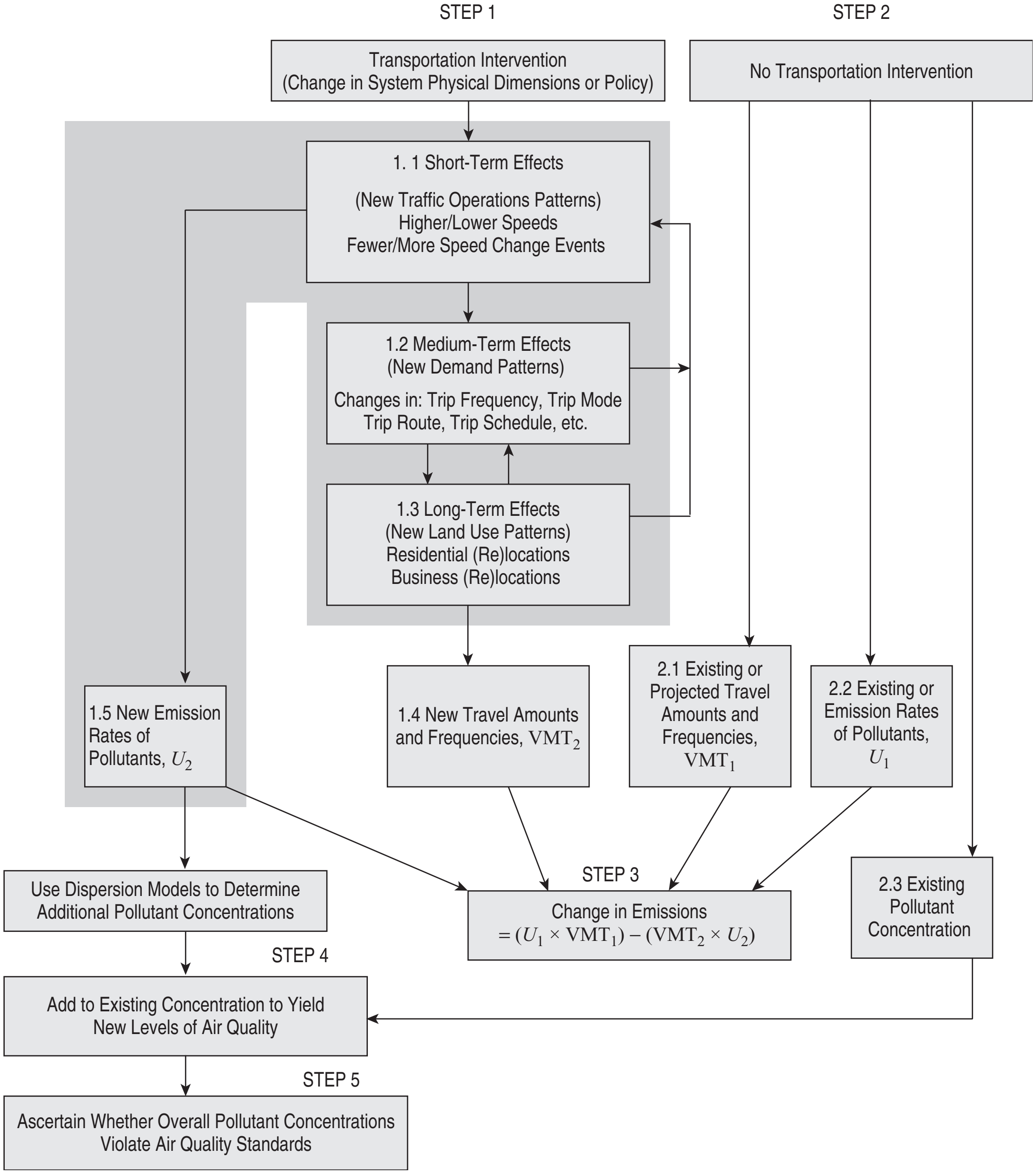


Figure 10.4 Procedure for assessing air quality impacts of transportation interventions.

transportation interventions, most analytical procedures implicitly exclude this step by stopping at the short-term effects (see the shaded area in Figure 10.4.). As such, these procedures assume implicitly that the second- and third-order effects are negligible.

Step 1.5: Establish the New Emission Rates of Pollutants Changes in the emission rates of pollutants may be due to (a) transportation intervention policies that directly affect the rates of pollutant emissions, such as new emission standards, restriction of vehicles with excessive pollutants, and enforcement of vehicle exhaust inspections and laws, and (b) changes in speed and acceleration–deceleration events arising from physical improvements such as channelization and lane addition. MOBILE6 can be used to estimate the new emission rates due to both types of interventions. The MOBILE6 model and software are described in Sections 10.2.3(a) and 10.2.5, respectively.

Steps 1.6 and 1.7: Estimate the New Total Pollutant Emissions and Concentrations

(a) *Change in Emissions* Knowing the emission rate per travel activity (from step 1.5) and the amount of travel activity (step 1.4), estimating the total emissions (also referred to as *emissions inventory*) is a straightforward task. The differences in various approaches for estimating total emissions stem largely from their respective definitions of the term *travel activity*. In approaches where MOBILE6 is used to establish emission rates (step 1.5), travel activity is defined in terms of vehicle-miles of travel. Total emissions are estimated as follows:

$$\begin{aligned}\text{total emissions} &= \text{emission per vehicle-mile of travel}\\ &\quad \times \text{total vehicle-miles of travel for the project} \qquad (10.3)\end{aligned}$$

In other approaches, such as the comprehensive modal emission model (Dowling, 2005), which define travel activity in terms of vehicle-hours of travel, total emissions are estimated as follows:

$$\begin{aligned}\text{total emissions} &= \text{emission per vehicle-hour of travel}\\ &\quad \times \text{total vehicle-hours of travel for the project} \qquad (10.4)\end{aligned}$$

(b) *Change in Ambient Concentrations* Given the new level of emissions due to the transportation intervention, the associated concentration can be estimated if the levels of dispersion factors (wind speed and direction, mixing height, etc.) are known (see Section 10.3).

Steps 2.1 and 2.2: Analyze the Existing Situation (at the Current or Some Future Year) This step analyzes a base-case scenario against which the air pollution impacts of intervention can be assessed. If the base case is taken as the current year, the base-case air quality impacts (pollutant concentrations) are established by one of the following methods: (a) measuring the pollutant concentrations directly using air quality monitoring equipment, or (b) carrying out steps similar to steps 1.1 to 1.6 using current-year data on emission rates, traffic operations, and so on. If the base case is for some future year projected from a current do-nothing situation, then estimates of the base case air quality can be predicted by carrying out steps similar to steps 1.1 to 1.6 using data projected for emission rates, traffic operations, and so on, at the future year of interest.

Step 3: Determine the Difference in Total Pollutant Emissions If the intent of the analysis is to ascertain whether the transportation intervention had (or will have) an impact on the existing air quality of the area, step 3 should be included. Step 3 simply expresses the new emission relative to the base-case emission and quantifies the extent to which the intervention contributes to the improvement or degradation of air quality.

Steps 4 and 5: Estimate the Overall Pollutant Concentrations If the intent is to determine whether the transportation intervention would lead to a violation of air quality standards or ameliorate existing levels to acceptable levels, it is necessary to carry out step 4. In this step, pollutant concentrations due to mobile sources are added to those from stationary sources. In step 5, the overall concentration for each pollutant is compared with established air quality thresholds to ascertain whether any standards have been violated.

10.2.5 Software for Estimating Pollutant Emissions

The most common software used for estimating pollutant emissions is MOBILE6, whose theoretical procedure is discussed in Section 10.2.3(a). This package utilizes inputs, such as the frequency of starts per day and their distribution by hour and the enforcement of inspection maintenance programs, and incorporates external conditions such as temperature and humidity. MOBILE6 also requires a temporal distribution of traffic during the day for major traffic indicators. Hourly distributions can be input instead of 24-hour averages. Also, the fleet characterization projections of future vehicle fleet size and the fraction of travel are based on considerations that include vehicle age, mileage accumulation rate, and vehicle class. (Vehicles classes are shown in Table 10.4.) Data on the key traffic-related variables (vehicle registration distribution, annual mileage accumulation rate, and the distribution of vehicle miles of travel) are input by vehicle class and roadway type. Local data on mileage accumulation are typically more difficult to obtain because odometer readings are typically not recorded on an annual basis unless an inspection and maintenance program is operational in the region under study. MOBILE6 outputs the emission rates (g/vehicle-mile) for three pollutants: HC, NO_x, and CO. Description of the general MOBILE6 input file and a sample output file are provided in Appendix A-10.

Example 10.1 A portfolio of transportation projects, including traffic signal optimization, lane widening, and channelization, has been undertaken in the city of Townsville. These projects have helped to reduce the traffic congestion in the city and have increased the average speeds of vehicles. However, these improvements have been accompanied by an increase in the amount of travel, due partly to city residents taking advantage of lower congestion and induced demand from nearby towns. It is sought to evaluate the impact of the transportation projects on vehicle emissions in the city. Amounts of travel (by vehicle class) and the speeds corresponding to the without- and with-improvement scenarios are presented in Table E10.1.1. Use MOBILE6 to evaluate the impact of the portfolio of transportation improvements on air quality in terms of emission rate changes of the three key pollutants (HC, CO, and NO_x). Assume a 10-mile road length; consider 2004 and 2006 as the without and with-improvement years, respectively; for other air quality parameters, use the default values, provided in MOBILE6.

SOLUTION

1. Input data: VMT fractions (for the vehicle classes listed in the first column of Table E10.1.1) are entered in the input file. Other input data including speeds and analysis years are entered into the input file as described in Appendix A10.

(1) *Calculation of VMT fractions* (see Table E10.1.1):

$$\text{VMT fraction} = \frac{\text{VMT}}{\text{total VMT}}$$

For example, VMT Fraction for LDV in the without-improvement scenario = 9,975/25,000 = 0.399

(2) *Estimation of emissions*

The vehicle classes (and combinations thereof) that appear in the default descriptive outputs are listed as follows:

Table 10.4 Vehicle Classes in MOBILE6

Number	Abbreviation	Description
1	LDGV	Light-Duty Gasoline Vehicle (Passenger Cars)
2	LDDV	Light-Duty Diesel Vehicles (Passenger Cars)
3	LDGT1	Light-Duty Gasoline Trucks 1 (0-6,000 lbs. GVWR: 0-3,750 lbs. LVW)
4	LDGT2	Light-Duty Gasoline Trucks 2 (0-6,000 lbs. GVWR: 3,751-5,750 lbs. LVW)
5	LDDT12	Light-Duty Diesel Trucks 1 and 2 (0–6,000 lbs. GVWR)
6	LDGT3	Light-Duty Gasoline Trucks 3 (6,001–8,500 lbs. GVWR: 0–5,750 lbs. ALVW[a])
7	LDGT4	Light-Duty Gasoline Trucks 4 (6,001–8,500 lbs. GVWR: 5,751 lbs. and greater ALVW)
8	LDDT34	Light-Duty Diesel Trucks 3 and 4 (6,001–8,500 lbs. GVWR)
9	HDGV2B	Class 2b Heavy-Duty Gasoline Vehicles (8,501–10,000 lbs. GVWR)
10	HDDV2B	Class 2b Heavy-Duty Diesel Vehicles (8,501–10,000 lbs. GVWR)
11	HDGV3	Class 3 Heavy-Duty Gasoline Vehicles (10,001–14,000 lbs. GVWR)
12	HDDV3	Class 3 Heavy-Duty Diesel Vehicles (10,001–14,000 lbs. GVWR)
13	HDGV4	Class 4 Heavy-Duty Gasoline Vehicles (14,001–16,000 lbs. GVWR)
14	HDDV4	Class 4 Heavy-Duty Diesel Vehicles (14,001–16,000 lbs. GVWR)
15	HDGV5	Class 5 Heavy-Duty Gasoline Vehicles (16,001–19,500 lbs. GVWR)
16	HDDV5	Class 5 Heavy-Duty Diesel Vehicles (16,001–19,500 lbs. GVWR)
17	HDGV6	Class 6 Heavy-Duty Gasoline Vehicles (19,501–26,000 lbs. GVWR)
18	HDDV6	Class 6 Heavy-Duty Diesel Vehicles (19,501–26,000 lbs. GVWR)
19	HDGV7	Class 7 Heavy-Duty Gasoline Vehicles (26,001–33,000 lbs. GVWR)
20	HDDV7	Class 7 Heavy-Duty Diesel Vehicles (26,001–33,000 lbs. GVWR)
21	HDGV8A	Class 8a Heavy-Duty Gasoline Vehicles (33,001–60,000 lbs. GVWR)
22	HDDV8A	Class 8a Heavy-Duty Diesel Vehicles (33,001–60,000 lbs. GVWR)
23	HDDV8B	Class 8b Heavy-Duty Gasoline Vehicles (>60,000 lbs. GVWR)
24	HDGV8B	Class 8b Heavy-Duty Diesel Vehicles (>60,000 lbs. GVWR)
25	HDGB	Gasoline Buses (School, Transit and Urban)
26	HDDBT	Diesel Transit and Urban Buses
27	HDDBS	Diesel School Buses
28	MC	Motorcycles (Gasoline)

[a] ALVW = Alternative Vehicle Weight: The adjusted loaded vehicle weight is the numerical average of the vehicle curb weight and the gross vehicle weight rating (GVWR).

Table E10.1.1 VMT Fractions by Vehicle Class for Each Scenario[a]

			AADT		VMT Fraction	
Vehicle Class		Percentage %	Without Improvement	With Improvement	Without Improvement	With Improvement
LDV	LDGV	80	9975	13120	0.399	0.403
	LDDV	20				
LDT1	LDGT1	80	1425	1856	0.057	0.057
	LDDT1	20				
LDT2	LDGT2	80	4750	6112	0.19	0.188
	LDDT2	20				
LDT3	LDGT3	80	450	608	0.018	0.019
	LDDT3	20				
LDT4	LDGT4	80	225	288	0.009	0.009
	LDDT4	20				
HDV2B	HDGV2B	50	1900	2464	0.076	0.076
	HDDV2B	50				
HDV3	HDGV3	50	450	576	0.018	0.018
	HDDV3	50				
HDV4	HDGV4	50	400	480	0.016	0.015
	HDDV4	50				
HDV	HDGV5	50	200	256	0.008	0.008
	HDDV5	50				
HDV6	HDGV6	50	850	1120	0.034	0.034
	HDDV6	50				
HDV7	HDGV7	25	1200	1536	0.048	0.047
	HDDV7	75				
HDV8A	HDGV8A	25	700	928	0.028	0.028
	HDDV8A	75				
HDV8B	HDGV8A	10	1625	2080	0.065	0.064
	HDDV8A	90				
HDBS	HDGB	5	75	128	0.003	0.004
	HDDBS	95				
HDBT	HDDBT	100	475	640	0.019	0.020
MC			300	384	0.012	0.012

[a] Average speed without improvement = 28 mph. Predicted average speed with improvement = 35 mph.

For LDGV: LDGT 1 and 2 combined—LDGT 12
LDGT 3 and 4 combined—LDGT 34
LDGT 1, 2, 3, and 4 combined—LDGT

For LDDV: LDDT 1, 2, 3 and 4 combined—LDDT
For all HDGV and HDGB combined—HDG
For all HDDV and HDDB combined—HDD

For all 28 sub-classes combined—All Vehicles

In the descriptive output file of MOBILE6, emissions for all 28 vehicle sub-classes can be reported by using the following commands: EXPAND LDT EFS, EXPAND HDGV EFS, EXPAND HDDV EFS, and EXPAND BUS EFS.

Emission estimates with and without the improvement are given in Table E10.1.2.

The VMT distributions and emission values for the "with improvement" scenario are shown in parentheses. Emission rates are shown for each vehicle type and pollutant type. The exhaust HC, CO, and NO_x emissions of heavy-duty vehicles are reported only as "composite" exhausts, not as either start or running. Figure E10.1 shows the levels of major pollutants for the "with improvement" and "without improvement" scenarios.

Table E10.1.2 Emission Values for Without- and With-Improvement Scenarios

Vehicle Type		LDGV	LDGT12	LDG34	LDGT	HDGV	LDDV	LDDT	HDDV	MC	All Veh
GVWR			< 6000	> 6000	(All)						
VMT Distribution		0.3968	0.2459	0.0267		0.0922	0.0022	0.0014	0.2228	0.012	1
		(0.4005)	(0.2435)	(0.0272)		(0.0918)	(0.0023)	(0.0014)	(0.2216)	(0.0118)	(1)
Composite emission factors (g/mi)	Composite VOC	1.141	1.373	2.221	1.456	4.198	0.989	2.287	1.083	3.01	1.519
		(0.763)	(0.932)	(1.684)	(1.007)	(3.207)	(0.929)	(1.724)	(0.882)	(3)	(1.108)
	Composite CO	6.4	10.08	14.35	10.5	45.36	2.306	3.786	6.297	25.02	11.299
		(4.3)	(6.87)	(10.45)	(7.23)	(32.19)	(2.302)	(2.931)	(5.438)	(25.06)	(8.144)
	Composite NO_x	0.651	0.823	1.111	0.852	4.405	1.591	2.511	12.847	0.77	3.775
		(0.444)	(0.611)	(0.923)	(0.643)	(3.697)	(1.534)	(1.973)	(10.452)	(0.77)	(3.022)
Exhaust emissions (g/mi)	VOC start	0.145	0.208	0.354	0.222		0.179	0.685		0.389	
		(0.086)	(0.129)	(0.244)	(0.141)		(0.169)	(0.473)		(0.389)	
	VOC running	0.276	0.487	0.854	0.523		0.81	1.602		2.083	
		(0.135)	(0.254)	(0.524)	(0.281)		(0.76)	(1.251)		(2.087)	
	VOC total exhaust	0.421	0.695	1.208	0.745	2.52	0.989	2.287	1.083	2.47	0.879
		(0.221)	(0.384)	(0.768)	(0.422)	(1.715)	(0.929)	(1.724)	(0.882)	(2.48)	(0.59)
	CO start	1.83	3.19	4.51	3.32		0.499	1.286		2.898	
		(1.44)	(2.46)	(3.72)	(2.59)		(0.501)	(0.924)		(2.9)	
	CO running	4.58	6.89	9.84	7.18		1.807	2.5		22.12	
		(2.86)	(4.41)	(6.73)	(4.64)		(1.802)	(2.006)		(22.161)	
	CO total exhaust	6.4	10.08	14.35	10.5	45.36	2.306	3.786	6.297	25.02	11.299
		(4.3)	(6.87)	(10.45)	(7.23)	(32.19)	(2.302)	(2.931)	(5.438)	(25.06)	(8.144)
	NO_x start	0.11	0.136	0.179	0.14		0.046	0.128		0.318	
		(0.065)	(0.089)	(0.128)	(0.093)		(0.045)	(0.097)		(0.318)	
	NO_x running	0.541	0.688	0.932	0.712		1.546	2.383		0.453	
		(0.379)	(0.523)	(0.795)	(0.55)		(1.49)	(1.876)		(0.454)	
	NO_x total exhaust	0.651	0.823	1.111	0.852	4.405	1.591	2.511	12.847	0.77	3.775
		(0.444)	(0.611)	(0.923)	(0.643)	(3.697)	(1.534)	(1.973)	(10.452)	(0.77)	(3.022)
Non-exhaust emissions (g/mi)	Hot soak loss	0.108	0.085	0.124	0.089	0.32	0	0	0	0.131	0.098
		(0.096)	(0.082)	(0.135)	(0.088)	(0.278)	(0)	(0)	(0)	(0.132)	(0.089)
	Diurnal loss	0.031	0.032	0.056	0.034	0.103	0	0	0	0.027	0.031
		(0.024)	(0.027)	(0.05)	(0.029)	(0.092)	(0)	(0)	(0)	(0.025)	(0.026)
	Resting loss	0.111	0.109	0.195	0.118	0.345	0	0	0	0.376	0.112
		(0.087)	(0.092)	(0.177)	(0.101)	(0.306)	(0)	(0)	(0)	(0.368)	(0.095)
	Running loss	0.446	0.405	0.564	0.42	0.729	0	0	0	0	0.359
		(0.318)	(0.31)	(0.49)	(0.328)	(0.645)	(0)	(0)	(0)	(0)	(0.275)
	Crankcase loss	0.006	0.009	0.011	0.009	0.012	0	0	0	0	0.006
		(0.005)	(0.009)	(0.01)	(0.009)	(0.011)	(0)	(0)	(0)	(0)	(0.005)
	Refueling loss	0.018	0.038	0.064	0.041	0.17	0	0	0	0	0.034
		(0.012)	(0.028)	(0.055)	(0.03)	(0.16)	(0)	(0)	(0)	(0)	(0.028)
	Total non-exhaust	0.719	0.678	1.013	0.766	1.679	0	0	0	0.534	0.64
		(0.542)	(0.548)	(0.916)	(0.645)	(1.492)	(0)	(0)	(0)	(0.525)	(0.518)

The default HC specification is VOC. However, the analyst can select the HC pollutant(s) for which emissions should be reported by including one of the five optional run-level commands in the "command" input file. The HC pollutants are total hydrocarbons (THC), nonmethane hydrocarbons (NMHC), volatile organic compounds (VOC), total organic gases (TOG), and nonmethane organic gases (NMOG).

(3) *Estimation of air quality impacts*

Table E10.1.3 presents the results of the analysis. Air quality impacts are experienced not only by users, but the society as a whole. Their impacts can be estimated as the difference between emissions with and without the improvement. The impact values in Figure E10.1 and Table E10.1.3 are for all vehicles, and computations are:

$$\text{Emission impact} = U_1(\text{VMT}_1) - U_2(\text{VMT}_2)$$

where U_1, U_2 are emission rates, and VMT_1, VMT_2 are vehicle-miles of travel without and with the improvement, respectively. For example,

$$\begin{aligned}\text{VOC impact} &= (1.519 \times 250{,}000 - 1.108 \times 325{,}760)\\ &= 18{,}800 \text{ g/day}\end{aligned}$$

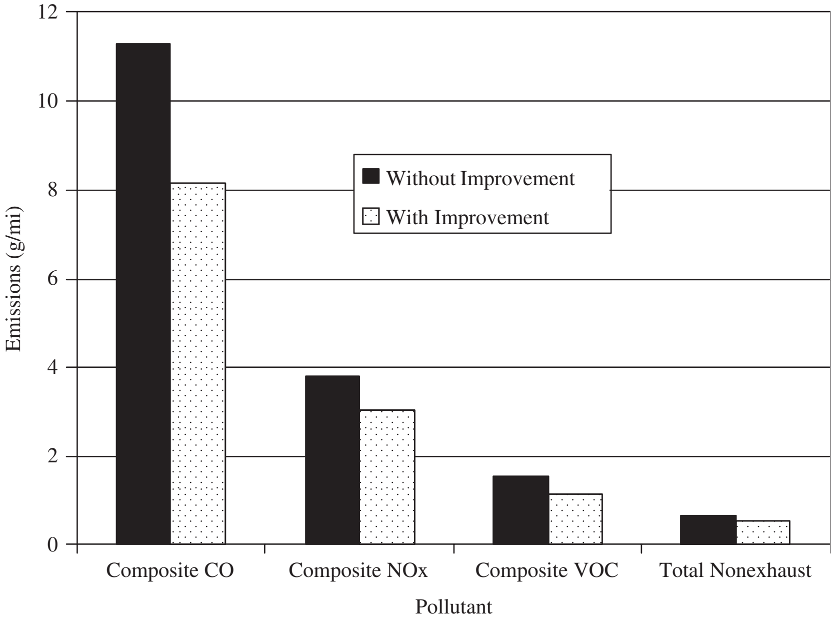


Figure E10.1 Estimates of Emissions from MOBILE6.

Table E10.1.3 Air Quality Impacts of the Improvement

Pollutants	Without Improvement (g/mile)	With Improvement (g/mile)	Impacts (g/day)
Composite VOC	1.519	1.108	18,800
Composite CO	11.299	8.144	171,760
Composite NO_x	3.775	3.022	40,700

10.3 ESTIMATING POLLUTANT CONCENTRATION

Steps 1.6(b) and 1.7(b) of the procedure for air quality impact assessment (see Section 10.2) involve an estimation of pollutant concentrations. Details of this task are presented in the present section.

Pollutants emitted from their sources disperse into the atmosphere, where they are transformed or diluted. The resulting amount (mass or volume) of a pollutant per unit volume of air is described as the *concentration* of the pollutant in the air. The atmospheric concentration of a pollutant is affected by the level of emissions, topographical features, altitude, meteorological conditions, and physical mixing and chemical reactions in the atmosphere. The harmful effects of air pollutants are typically measured in terms of their concentrations.

The dispersion of transportation pollutant emissions in an area or space can be likened to a small hypothetical box into which a specific amount of gas is instantaneously emitted. In the real world, however, the situation is made more complex by the fact that (1) the emission occurs continuously; (2) dispersion of the pollutant occurs not only by diffusion but is aided (and thus rendered more complex from the analytical standpoint) by laminar or turbulent advection (movement) of wind, deposition, chemical reactions, confinement of air masses through the effects of topography, and/or the *inversion* phenomenon (trapping of polluted air due to differences in temperature of air masses); and (3) the pollutant emitted is really not confined to the box but is released from that enclosed space at a certain varying rate that depends on dynamic factors such as ambient temperature and wind speed.

10.3.1 Factors Affecting Pollutant Dispersion

(*a*) *Meteorological Factors* The atmosphere is the typical medium for pollutant transfer from emission sources to receptors (humans, vegetation, etc.). Atmospheric conditions, which can be expressed in terms of temperature, atmospheric stability, precipitation, wind speed and direction, humidity, and intensity of solar radiation, govern the temporal (hourly, daily, and seasonal) and spatial variation of the transmission and therefore the concentration of air pollutants. Atmospheric stability is related to the change in temperature or wind speed or direction with height (also referred to as *temperature gradient* and *wind shear*, respectively). A stable atmosphere suppresses vertical motion within its domain and therefore generally leads to higher pollutant concentrations, while an unstable atmosphere enhances motion and ultimately lowers pollutant concentration. *Thermal inversion* is a phenomenon characterized by an increase in temperature with height (a reversal of the normal condition) leading to the entrapment of cold air layers by a higher layer of warm air. Such conditions lead to the accumulation of pollutants in the underlying layer of cold air. Wind speed is also a significant factor; the greater the wind speed, the higher the dispersion of air pollutants. Another meteorological factor is surface roughness; the movement of air near Earth's surface is resisted by frictional effects proportional to the surface roughness. *Ceiling height*, which is defined as the height above which relatively rigorous vertical mixing occurs, varies by day and by season. Ceiling heights may reach several thousand feet during summer daylight hours but only a few hundred feet on winter nights. As such, nighttime and winter conditions are associated with a relatively small volume of air available for dispersion and are therefore generally characterized by higher pollutant concentrations.

(*b*) *Topography and Urban Spatial Form* Through the phenomena of air drainage and radiation, the topography of a region affects the wind speed and direction and the atmospheric temperature and subsequently affects the dispersion (and concentration) of pollutants. Air pollution problems are aggravated in metropolitan areas that experience the street "canyon" effect created by tall buildings. Assessing the causes and magnitude of air pollution in metropolitan areas can be a complex undertaking, due to the range and diversity of polluting sources, meteorological conditions, topographic features, and urban spatial forms.

10.3.2 Pollutant Dispersion Models

Pollutants emitted into the atmosphere are dispersed by molecular diffusion, eddy diffusion, and random shifts (Wayson, 2002). Dispersion factors include meteorological conditions such as the wind speed and temperature gradient, the number of emission sources, and the emission rates of these sources. Atmospheric stability is the resistance to vertical motion of wind. High atmospheric stability as in flat terrain, retards dispersion, whereas low stability (high turbulence) facilitates dispersion. The three most common methods for assessing the impact of emissions on pollutant concentration are the box model, the Gaussian plume model, and the numerical model.

(*a*) *Box Model* This model assumes uniform dispersion of pollutants to fill a single large boxlike space. Two key factors that control pollutant dispersion (and thus concentration) in the local environment are wind speed and mixing height, and the *ventilation factor* is the product of these two factors. Increasing either the mixing height or the wind speed increases the effective volume in which pollutants are allowed to mix. Consider a city with an area A ($a \times b$) square miles, mixing height H miles, and an average wind speed of v mph (Figure 10.5).

For a pollutant particle emitted at one corner of the city:

1. The maximum distance for transport across the city (i.e., the distance necessary to reach the upwind edge of the box) is $\sqrt{a^2 + b^2 + H^2}$ miles.
2. The maximum time taken to be transported across the city to the upwind edge,

$$t_{\max} = \frac{\text{distance}}{\text{speed}} = \frac{\sqrt{(a^2 + b^2 + H^2)}}{v} \text{ hours}$$

3. For all particles emitted throughout the city, average time taken to be transported across the city to the

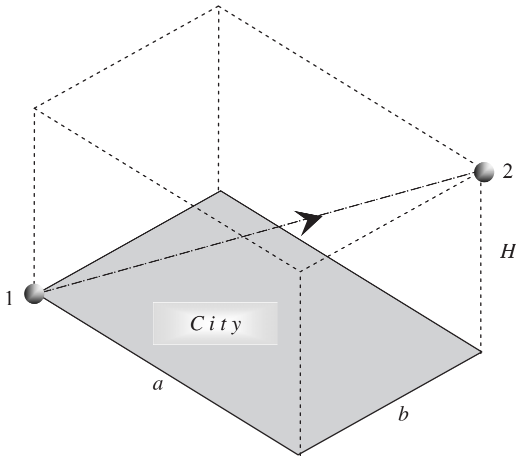


Figure 10.5 Box model for pollutant dispersion.

upwind edge,

$$t_{\text{avg}} = \frac{\sqrt{(a^2 + b^2 + H^2)}}{2v} \text{ hours}$$

Assuming that M grams of pollutant are released every $t_{\max}$ hour, the concentration of pollutant every $t_{\max}$ hours is given by

$$\frac{M}{abH} \text{ g/mi}^3 \qquad (10.5)$$

Example 10.2 The city of Santa Mateo is approximately rectangular in shape with dimensions of 3.5 miles by 2.1 miles. The topographical nature of the area is such that the effective mixing height is 1.2 miles. A particle of a certain pollutant is emitted at the southeastern corner of the city.

(a) Find the maximum distance taken by the particle to travel out of the box.
(b) If the wind speed is 3.5 mph in a SE–NW direction, find the (1) maximum time and (2) the average time taken by a particle of the pollutant emitted from any section of the city to clear the mixing box.
(c) If 1000 g of the pollutant is released in bursts every 2 hours, find the maximum concentration of the pollutant at any given time.

SOLUTION A mixing box is defined with the following dimensions (in miles): 3.5 × 2.1 × 1.2

(a) The maximum distance for transport across the city is

$$\sqrt{a^2 + b^2 + H^2} = (3.5^2 + 2.1^2 + 1.2^2)^{0.5}$$
$$= 4.25 \text{ mi}$$

(b) For all particles emitted throughout the city:

(1) Maximum time taken to be transported across the city and out of the box,

$$t_{\max} = \frac{\text{distance}}{\text{speed}} = \frac{4.25}{\text{wind speed}}$$
$$= \frac{4.25}{3.5} = 1.21 \text{ h}$$

(2) Average time taken to be transported across the city and out of the box,

$$t_{\text{avg}} = \frac{1.21}{2} = 0.61 \text{ h}$$

(c) From (b) (1), all pollutant emissions would disperse out of the mixing box completely in 1.21 hours (the residual concentration after 1.21 hours is zero). Two hours after release, therefore, the residual concentration of the pollutant is zero. Therefore, if 1000 g of the pollutant are released in bursts every 2 hours, the maximum concentration will be

$$\frac{1000}{(3.5)(2.1)(1.2)} = 113.38 \text{ g/mi}^3$$

Clearly, the reliability of the results from the box model approach depends on a number of assumptions such as uniformity of dispersion. At any specific receptor site within the box, this assumption is typically violated, particularly when the averaging time is very small. The box model has also been applied to nonhighway modes. Cohn and McVoy (1982) cited an example of the FAA box model that can be used to assess CO emissions at airports. In the case of airports, the receptors are passenger loading areas (where emissions are from ground aircraft and service vehicles) and passenger pickup and drop-off areas (where emissions are from highway vehicles dropping or picking up passengers). Whereas the short-term maximum concentrations in such areas may be unbearable to persons (receptors) at such points, the overall average concentration throughout the entire airport box space may be too little to be of concern. The box model therefore may underestimate air pollution severity, particularly at localized but sensitive receptors.

(*b*) *Gaussian Plume Model* This model is based on the random wafting of plumes side to side and up and down, resulting in the increased plume size with time. At any point in the plume, pollutant concentration can be described using a normal distribution, with the plume center having the highest concentration. As one moves away from the source, the maximum concentration level decreases while the concentration standard deviation increases (Figure 10.6).

The Gaussian plume model assumes that (1) there is continuous emission from the source and that diffusion in the direction of travel is negligible, (2) diffused material is a stable gas that remains suspended in the air for long periods and therefore no material is deposited from the plume as it moves downwind, (3) at any point in the plume (cross- sectional plane perpendicular to the direction of dispersion), the distribution of pollutant concentration (from the crosswind and vertical directions) is normal, and (4) the spread of the plume can be represented by the standard deviation of the pollutant concentration, which is consistent with the averaging time of the concentration estimate.

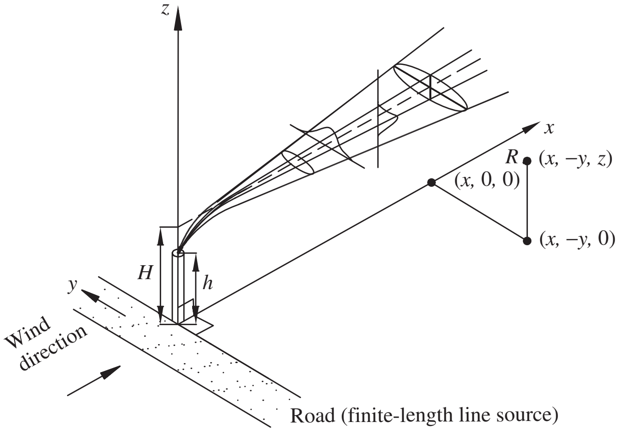


Figure 10.6 Gaussian model for plume formation.

The Gaussian equation is used by most dispersion models to estimate the dispersion of nonreactive pollutants released from an emitting source at a steady rate. The steady-state pollutant concentration, C (μg/ft^3), at a point specified by the x, y, and z coordinates in the vicinity of the transportation facility is given by

$$C = \frac{Q}{2\pi U \sigma_y \sigma_z} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \exp\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right] \times \exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right] \tag{10.6}$$

where Q is the emission rate of the pollutant (μg/s), U the average wind speed at stack height (ft/s), σ_y, and σ_z the standard deviation of dispersion in the y and z directions, respectively; y the horizontal distance from the plume centerline, z the vertical distance from ground level, and H the effective stack height in ft (= physical stack height + vertical rise of plume).

A uniform average emission rate, Q, is defined for the finite-length line source (FLLS) in weight units of pollutant emissions per unit distance per unit time (e.g., μg/ft-s). The x-axis is parallel to the wind direction and the y-axis is parallel to the FLLS. In Figure 10.6, the road (FLLS) is perpendicular to the wind, but this is not always true. In configurations where the road is not perpendicular to the wind, an equivalent FLLS that is perpendicular to the wind can be established. Equation (10.6) is for a single point source. Where there are multiple sources, the concentration at a receptor due to emissions from each source can be calculated separately, and the total concentration is the sum of such concentrations from pollutants moving along the line, in the direction of the y-axis. Cooper and Alley (2002) showed that the sum of concentrations experienced at the receptor due to an emission source moving between limits y_1 and y_2 along the finite-length line source is given by

$$C = \frac{K}{\sqrt{2\pi}}(G_U - G_L) \tag{10.7}$$

where

$$K = \frac{Q}{U\sigma_z}\left[\exp\left(\frac{-(z-H)^2}{2\sigma_z^2}\right) + \exp\left(\frac{-(z+H)^2}{2\sigma_z^2}\right)\right]$$

and G_U and G_L are Gaussian distribution functions (see Appendix A10.2) corresponding to the upper and lower values of y_1/σ_{y1} and y_2/σ_{y2}, respectively, where σ_{y1} and σ_{y2} are the variances of pollutant concentration at endpoints 1 and 2 of each FLLS.

The Gaussian plume model is widely used to assess pollutant dispersion and concentration, but its assumptions may not always hold, particularly in cases of fluctuating wind directions. Also, the assumption of stable gases may not always be appropriate where the pollutants themselves undergo chemical reactions as they are being dispersed. Furthermore, deposition can and does occur in the case of certain pollutants, such as lead particles and hydrocarbon droplets. Also, the model can lead to misleading results in nonhomogeneous terrain. There are other point-specific models that can overcome some of these limitations (Kretzschmar et al., 1994).

Example 10.3 A busy highway passes near a nursing home for elderly persons. A plan view of the road at that location is shown in Figure E10.3.1. Determine the expected CO concentration at ground level at the nursing home. The CO emission factor is 20 g/mi per vehicle. Wind speed is 2 ft/s, $H = 0$ ft, and traffic volume is 15,000 veh/h. Assume that when $x = 50$ ft, σ_y and σ_z are 20 and 12 ft, respectively; and when $x = 67.5$ ft, σ_y and σ_z are 22 and 14 ft, respectively. Assuming that the road is the sole CO source, determine whether the concentration at the nursing home violates the standard of 35 ppm.

SOLUTION The emission rate of 20 g/mile per vehicle is expressed in temporal terms as follows:

$$Q = \left(\frac{20\text{ g}}{\text{mile-veh}}\right)\left(\frac{15{,}000\text{ veh}}{1\text{ h}}\right)\left(\frac{1\text{ h}}{3600\text{ s}}\right) = 83\text{ g/mile-s}$$

This means that for each mile of the study segment, 83 g of CO is emitted every second. For consistency with the

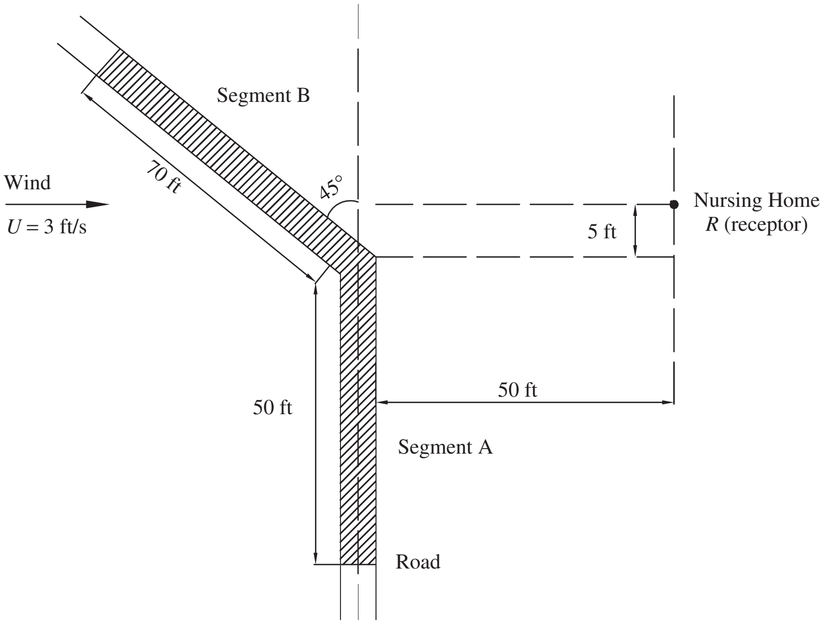


Figure E10.3.1 Road layout near nursing home.

dispersion equation, this can be expressed in micrograms and feet:

$$Q = (83)\left(\frac{1\text{ mile}}{5280\text{ ft}}\right)\left(\frac{10^6\ \mu\text{g}}{1\text{ g}}\right) = 15{,}720\ \mu\text{g/ft-s}$$

Then, the emission rates are adjusted to account for the relative direction between the wind and road traffic. To do this, finite-length line source lines are established perpendicular to the wind direction and passing through the midpoints of the two segments (Figure E10.3.2).

For road segment A: The centerline is perpendicular to the wind source, so there is no need for any adjustment. The emission rate on FLLS A (the finite-length line source) due to traffic on segment A is simply equal to 15,720 μg/ft-s. The length of FLLS-A is 50 ft.

For road segment B: The distance P shown in Figure E10.3.2 is (70 sin 45°)/2 = 24.75 ft.

$$\text{Length of FLLS-B} = (70\text{ ft})(\cos 45^\circ) = 49.45\text{ ft}$$

$$\text{Equivalent emission rate at FLLS-B}$$
$$= (15{,}720)(70/49.5) = 22{,}230\ \mu\text{g/ft-s}$$

The x, y, and z coordinates of each endpoint of the FLLS lines are determined as follows:

FLLS-A: start point $x = 50$ ft; $y = -55.0$ ft, $z = 0$ ft; endpoint $x = 50$ ft, $y = -5.0$ ft, $z = 0$

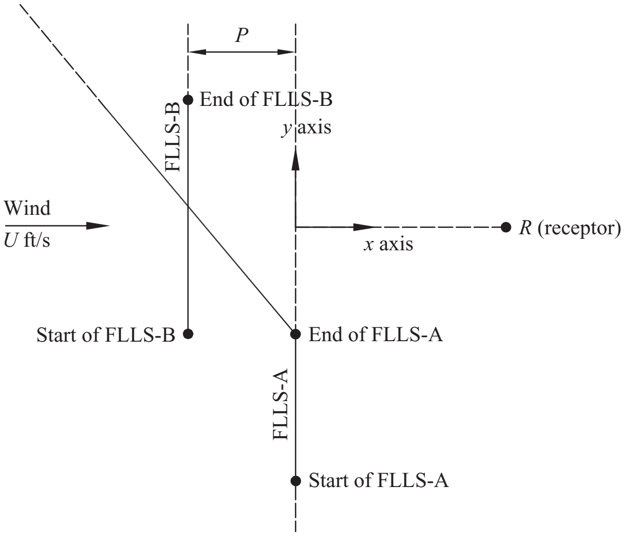


Figure E10.3.2 Finite length line source line.

FLLS-B: start point $x = 74.7$ ft; $y = -5$ ft, $z = 0$ ft; endpoint $x = 74.7$ ft; $y = 44.5$ ft; $z = 0$

Consider FLLS-A: $y_1/\sigma_{y1} = -55/20 = -2.75$ and $y_2/\sigma_{y2} = -5.0/20 = -0.25$. From Appendix A10.2, $G_1 = G(-0.25) = 0.4013$ and $G_2 = G(-2.75) = 0.0030$. Thus, $G_1 - G_2 = 0.3983$.

$$K = \frac{15{,}720}{(2)(12)}\left[\exp\left(\frac{-(0-0)^2}{(2)(12^2)}\right) + \exp\left(\frac{-(0+0)^2}{(2)(12^2)}\right)\right] = 1310.00$$

$$C_{\text{FLLS-A}} = \left(\frac{1310}{\sqrt{2\pi}}\right)(0.3983) = 208.16\ \mu\text{g/ft}^3$$

Consider FLLS-B: $y_1/\sigma_{y1} = -5/22 = -0.227$, and $y_2/\sigma_{y2} = +44.5/22 = 2.023$. From Appendix A10.4, $G_1 = G(2.023) = 0.9785$ and $G_2 = G(-0.227) = 0.4102$. Thus, $G_1 - G_2 = 0.5683$.

$$K = \frac{22{,}230}{(2)(14)}\left[\exp\left(\frac{-(0-0)^2}{(2)(12^2)}\right) + \exp\left(\frac{-(0+0)^2}{(2)(12^2)}\right)\right] = 1587.86$$

$$C_{\text{FLLS-B}} = \left(\frac{1587.86}{\sqrt{2\pi}}\right)(0.5683) = 359.98\ \mu\text{g/ft}^3$$

Therefore, the total concentration at the receptor is $208.16 + 359.98 = 568.14\mu\text{g/ft}^3$ or 17.54 ppm. This does not exceed the threshold concentration of 35 ppm, so the estimated air quality level at the nursing home does not violate established standards.

(*c*) *Numerical Models* A numerical air quality model involves a three-dimensional grid of conceptual boxes that occupy the space above a transportation corridor. Emissions from the highway vehicles are considered as a pollutant source “feeding” the series of boxes immediately overlying the highway. Within each box, the pollutant particles diffuse to fill the box at some given rate. Then the pollutant diffuses into the immediately outlying boxes at some given rate. The movement of pollutant from box to box is aided further by local wind effects. Assuming that the local wind effects, diffusion, and emissions are reasonably represented with well-behaved functions of time, the movement of pollutant particles across the boxes can be predicted with successive time increments. The smaller the boxes, the more valid is the assumption that there is uniform concentration within each box. As such, estimates of pollutant concentration can be made at any spatial point within the region, represented by the three-dimensional box grid. When the numerical model is used, restrictive assumptions in the case of the Gaussian plume or box models regarding nondeposition, nonreactions, and so on, are overcome: It is possible to simulate the deposition of pollutants or chemical reactions involving pollutants in each box, as had been done successfully for photochemical oxidant models for the city of Los Angeles (Cohn and McVoy, 1982). The computational effort and data collection associated with the numerical approach can be very challenging, but the advent of faster computers has helped make this approach very attractive for use.

10.3.3 Software for Estimating Pollutant Dispersion and Concentrations

A number of air dispersion models have been developed for highway and transportation projects. These include the HYROAD, ADMS, California Line Source (CALINE 4), HIWAY, PAL, TEXIN 2, and CAL3QHC models. The HIWAY and PAL models can only be used for free-flow conditions (Wayson, 2002). Models recommended by the EPA, such as TEXIN 2, CALINE 4, and CAL3QHC, account for queueing delays and excess emissions due to variations in engine modes and cruise.

(*a*) *HYROAD (HYbrid ROADway Model)* HYROAD analyzes intersections and predicts their ambient carbon monoxide concentrations. The model, which is equipped with a graphical user interface, comprises three modules: traffic, emissions, and dispersion. First, the traffic module microscopically simulates the traffic flow by modeling the movement of each vehicle at the intersection. This module yields speed distribution information that is used in the emission module to establish composite emission factors and spatial and temporal distribution of emissions. For each 10-m roadway segment and for each signal phase, vehicle speed and acceleration distributions are observed, and flow and turbulence are analyzed. The last module establishes pollutant dispersion characteristics near the intersection. The model gives hourly concentration of pollutants, including carbon monoxide and other gas-phase pollutants, particulate matter, and air toxins, at specific distances from the intersection (System Application International, 2002).

(*b*) *ADMS-3 (Atmospheric Dispersion Modeling System)* Developed by Cambridge Environmental Research Consultants of UK, ADMS-3 is an advanced model for calculating the concentrations of pollutants that are emitted continuously from point, line, volume, and area sources, or discretely from point sources. The model includes algorithms which take into account the terrain, wet deposition, gravitational settling, dry deposition, chemical reactions, plume rise as a function of distance, and meteorological conditions, among others (Carruthers et al., 1994).

(*c*) *CALINE Version 4* The California Line Source Dispersion Model version 4 (CALINE4), predicts air pollution concentrations near lineal transportation facilities.

Developed by the California Department of Transportation, this model is based on the Gaussian diffusion equation and employs a mixing zone concept to characterize pollutant dispersion from the roadway. Given the source strength (emissions), meteorology, and site geometry, CALINE4 can predict pollutant concentrations at receptors located within 500 m of the facility. It also has special options for modeling air quality near highway intersections, street canyons, and parking facilities.

Example 10.4 A certain interstate highway section in the U.S. Midwest consists of three links; A, B, and C (Figure E10.4.1). The highway section passes through a suburban area, and the mean elevation is sea level. The coordinates of each link are as follows: A start (4000, 4000); A end (4200, 4000); B start (4200, 4000); B end (4500, 3500); C start (4500, 3500), C end (5000, 3500). Assume a background CO concentration of 0 ppm, a wind direction standard deviation of 5, and a width of the pollutant mixing zone of 20 m. The link activity and running conditions are provided in Table E10.4.1. Determine the mean concentration of CO at the following receptor sites: site 1 (4100, 3950, 1.8); site 2 (4300, 3700, 1.8), and site 3 (4750, 3550, 1.8).

SOLUTION A sample of the CALINE4 output is provided in Figure E10.4.2. Multiple runs of the model for the various time periods yield the results shown in Table E10.4.2. CO concentrations are in ppm.

10.4 AIR POLLUTION FROM OTHER MODES

Figure 10.7 shows comparative pollutant emission rates from various transportation modes (Holmen and Niemeier, 2003). Compared to other modes, diesel trains and trucks emit relatively low pollutants per passenger-mile or per ton-mile. Electric trains do not cause local pollution except when their power sources are fossil-burning electricity plants that lack pollution controls. With regard to NO_x, the greatest polluters are automobiles and trucks. Diesel trains and buses also emit some NO_x, and the least-emitting sources are electric trains (at the points of power generation). For SO_x, the most significant source is electric trains (at the points of power generation). CO_2 emission is largely due to the use of fossil fuels. Automobiles and trucks are the most significant sources of CO_2; electric trains are the least.

10.4.1 Air Transportation

Air transportation pollution comes from two sources: airport activities and aircraft emissions. With regard to air pollutant emissions due to airport activities it is estimated that aircraft engines contribute approximately 45%; ground access vehicle operations, including passenger drop-offs and pickups, contribute 45%; and ground support equipment contributes 10% (Holmen and Niemeier, 2003). Future aviation trends seem to involve high-flying subsonic and supersonic aircraft, and such travel is expected to cause further depletion of ozone in the stratosphere.

Air Quality Impact Analysis for Air Transportation: The Emissions and Dispersion Modeling System (EDMS) is an FAA-approved model specifically developed for the aviation community to assess the air quality impacts of proposed airport development projects. EDMS is designed to assess the air quality impacts of airport emission

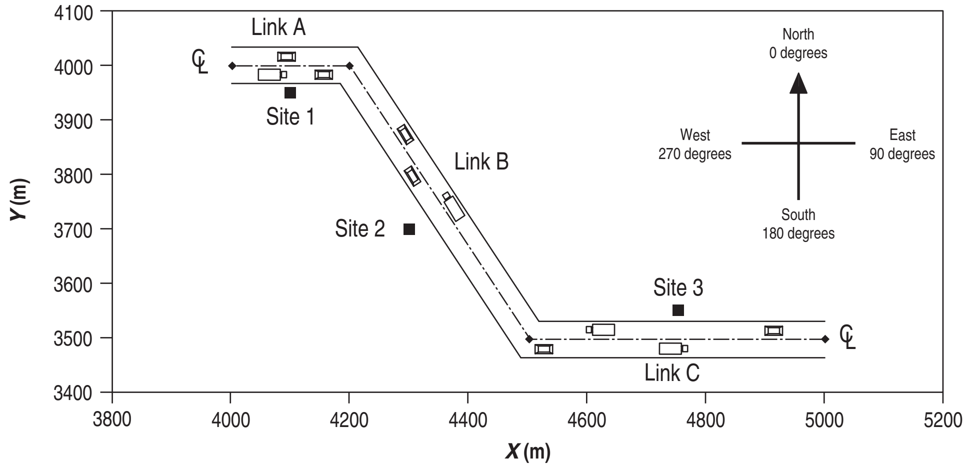
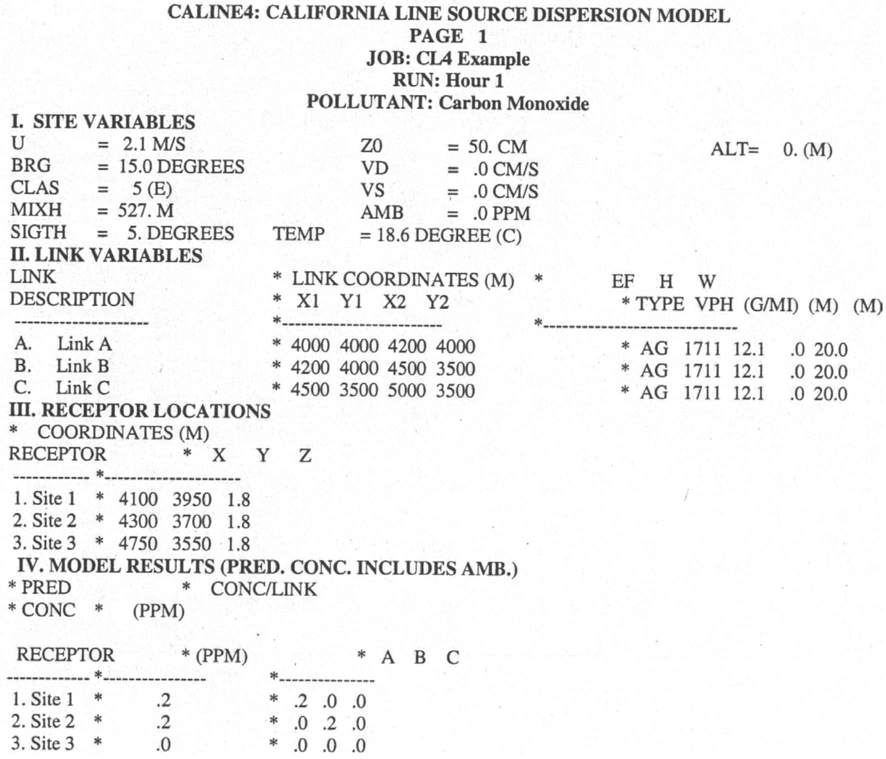


Figure E10.4.1 Site layout for CALINE4 run.

Table E10.4.1 Link Activity and Running Conditions for CALINE4 Run

Time (h)	No. of Cars/Hour, Four Lanes	CO Emission Factor (g/mi)	Wind Speed (m/s)	Stability	Mixing Height (m)	WDIR (deg)	Temperature (°C)
1	2263	12.06	1.94	5	520	10	19.4
2	1670	12.06	1.87	5	526	12	18.9
3	1711	12.06	2.05	5	527	15	18.6
4	1962	12.06	1.44	5	527	10	18.3
5	3173	9.06	2.04	5	561	15	18.0
6	4816	9.06	2.66	4	642	40	17.8
7	5579	9.06	1.41	4	738	70	19.0
8	5938	6.19	1.71	3	834	50	21.0
9	6160	6.19	2.56	3	930	50	22.9
10	6305	6.19	2.96	3	1026	20	24.3
11	6400	9.57	2.29	3	1122	0	25.3
12	6550	14.66	2.78	3	1218	355	26.1
13	6700	18.03	3.01	3	1314	350	26.3
14	6550	14.66	3.02	3	1410	0	26.5
15	6400	9.57	2.30	3	1410	20	26.9
16	6350	7.14	2.90	4	1410	10	26.8
17	6320	7.14	1.96	4	1410	25	26.5
18	5774	6.19	2.06	4	1407	40	26.0
19	5399	6.19	1.73	4	1375	60	25.1
20	5325	6.19	1.60	5	1243	110	23.7
21	4838	6.19	1.65	5	1059	150	22.0
22	4253	6.19	1.72	5	882	70	21.0
23	3785	6.19	1.25	5	689	55	20.3
24	3160	9.06	1.95	5	527	40	19.9



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                CALINE4: CALIFORNIA LINE SOURCE DISPERSION MODEL
                                   PAGE  1
                               JOB: CL4 Example
                                 RUN: Hour 1
                        POLLUTANT: Carbon Monoxide
I. SITE VARIABLES
U        =  2.1 M/S                   Z0      =  50. CM            ALT=   0. (M)
BRG      =  15.0 DEGREES              VD      =  .0 CM/S
CLAS     =    5 (E)                   VS      =  .0 CM/S
MIXH     =  527. M                    AMB     =  .0 PPM
SIGTH    =    5. DEGREES    TEMP      = 18.6 DEGREE (C)
II. LINK VARIABLES
LINK                        * LINK COORDINATES (M)  *        EF   H   W
DESCRIPTION                 *  X1   Y1   X2   Y2          * TYPE VPH (G/MI) (M) (M)
-------------------         *---------------------  *----------------------------
 A.   Link A                * 4000 4000 4200 4000         * AG  1711  12.1   .0 20.0
 B.   Link B                * 4200 4000 4500 3500         * AG  1711  12.1   .0 20.0
 C.   Link C                * 4500 3500 5000 3500         * AG  1711  12.1   .0 20.0
III. RECEPTOR LOCATIONS
*   COORDINATES (M)
RECEPTOR         *   X    Y    Z
----------- *-------------------
 1. Site 1  *  4100  3950  1.8
 2. Site 2  *  4300  3700  1.8
 3. Site 3  *  4750  3550  1.8
 IV. MODEL RESULTS (PRED. CONC. INCLUDES AMB.)
* PRED           *   CONC/LINK
* CONC   *     (PPM)

 RECEPTOR        * (PPM)              *  A   B   C
------------ *--------------    *-------------
 1. Site 1   *       .2         *  .2  .0  .0
 2. Site 2   *       .2         *  .0  .2  .0
 3. Site 3   *       .0         *  .0  .0  .0
```

Figure E10.4.2 Sample output of a standard CALINE4 run.

Table E10.4.2 Estimated CO Concentrations (ppm)

Time (h)	Receptor Site 1	Receptor Site 2	Receptor Site 3
1	0.20	0.20	0.00
2	0.20	0.20	0.00
3	0.20	0.20	0.00
4	0.30	0.30	0.00
5	0.20	0.20	0.00
6	0.30	0.20	0.00
7	0.30	0.40	0.00
8	0.40	0.20	0.00
9	0.30	0.20	0.00
10	0.20	0.20	0.00
11	0.40	0.40	0.00
12	0.50	0.50	0.00
13	0.60	0.60	0.00
14	0.50	0.50	0.00
15	0.40	0.30	0.00
16	0.20	0.20	0.00
17	0.30	0.30	0.00
18	0.30	0.20	0.00
19	0.30	0.20	0.00
20	0.20	0.40	0.40
21	0.00	0.00	0.30
22	0.20	0.20	0.00
23	0.30	0.20	0.00
24	0.30	0.20	0.00

sources, particularly aviation sources, which consist of aircraft, auxiliary power units, and ground support equipment. EDMS offers a limited capability to model other airport emission sources that are not aviation-specific, such as ground access vehicles and stationary sources. EDMS performs emission and dispersion calculations and uses updated aircraft engine emission factors from the International Civil Aviation Organization's engine exhaust emissions data bank and vehicle emission factors from the EPA's MOBILE6 model.

10.4.2 Rail Transportation

Rail pollution depends on the power source, which includes coal and steam, diesel, and electricity. In the United States and Western Europe, steam traction has been phased out almost entirely. In other parts of the world, steam is still one source of rail power. Coal-powered steam locomotives consume coal to build up steam that is used to power the vehicles. In doing so, they emit heavy spurts of smoke containing CO_2, SO_x, and NO_x into the atmosphere and pollute the areas near rail lines with smoke particulates. Because steam engines are far less thermally efficient than gasoline, diesel, or electric vehicles, they emit higher amounts of pollutants per energy produced than the other power types. Diesel-powered locomotives and highway trucks produce similar pollutants: CO, NO_x, HC, and carbon-based particulates. In terms of emission per ton-mile, however, diesel rail locomotives are approximately three times cleaner than trucks (Holmen and Niemeier, 2003). For electric-powered rail, the only contribution to air pollution may come from the power sources that generate the electricity used to power such vehicles, particularly where the fuel used is coal or other fossil fuels. Other atmospheric effects of electric railways are emissions resulting from high-speed contact of pantographs on wires, but these are considered negligible (Carpenter, 1994).

10.4.3 Marine Transportation

Commercial marine vessels are responsible for only 2% of the global fossil fuel consumption, but constitute a significant source of ocean air pollution. In terms of emissions per ton of fuel consumed, vessel engines are the least clean combustion sources. These engines produce 14% of the global nitrogen emissions from fossil fuels and 16% of all sulfur emissions from petroleum (Talley, 2003). Marine transportation causes emission of reactive organic gases (ROGs), CO, and NO_x but there have been relatively few studies to quantify the levels of such emissions. Compared to highway sources, waterborne vessels emit relatively small amounts of HC and CO, but their relative contribution to overall pollution is expected to increase with increasing enforcement of pollution standards of other modes (Holmen and Niemeier, 2003).

10.4.4 Transit (Various Modes)

Potter (2003) presented information regarding typical emissions from various transit types in Germany and the United Kingdom (Table 10.3) and established that urban public transit is significantly cleaner than automobiles in terms of NO_x and CO emissions per passenger-distance. For electric rail, indirect SO_2 emissions (i.e., from power-generating plants that produce such electricity) are high but emissions of other pollutants are low, relative to other transit types.

Table 10.5 provides emission rates for both newly manufactured and remanufactured locomotives built originally after 1972. These values are expressed in grams per brake horsepower-hour (g/bhp-hr) and grams of pollutant emitted per gallon of fuel consumed (g/gal). The latter emission rates are obtained by multiplying the emission rates

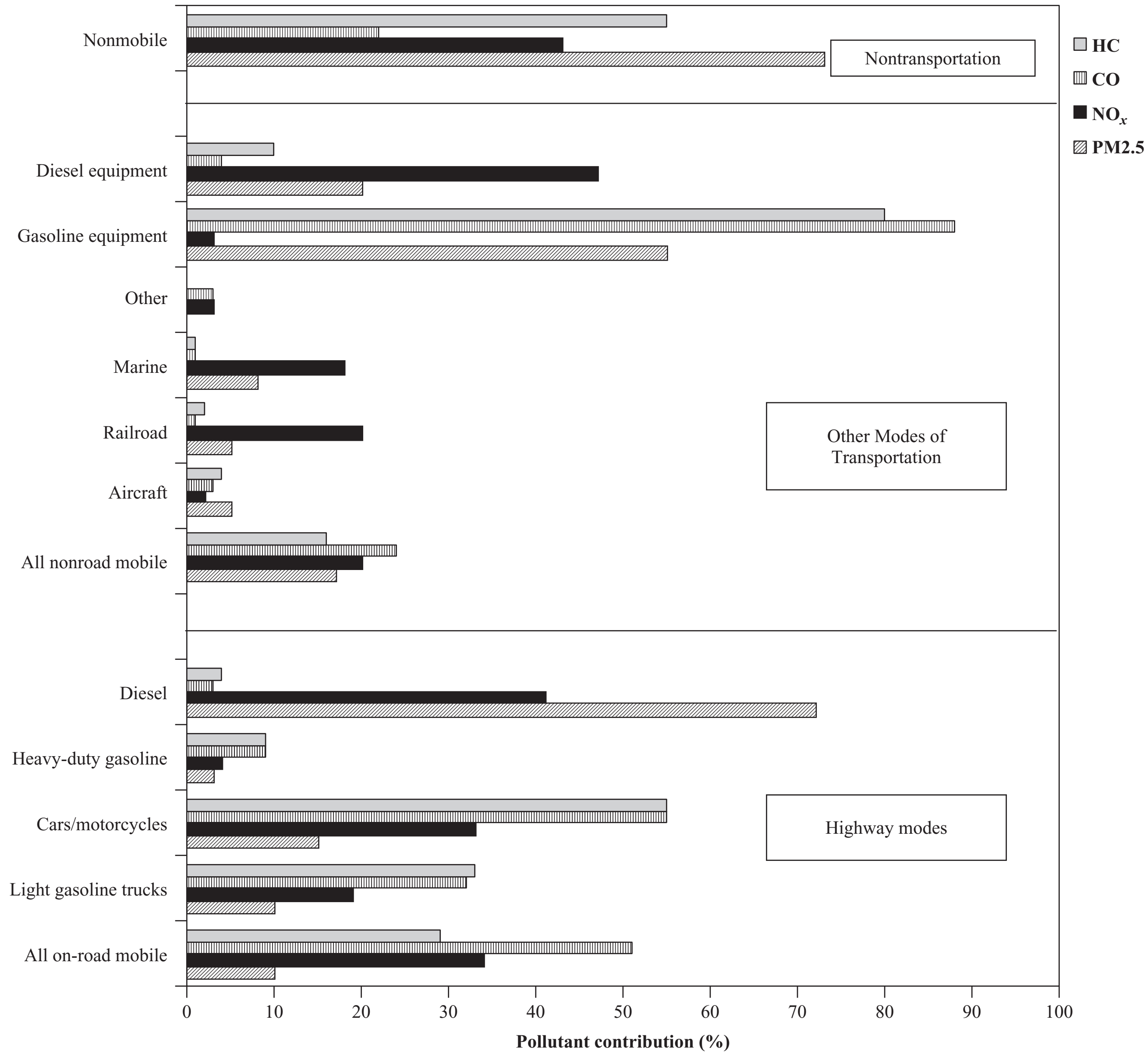

Figure 10.7 Pollutant contributions by mode. (From Holmen and Niemeier, 2003.).

in g/bhp-h with an appropriate conversion factor of 20.8 bhp-h/gal set by the EPA.

10.5 MONETARY COSTS OF AIR POLLUTION

The cost of environmental or resource degradation can be measured in one of three ways: (1) as the cost of cleaning up the air near the source of degradation, (2) as the cost associated with addressing the effects of degradation, and (3) as the willingness of persons to pay to avoid the degradation of their residences or businesses.

10.5.1 Methods of Air Pollution Cost Estimation

(*a*) *Cost Based on Cleaning up the Air at or near the Polluting Source* The costs of cleaning up the air before or after its dispersion involves the installation of air scrubbers at intervals along the polluting line source to clean the air before or as it disperses to adjoining populated areas, a measure which may be less feasible in rural areas than in urban areas. The installation intervals would depend on the characteristics of the traffic (volume, % trucks, speed, etc.), the environment (temperature,

Table 10.5 Emission Rates for Tier 0, Tier 1, and Tier 2 Locomotives[a]

		HC		CO		NO_x		PM	
Tier	Type of Haul	g/bhp-h	g/gal	g/bhp-h	g/gal	g/bhp-h	g/gal	g/bhp-h	g/gal
Tier 0 (locomotives manufactured 1973–2001)	Line-haul	0.48	10	1.28	26.6	8.6	178	0.32	6.7
	Switch	1.01	21	1.83	38.1	12.6	262	0.44	9.2
Tier 1 (locomotives manufactured 2002–2004)	Line-haul	0.47	9.8	1.28	26.6	6.7	139	0.32	6.7
	Switch	1.01	21	1.83	38.1	9.9	202	0.44	9.2
Tier 2 (locomotives manufactured after 2004)	Line-haul	0.26	5.4	1.28	26.6	5.0	103	0.17	3.6
	Switch	0.52	11	1.83	38.1	7.3	152	0.21	4.3

Source: USEPA (1997).

[a] Estimated controlled values.

wind speed, direction, etc.), and the scrubber capacities. Air pollution costs, if quantified in this manner, can be rather excessive, as the costs of purchasing, operating, and maintaining scrubbers are very high.

(*b*) *Cost Based on Addressing the Effects of Pollution* This cost could be described as the *social damage* effect of air pollution. It includes the health care expenses involved with treating respiratory illnesses engendered or exacerbated by an air pollution problem and the cost to repair physical infrastructure and compensation for or remediation of destroyed or degraded crops, forests, and groundwater by acidic depositions formed by chemical reactions between pollutants and atmospheric gases.

(*c*) *Costs Based on the Willingness-to-Pay Approach* The costs of air pollution can be estimated by assessing the extent to which affected persons and businesses are willing to pay to avoid an air pollution problem. The assumption is that people are perfectly aware of the adverse impacts of air pollution on their health and property, and that their stated preferences closely reflect their actual or revealed preference.

10.5.2 Air Pollution Cost Values

The European Economic Commission has supported a great amount of research aimed at valuing the pollution costs of transportation; and air pollution cost estimates have been developed for various pollutant types, transportation modes, and operating speeds. For example, it is estimated that at 1999 conditions, the cost of CO_2 emissions was $26/ton, a value considered consistent with other estimates of global abatement costs for meeting the Kyoto Protocol (Friedrich and Bickel, 2001).

Delucchi (2003) provided external cost estimates of direct motor vehicle use in urban areas of the United States in 1990 (Table 10.6). The marginal costs for health, visibility, and crops were estimated for each kilogram of pollutants, emitted as shown in the table, and are for each 10% change in motor vehicle use.

Table 10.6 Incremental External Costs of Direct Auto Use in Urban Areas[a]

	PM_{10}	NO_x	SO_x	CO	VOCs
Health	13.7–187	1.6–23.3	9.6–90.9	0.0–0.1	0.1–1.5
Visibility	0.4–3.9	0.2–1.1	0.9–4.0	0.0	0.0
Crops	NE[b]	NE	NE	0.0	0.0
Total	14.1–191	1.8–24.5	10.5–94.9	0.0–0.1	0.1–1.5

Source: Delucchi (2003).

[a] Dollars/kilogram for a 10% change in auto use.

[b] NE means not established.

Table 10.7 U.S. National Ambient Air Quality Standards

Pollutant	Measure	Standard Value	Standard Type
Carbon monoxide (CO)	8-h average	9 ppm (10 mg/m^3)	Primary
	1-h average	35 ppm (40 mg/m^3)	Primary
Nitrogen dioxide (NO_2)	Annual arithmetic mean	0.053 ppm (100 μg/m^3)	Primary and secondary
Ozone (O_3)	1-h average	0.12 ppm (235 μg/m^3)	Primary and secondary
	8-h average	0.08 ppm (157 μg/m^3)	Primary and secondary
Lead (Pb)	Quarterly average	1.5 μg/m^3	Primary and secondary
Particulate PM 10 (particles with diameters of 10 μm or less)	Annual arithmetic mean	50 μg/m^3	Primary and secondary
	24-h average	150 μg/m^3	Primary and secondary
PM 2.5 (particles with diameters of 2.5 μm or less)	Annual arithmetic mean	15 μg/m^3	Primary and secondary
	24-h average	65 μg/m^3	Primary and secondary
Sulfur dioxide (SO_2)	Annual arithmetic mean	0.03 ppm (80 μg/m^3)	Primary
	24-h average	0.14 ppm (365 μg/m^3)	Primary
	3-h average	0.50 ppm (1300 μg/m^3)	Secondary

Source: USEPA (2002).

10.6 AIR QUALITY STANDARDS

Environmental agencies in most countries have established air quality standards. The U.S. ambient air quality standards are shown in Table 10.7. *Primary standards* represent the minimum requirements to maintain public health. *Secondary standards* are set to protect public welfare, which includes the prevention of soiling of buildings and other public infrastructure, restriction of visibility, and degradation of materials. Other definitions are as follows:

- *Specified concentration level:* the maximum concentration of air pollutant specified.
- *Averaging time:* the time duration that an area is subjected to an air pollutant.
- *Return period:* the maximum frequency or minimum interval with which the maximum concentration specified can be exceeded.

An example of an air quality standard is as follows: *The eight-hour average ambient CO standard is nine ppm (ten mg/m*^{3}*) not to be exceeded more than once in a year.* Many urban areas experience occasional violations of the 8-hour standard. On the other hand, violations of the 1-hour standard are rare and occur when there is unusually heavy traffic lasting for only a few hours of the day due to, for example, peak-hour travel or freeway incidents.

Emission standards can also be expressed as the weight of pollutants emitted per unit of power generated. Table 10.8, for example, shows the emission standards in g/kWh for heavy-duty diesel vehicles in Europe, Japan, and the United States.

Table 10.8 Emission Standards for Heavy-Duty Diesel Vehicles (g/kWh)

	Europe (2005)	Japan (2004)	United States (1998)
CO	1.5	2.22	15.5
HC	0.46	0.87	1.3
NO_x	3.5	3.38	4.0
PM_{10}	0.02	0.18	0.1

Source: Stanley and Watkiss (2003).

Under international agreements, aircraft emission standards are set through the United Nations' International Civil Aviation Organization (ICAO). In the United States, the EPA establishes emission standards for aircraft engines and the FAA enforces these standards. The EPA regulates NO_x, hydrocarbon (HC), carbon monoxide (CO), and smoke emissions from aircraft.

10.7 MITIGATING AIR POLLUTION FROM TRANSPORTATION SOURCES

The reduction of automotive air pollution can be achieved through a variety of measures, including legislation and enforcement, vehicle engine standards, promotion of less polluting modes of transportation, improved fuel quality, alternative fuels, transportation planning and traffic management, and economic instruments (Faiz et al. 1996). In the United States the Congestion Mitigation and Air Quality (CMAQ) program funds projects designed to help metropolitan areas with poor air quality to reach the national air quality standards. Eligible projects are listed below:

- *Traffic flow improvements:* signal modernization and traffic management/control such as incident management and ramp metering and intersection improvements.
- *Transit improvements:* system or service expansion, replacement of buses with cleaner vehicles, and marketing strategies such as shared ride services: park-and-ride facilities, establishment of vanpool or carpool programs, and programs to match drivers and riders.
- *Demand management strategies:* promotion of employee trip reduction programs and development of transport management plans, including improved commercial vehicle operations in urban areas.
- *Nonmotorized transportation:* development of bicycle trails, storage facilities, and pedestrian walkways, as well as promotional activities.
- *Inspection and maintenance:* updating vehicle inspection and maintenance quality assurance programs, construction of advanced diagnostic facilities or equipment purchases, conversion of a public fleet to alternative fuel vehicles, and other projects.
- *Other activities:* outreach activities, experimental pilot projects and innovative financing and fare and fee subsidy programs.

Other Modes: Airlines are investing significant amounts of resources and taking steps aimed at ensuring improved levels of environmental performance (Somerville, 2003). These include development of performance indicators, open reporting of environmental performance, participation in ICAO initiatives, and sponsoring research projects. With regard to marine air pollution, it has been proposed that to reduce the polluting effects at ports, transiting vessels should be required to stop their engines and receive power from shore-side sources of electricity (Talley, 2003).

10.8 AIR QUALITY LEGISLATION AND REGULATIONS

10.8.1 National Legislation

The Air Pollution Control Act of 1955 was the first in a long chain of federal legislation related to the air quality impacts of transportation. In 1963, the Clean Air Act (CAA) was passed (subsequently amended in 1965 and several times later) to enforce emission standards for new vehicles. The Air Quality Control Act of 1967 led to the establishment of air quality criteria. The CAA amendments of 1970 provided federal controls in individual states for regulating and reducing motor vehicle and aircraft emissions. To achieve this goal, the CAA established the National Ambient Air Quality Standards (NAAQS) for pollutants considered harmful to public health and the environment, whereby states were required to prepare state implementation plans (SIPs), a document that outlines how a state intends to deal with air pollution problems. Also, the NAAQS were established for six principal pollutants, called *criteria pollutants* (Section 10.1.2). Regions that do not meet these standards are classified as *nonattainment areas*. Depending on the severity of the air quality problem, nonattainment areas are classified as marginal, moderate, serious, and severe and/or extreme. Also, passed in 1970, the Federal Aid Highway Act required the U.S. Department of Transportation and the EPA to develop and issue guidelines governing the air quality impacts of highways and required the development of transportation control plans and measures for air quality improvement. In a 1977 amendment to the CAA, penalties were established for areas that failed to carry out good faith efforts to meet air quality standards. The 1990 CAA strengthened conformity requirements that require metropolitan planning organizations in nonattainment and maintenance areas to use the most recent mobile source emission estimate models to show that (a) all federally funded and "regionally significant projects," including nonfederal projects in regional transportation improvement programs (TIPs) and plans will not lead to emissions higher than those in the 1990 baseline year, and (2) by embarking on these projects, emissions will be lower than in the no-build scenario. If a transportation plan, program, or project does not meet conformity requirements, it must be modified to offset the negative emission impacts or the EPA will need to work with the appropriate state agency to modify the SIP. If any of the foregoing actions is not accomplished, the transportation plan, program, or project cannot be implemented. The Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) reinforced the CAA90 requirement that transportation plans conform to air quality enhancement initiatives and provided state and local governments with the funding and flexibility to improve air quality through development of a balanced, environmentally sound intermodal transportation program. In the SAFETEA-LU act of 2005, the air quality conformity process was improved with changes in the frequency of conformity determinations and conformity horizons.

10.8.2 Global Agreements

On the global level, there have been efforts to regulate the extent of the global warming phenomenon (of which transportation sources are a major contributor). The Kyoto Protocol is an agreement negotiated in 1997 in Kyoto, Japan as an amendment to the United Nations Framework Convention on Climate Change (an international treaty on global warming that was adopted at the Earth Summit in Rio de Janeiro in 1992). By ratifying this protocol, countries committed to a reduction in their emissions of carbon dioxide, methane, nitrous oxide, sulfur hexafluoride, HFCs, and PFCs, or to engage in emissions trading if they maintain or increase emissions of these pollutants. In the agreement, industrialized countries are expected to reduce their collective emissions of greenhouse gases by approximately 5% (over 1990 levels). At the treaty's implementation in February 2005, the agreement was ratified by 141 countries whose collective emissions represent over 60% of the total global levels. Several countries including the U.S. have not ratified the Kyoto Protocol, citing economic reasons. However, the evidence on the possible cataclysmic effect of global warming is mounting (Gore, 2006). A recent study commissioned by the British government indicated that the costs related to climate change due to carbon emissions could seriously affect the world's economy, reducing as much as 20% of the total gross domestic product (Timmons, 2006).

SUMMARY

Transportation, particularly the highway mode, continues to be a major contributor to air pollution. It has adverse effects not only on a local and regional scale but also on a global scale by contributing to global warming. The major factors affecting pollutant emissions are travel related, and the EPA-sponsored software MOBILE6 is the common emission estimation tool. Factors that affect dispersion of air pollutants include meteorological conditions, topographical features, and the number and rate of emission sources. Methods for pollutant concentration estimation include the Gaussian plume, numerical, and box models. CALINE 4 is the most commonly used software package for estimating the concentration of pollutants.

The cost of air pollution can be measured by assessing the cost of cleaning the air near the pollution source, the cost of restoring the health and condition of affected persons and property, and the willingness of persons to pay to avoid degradation of air quality at their residences or businesses. Air quality standards, established to preserve public health and welfare from air pollution damage, involve specified concentration levels, averaging times, and return periods.

Efforts to reduce automotive air pollution has been spearheaded by industrialized countries through a variety of measures, including legislation and enforcement, vehicle engine standards, promotion of less polluting modes of transportation, improved fuel quality, use of alternative fuels, and transportation planning and traffic management. The Congestion Mitigation and Air Quality Improvement program provides funds to states for projects designed to help metropolitan areas to attain and maintain the national ambient air quality standards. The Clean Air Act provided strong governmental control in regulating and reducing motor vehicle and aircraft emissions. At the global level, the Kyoto Protocol ratified in 2005 signifies a genuine effort to regulate the anthropogenic causes of the global warming phenomenon.

EXERCISES

10.1. An increase in gasoline prices led to the following changes in VMT on the local street network of Cityville: light-duty vehicles, 5% reduction; motorcycles, 10% increase; heavy-duty vehicles, 8% reduction. If the average speed is expected to increase from 20 mph to 22 mph and all other default data in MOBILE6 remain the same, estimate the impact of the change in gas price on the emissions of CO, HC, and NO_x.

10.2. A series of CMAQ programs in a certain metropolitan area led to a 7% reduction in VMT for all vehicle classes and an increase in average speed from 16 mph to 25 mph. Using MOBILE6, assess the impact of the CMAQ programs on emissions of key air pollutants. Assume that all other data are the same as the data used in Example 10.1.

10.3. A state increased its rural interstate speed limit from 65 mph to 70 mph. Assuming that all other factors are the same, what will be the impact on air pollution emissions? Use MOBILE6. Assume that all other data are the same as the data used in Example 10.1.

10.4. A number of road-widening, intersection improvement, and curve-straightening projects on Interstate 778 led to an increased average speed from 45 mph to 60 mph. What was the net impact of the improvements on emissions? Assume that all other data are the same as the data used in Example 10.1. Use MOBILE6.

10.5. A freeway passes near a school. Determine the expected CO concentration at a height of 2 ft at the school. The CO emission factor is 25 g/mi. Wind speed is 3.5 ft/s, $H = 1$ ft, and traffic volume is 9000 veh/h. Assume that when $x = 50$ ft, σ_y and σ_z are 30 and 15 ft., respectively; and when $x = 67.5$ ft., σ_y and σ_z are 25 and 16 ft, respectively. Assume the same configuration as shown for Example 10.2.

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APPENDIX A10.1: USING MOBILE6 TO ESTIMATE EMISSIONS

A10.1.1 Details of the MOBILE6 Input File

The input file used by MOBILE6 comprises the control file, which manages the input data, program execution, and output; the basic files, which contain input data, are common to all scenarios at each program run; and the scenario files, which provide information on individual scenarios under investigation. The basic files enable the input of any emission-related parameters that differ from the default values available in MOBILE6. For several emission parameters, MOBILE6 utilizes default values that are representative of national averages but can be substituted by local data to yield more reliable emission estimates. A typical MOBILE6 *output file* consists of total exhaust and nonexhaust emissions by vehicle type and composite emission factors.

(*a*) *Basic Data File* This basic date file contains information (Figure A10.1) that is input only once (at the first use) of the MOBILE6 for a particular program run. Inputs in this file, which are specific to the location, are substitutes for the default national average values in MOBILE6.

Engine Starts per Day and Distribution by Hour: The frequency of starts per day influences engine exhaust start emission estimates for light-duty gasoline cars, diesel passenger cars, trucks, and motorcycles but does not affect the emission estimates for heavy-duty diesel-fueled vehicles and buses. For gasoline-fueled vehicles, including heavy-duty vehicles and buses, this parameter also affects the extent of evaporative hot-soak losses that occur at trip ends. MOBILE6 assigns a separate default value for the number of engine starts per day to each of 25 vehicle classes and for each of 25 vehicle age categories. These values differ by the day of week. The analyst needs to input (1) values for engine starts per day for all vehicle classes affected by the **Starts per Day** command; and (2) average fraction of all engine starts that occur in each hour of a 24-hour day, for both weekdays and weekends.

Inspection Maintenance Program Status: The user can specify the status of any existing I/M program using the **I/M Program** command. If this command is not used,

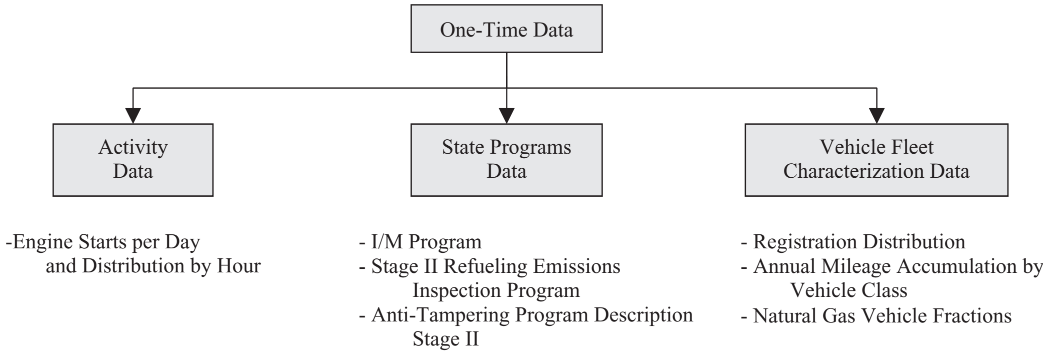


Figure A10.1 Basic data for MOBILE6.

MOBILE6 assumes that no I/M program exists. Input data include number of I/M programs that will be considered in the program run, calendar year at the start of the I/M program, calendar year at termination of the I/M program, frequency of I/M inspection (annual vs. biennial), I/M program type, and I/M inspection type.

Stage II Refueling Emissions Inspection Program: The **Effects of Stage II on Refueling Emissions** command enables the user to specify the impact of refueling emissions required by a stage II vapor recovery system. There is no default calculation of impact of a stage II program.

Stage II Antitampering Program Description: This gives the user the option to model the impact of an antitampering program using the **Anti-Tampering Programs** command. No default values are provided.

Vehicle Registration Distribution: This enables the user to supply vehicle registration distributions by vehicle age for any of the 16 composite (combined gas and diesel) vehicle types. A list of these vehicle types can be found in the main *User's Manual*.

Annual Mileage Accumulation by Vehicle Class: The **Annual Mileage Accumulation Rates** command allows the user to input the annual mileage accumulation rates by vehicle age for any of 28 individual vehicle types. Vehicle age groups are 0 to 25 and over 25 years.

Natural Gas Vehicle (NGV) Fractions: With this parameter, the user can specify the percentage of vehicles in the fleet that are certified to operate on either compressed or liquefied natural gas for each of the 28 individual classes beginning with the model year. The default fraction of NGV vehicles in the fleet is equal to zero.

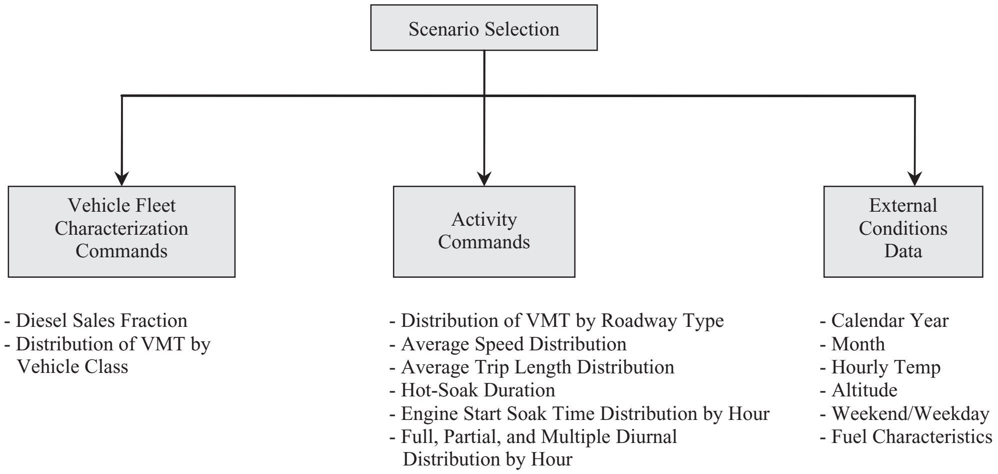


Figure A10.2 Scenario specific data for MOBILE6.

(*b*) *Scenario Selection File* This is used to assign scenario-specific values to emission variables. Various types of data needed for this file are shown in Figure A10.2.

(*c*) *Traffic-Related Data* MOBILE6 enables a relatively fine temporal distribution of traffic during the day for major traffic indicators. Hourly distributions can be input instead of 24-hour averages. Also, the fleet characterization projections of future vehicle fleet size and fraction of travel are based on a number of considerations, including vehicle age, mileage accumulation rate, and 28 vehicle classes. Data on the key traffic-related inputs (vehicle registration distribution, annual mileage accumulation rate, and the distribution of vehicle-miles traveled) are input by vehicle class and roadway type. Local data on mileage accumulation are typically more difficult to obtain because odometer readings are typically not recorded on an annual basis unless an inspection maintenance program is operational in the region under study.

A10.1.2 Sample MOBILE6 Output

Figure A10.3 below shows a sample of the output file generated by MOBILE6.

```
***************************************************************************
* MOBILE6.2.01 (31-Oct-2002)                                              *
* Input file: AFTER.IN (file 1, run 1).                                   *
***************************************************************************

* # # # # # # # # # # # # # # # # # # # # # # # # #
* Scenario Title : Master Example Input Demonstration
* File 1, Run 1, Scenario 1.
* # # # # # # # # # # # # # # # # # # # # # # # # #

                    Calendar Year:  2006
                            Month:  Jan.
                         Altitude:  Low
              Minimum Temperature:  64.0 (F)
              Maximum Temperature:  92.0 (F)
                Absolute Humidity:  115. grains/lb
                 Nominal Fuel RVP:   7.0 psi
                    Weathered RVP:   6.8 psi
              Fuel Sulfur Content:   33. ppm

              Exhaust I/M Program:  Yes
                 Evap I/M Program:  No
                      ATP Program:  Yes
                 Reformulated Gas:  No

Emissions determined from WEEKEND hourly vehicle activity fractions.

   Ether Blend Market Share: 0.500       Alcohol Blend Market Share: 0.500
   Ether Blend Oxygen Content: 0.020     Alcohol Blend Oxygen Content: 0.010
                                          Alcohol Blend RVP Waiver: No

       Vehicle Type:      LDGV    LDGT12    LDGT34      LDGT      HDGV      LDDV      LDDT      HDDV        MC   All Veh
               GVWR:               <6000     >6000     (All)
                        ------    ------    ------    ------    ------    ------    ------    ------    ------    ------
   VMT Distribution:    0.4005    0.2435    0.0272              0.0918    0.0023    0.0014    0.2216    0.0118    1.0000
  ----------------------------------------------------------------------------------------------------------------------
 Composite Emission Factors (g/mi):
     Composite VOC :      0.763     0.932     1.684     1.007     3.207    0.929     1.724     0.882      3.00     1.108
     Composite CO  :       4.30      6.87     10.45      7.23     32.19    2.302     2.931     5.438     25.06     8.144
     Composite NOX :      0.444     0.611     0.923     0.643     3.697    1.534     1.973    10.452      0.77     3.022
  ----------------------------------------------------------------------------------------------------------------------
Exhaust emissions (g/mi):
        VOC   Start:     0.086     0.129     0.244     0.141               0.169     0.473                0.389
      VOC   Running:     0.135     0.254     0.524     0.281               0.760     1.251                2.087
  VOC Total Exhaust:     0.221     0.384     0.768     0.422     1.715     0.929     1.724     0.882      2.48     0.590

           CO Start:      1.44      2.46      3.72      2.59               0.501     0.924                2.900
         CO Running:      2.86      4.41      6.73      4.64               1.802     2.006               22.161
   CO Total Exhaust:      4.30      6.87     10.45      7.23     32.19     2.302     2.931     5.438     25.06     8.144

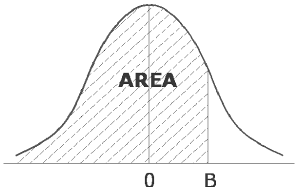
          NOx Start:     0.065     0.089     0.128     0.093               0.045     0.097                0.318
        NOx Running:     0.379     0.523     0.795     0.550               1.490     1.876                0.454
  NOx Total Exhaust:     0.444     0.611     0.923     0.643     3.697     1.534     1.973    10.452      0.77     3.022
  ----------------------------------------------------------------------------------------------------------------------
Non-Exhaust Emissions (g/mi):
      Hot Soak Loss:     0.096     0.082     0.135     0.088     0.278     0.000     0.000     0.000     0.132     0.089
       Diurnal Loss:     0.024     0.027     0.050     0.029     0.092     0.000     0.000     0.000     0.025     0.026
       Resting Loss:     0.087     0.092     0.177     0.101     0.306     0.000     0.000     0.000     0.368     0.095
       Running Loss:     0.318     0.310     0.490     0.328     0.645     0.000     0.000     0.000     0.000     0.275
     Crankcase Loss:     0.005     0.009     0.010     0.009     0.011     0.000     0.000     0.000     0.000     0.005
     Refueling Loss:     0.012     0.028     0.055     0.030     0.160     0.000     0.000     0.000     0.000     0.028
  Total Non-Exhaust:     0.542     0.548     0.916     0.645     1.492     0.000     0.000     0.000     0.525     0.518
  ----------------------------------------------------------------------------------------------------------------------
```

Figure A10.3 Sections of a sample MOBILE6 output file.

APPENDIX A10.2: VALUES OF THE GAUSSIAN DISTRIBUTION FUNCTION

$$G(B) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{B} \exp\left(\frac{-B^2}{2}\right) \mathrm{dB}$$

where $B = (x - \mu)/\sigma$.



B	0	1	2	3	4	5	6	7	8	9
−3.0	0.0013	0.0010	0.0007	0.0005	0.0003	0.0002	0.0002	0.0001	0.0001	0.0000
−2.9	0.0019	0.0018	0.0017	0.0017	0.0016	0.0016	0.0015	0.0015	0.0014	0.0014
−2.8	0.0026	0.0025	0.0024	0.0023	0.0022	0.0021	0.0021	0.0021	0.0020	0.0019
−2.7	0.0035	0.0034	0.0033	0.0032	0.0031	0.0030	0.0029	0.0028	0.0027	0.0026
−2.6	0.0047	0.0045	0.0044	0.0043	0.0041	0.0040	0.0039	0.0038	0.0037	0.0036
−2.5	0.0062	0.0060	0.0059	0.0057	0.0055	0.0054	0.0052	0.0051	0.0049	0.0048
−2.4	0.0082	0.0080	0.0078	0.0075	0.0073	0.0071	0.0069	0.0068	0.0066	0.0064
−2.3	0.0107	0.0104	0.0102	0.0099	0.0096	0.0094	0.0091	0.0089	0.0087	0.0084
−2.2	0.0139	0.0136	0.0132	0.0129	0.0125	0.0122	0.0119	0.0116	0.0113	0.0110
−2.1	0.0179	0.0174	0.0170	0.0166	0.0162	0.0158	0.0154	0.0150	0.0146	0.0143
−2.0	0.0228	0.0222	0.0217	0.0212	0.0207	0.0202	0.0197	0.0192	0.0188	0.0183
−1.9	0.0287	0.0281	0.0274	0.0268	0.0262	0.0256	0.0250	0.0244	0.0239	0.0233
−1.8	0.0359	0.0351	0.0344	0.0336	0.0329	0.0322	0.0314	0.0307	0.0301	0.0294
−1.7	0.0446	0.0436	0.0427	0.0418	0.0409	0.0401	0.0392	0.0384	0.0375	0.0367
−1.6	0.0548	0.0537	0.0526	0.0516	0.0505	0.0495	0.0485	0.0475	0.0465	0.0455
−1.5	0.0668	0.0655	0.0643	0.0630	0.0618	0.0606	0.0594	0.0582	0.0571	0.0559
−1.4	0.0808	0.0793	0.0778	0.0764	0.0749	0.0735	0.0721	0.0708	0.0694	0.0681
−1.3	0.0968	0.0951	0.0934	0.0918	0.0901	0.0885	0.0869	0.0853	0.0838	0.0823
−1.2	0.1151	0.1131	0.1112	0.1093	0.1075	0.1056	0.1038	0.1020	0.1003	0.0985
−1.1	0.1357	0.1335	0.1314	0.1292	0.1271	0.1251	0.1230	0.1210	0.1190	0.1170
−1.0	0.1587	0.1562	0.1539	0.1515	0.1492	0.1469	0.1446	0.1423	0.1401	0.1379
−0.9	0.1841	0.1814	0.1788	0.1762	0.1736	0.1711	0.1685	0.1660	0.1635	0.1611
−0.8	0.2119	0.2090	0.2061	0.2033	0.2005	0.1977	0.1949	0.1922	0.1894	0.1867
−0.7	0.2420	0.2389	0.2358	0.2327	0.2296	0.2266	0.2236	0.2206	0.2177	0.2148
−0.6	0.2743	0.2709	0.2676	0.2643	0.2611	0.2578	0.2546	0.2514	0.2483	0.2451
−0.5	0.3085	0.3050	0.3015	0.2981	0.2946	0.2912	0.2877	0.2843	0.2810	0.2776
−0.4	0.3346	0.3409	0.3372	0.3336	0.3300	0.3264	0.3228	0.3192	0.3156	0.3121
−0.3	0.3821	0.3783	0.3745	0.3707	0.3669	0.3632	0.3594	0.3557	0.3520	0.3483
−0.2	0.4207	0.4168	0.4129	0.4090	0.4052	0.4013	0.3974	0.3936	0.3897	0.3859
−0.1	0.4602	0.4562	0.4522	0.4483	0.4443	0.4404	0.4364	0.4325	0.4286	0.4247

Figure A10.4 Values of the Gaussian distribution function

B	0	1	2	3	4	5	6	7	8	9
0.0	0.5000	0.4960	0.4920	0.4880	0.4840	0.4801	0.4761	0.4721	0.4681	0.4641
0.1	0.5398	0.5438	0.5478	0.5517	0.5557	0.5596	0.5636	0.5675	0.5714	0.5753
0.2	0.5793	0.5832	0.5871	0.5910	0.5948	0.5987	0.6026	0.6064	0.6103	0.6141
0.3	0.6179	0.6217	0.6255	0.6293	0.6331	0.6368	0.6406	0.6443	0.6480	0.6517
0.4	0.6554	0.6591	0.6628	0.6664	0.6700	0.6736	0.6772	0.6808	0.6844	0.6879
0.5	0.6915	0.6950	0.6985	0.7019	0.7054	0.7088	0.7123	0.7157	0.7190	0.7224
0.6	0.7257	0.7291	0.7324	0.7357	0.7389	0.7422	0.7454	0.7486	0.7517	0.7549
0.7	0.7580	0.7611	0.7642	0.7673	0.7704	0.7734	0.7764	0.7794	0.7823	0.7852
0.8	0.7881	0.7910	0.7939	0.7967	0.7995	0.8023	0.8051	0.8078	0.8106	0.8133
0.9	0.8159	0.8186	0.8212	0.8238	0.8264	0.8289	0.8315	0.8340	0.8365	0.8389
1.0	0.8413	0.8438	0.8461	0.8485	0.8508	0.8531	0.8554	0.8577	0.8599	0.8621
1.1	0.8643	0.8665	0.8686	0.8708	0.8729	0.8749	0.8770	0.8790	0.8810	0.8830
1.2	0.8849	0.8869	0.8888	0.8907	0.8925	0.8944	0.8962	0.8980	0.8997	0.9015
1.5	0.9332	0.9345	0.9357	0.9370	0.9382	0.9394	0.9406	0.9418	0.9429	0.9441
1.6	0.9452	0.9463	0.9474	0.9484	0.9495	0.9505	0.9515	0.9525	0.9535	0.9545
1.7	0.9554	0.9564	0.9573	0.9582	0.9591	0.9599	0.9608	0.9616	0.9625	0.9633
1.8	0.9641	0.9649	0.9656	0.9664	0.9671	0.9678	0.9686	0.9693	0.9699	0.9706
1.9	0.9713	0.9719	0.9726	0.9732	0.9738	0.9744	0.9750	0.9756	0.9761	0.9767
2.0	0.9772	0.9778	0.9783	0.9788	0.9793	0.9798	0.9803	0.9808	0.9812	0.9817
2.1	0.9821	0.9826	0.9830	0.9834	0.9838	0.9842	0.9846	0.9850	0.9854	0.9857
2.2	0.9861	0.9864	0.9868	0.9871	0.9875	0.9878	0.9881	0.9884	0.9887	0.9890
2.3	0.9893	0.9896	0.9898	0.9901	0.9904	0.9906	0.9909	0.9911	0.9913	0.9916
2.4	0.9918	0.9920	0.9922	0.9925	0.9927	0.9929	0.9931	0.9932	0.9934	0.9936
2.5	0.9938	0.9940	0.9941	0.9943	0.9945	0.9946	0.9948	0.9949	0.9951	0.9952
2.6	0.9953	0.9955	0.9956	0.9957	0.9959	0.9960	0.9961	0.9962	0.9963	0.9964
2.7	0.9965	0.9966	0.9967	0.9968	0.9969	0.9970	0.9971	0.9972	0.9973	0.9974
2.8	0.9974	0.9975	0.9976	0.9977	0.9977	0.9978	0.9979	0.9979	0.9980	0.9981
2.9	0.9981	0.9981	0.9982	0.9983	0.9984	0.9984	0.9985	0.9985	0.9986	0.9986
3.0	0.9987	0.9987	0.9987	0.9988	0.9988	0.9989	0.9989	0.9989	0.9990	0.9990

Figure A10.4 (*continued*)