(State-funded report done by Contract)

AN EVALUATION OF CARBON MONOXIDE EMISSIONS MODELS AND MOBILE SOURCE DISPERSION MODELS APPLICABLE TO ALASKAN CITIES

FINAL REPORT

by

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IMPLEMENTATION STATEMENT

Planning changes or additions to any highway system in the U.S. within boundaries identified by the U.S. Environmental Protection Agency as "non-attainment areas" for air quality standards has long been recognized by State Transportation Departments and other responsible agencies as a task filled with pitfalls and uncertainties. To adequately address the needs of Environmental Impact Statements (EIS) and other planning and design requirements it would be highly desirable to have a *crystal ball* which would accurately predict the impact on air quality of each option being considered. Unfortunately in Alaska we currently have two cities, Anchorage and Fairbanks, where non-attainment of Carbon Monoxide (CO) standards are identified during winter periods and continue to cause environmental concern and we have yet to find a reliable source of *crystal balls*.

Beginning in 1973 this Department began experimenting with computer based mathematical models with the intention of approximating the ideal *crystal ball* for transportation planning and air quality impact. Then and since each such attempt has fallen far short of its goal but we have made progress. One of the most important lessens being: never confuse computer models with *crystal balls*.

This report describes an investigation of state-of-the-art models and identifies one, CALINE4, as a potentially useful tool to this Department. Based on this report and other investigations we in Facilities Research are of the opinion that this is an appropriate time to implement an air quality modeling capability into the routine operations of our Environmental Sections of the Divisions of Design and construction in both the Northern and Central Regions.

We will continue with our research by immediately moving into the implementation phase. Our goal will be to find a practical method and procedure where by air quality modeling can be integrated into the EIS and Design process. We do not expect to achieve *crystal ball* results. We will be satisfied initially with a qualitative result only, and with important consideration given to building familiarity and confidence by the user. If that much can be accomplished future refinement should follow as a natural consequence.

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1.0 INTRODUCTION

The State of Alaska Department of Transportation and Public Facilities (DOT&PF) has contracted Dames & Moore to evaluate current carbon monoxide (CO) emissions and dispersion models. The purpose of this study is to develop a better understanding of available models. As a result, it is hoped that the capability to predict and understand high CO concentrations in Anchorage and Fairbanks will be improved. As requested by DOT&PF, the initial study will focus on emissions and air quality in the Raspberry Road area of Anchorage.

The initial sections of this report present an evaluation of four computerized mobile source emissions models currently in use. These include MOBILE2, MOBILE2.5 and MOBILE3, developed by the U.S. Environmental Protection Agency, and Alaska-MOBILE2.5 (AKMOBILE2.5), developed by Sierra Research, Inc. for the Alaska Department of Environmental Conservation (ADEC). Provided in Section 2.0 through Section 4.0 of this report are discussions in the following areas:

- a brief description of these models with special emphasis placed on their differences,
- a comparison of calculated emission rates from each model, and description of these rates in relation to model formulation,
- model sensitivity studies on ambient temperature, inventory year, inspection and maintenance (I/M) program, vehicle speed, and engine mode (cold start, hot start, hot stabilized), and
- CO emissions along Raspberry Road.

These data will serve as the basis for emissions to be used in mobile source dispersion models.

In Section 5.0 through 8.0 of this report, an evaluation of three computerized mobile source dispersion models currently in use is presented. These include CALINE3 and CALINE4, developed by the California Department of Transportation (CALTRANS), and ROADWAY, developed by the U.S. Environmental Protection Agency (EPA). Discussion in the following areas are provided:

- a description of the dispersion models including a discussion on their similarities and differences,

- model sensitivity studies for various meteorological conditions such as wind speed, stability, and mixing height,

- a comparison of calculated air quality impacts from each model as it applies to the Raspberry Road area (Sand Lake monitoring site).

2.0 DESCRIPTION OF EMISSIONS MODELS

2.1 MOBILE2

The MOBILE2 emissions model program was developed by the Office of Mobile Source Air Pollution Control Technology Division, Test and Evaluation Branch (Ann Arbor, Michigan). MOBILE2 was finalized in December of 1980 and represents extensive revisions to MOBILE1 which was developed by the Office of Transportation and Land Use Policy prior to 1978.

MOBILE2 computes vehicle emissions using emission factors and calculating methodologies developed by the U.S. Environmental Protection Agency (USEPA) as presented in the publication Compilation of Air Pollutant Emission Factors: Highway Mobile Sources, March 1981 (Publication Number EPA/460/3-81-005). Emissions of hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen (NO_x) can be calculated for eight vehicle types within three regions of the United States: (1) non-California/low altitude, (2) non-California/high altitude, and (3) California/low altitude. For this study, only CO emissions in a non-California/low altitude region (representative of the Raspberry Road study area) are investigated. Calculated emission rates are dependent on several additional factors including vehicle inventory year, ambient temperature, vehicle speed, mileage accumulation and accrual distributions, vehicle-miles-traveled distributions, and engine operating mode (cold/warm).

The basic emission rates represent results of tests conducted on eight types of vehicles under standardized conditions representative of urban driving (future reference to these vehicle types will be made by abbreviations defined in Table 2-1). These conditions include cold start, hot start, hot stabilized, and idle engine modes. As shown in Table 2-1, test conditions incorporate an ambient temperature of between 68 and 86°F (generally 75°F), and a specific humidity of 75 grains H_2O per pound of air (used for NO_x emissions dependence). Also shown is the average engine mode mix for urban driving (20.6 percent cold start, 52.1 percent hot stabilized, and 27.3 percent hot start). Correction to emissions representative of other conditions can be made in MOBILE2. These include ambient temperature, vehicle speed, engine mode mix, air conditioning, extra load, trailer towing, and humidity. This study investigates sensitivity to ambient temperature, vehicle speed, and engine mode mix.

Due to the absence of specific usage data, air conditioning, extra load, and trailer towing parameters were not investigated.

One additional and important optional feature of MOBILE2 is the capacity to account for inspection and maintenance (I/M) credits. These credits are dependent on the type of I/M program implemented and can be characterized by the following six factors:

(1) The estimated first year failure rate (stringency factor) for the pre-1981 low altitude non-California LDGV's (or other vehicle types with similar emission control technologies). The pre-1975 vehicles are defined as Technology I vehicles and 1975-1980 vehicles are defined as Technology II vehicles.

TABLE 2-1

BASIC EXHAUST EMISSION LEVEL
STANDARDIZED TEST CONDITIONS
(FEDERAL TEST PROCEDURES - FTP)

	Vehicle Type[a]				
	LDGV, LDGT1 & LDGT2	HDGV	LDDV & LDDT	HDDV	MC
Engine Off Period for Cold Start	12-36 hours	12+hrs[b]	12-36 hours	12+ hrs[b]	6-36 hours[c]
Engine Off Period for Hot Start	10 minutes	20 minutes	10 minutes	20 minutes	10 minutes
Engine Off Ambient Temperature	68-86°F	68-86°F	68-86°F	68-86°F	68-86°F
NO_x Corrected to Ambient Humidity (grains of H_2O/lb. dry air)	75	75 N/A[d]	N/A	N/A	75
Average Trip Length	7.5 miles	6.5 miles	7.5 miles	6.4 miles	6.8-7.5 miles[c]
Average Trip Speed	19.6 mph	19.9 mph 20 mph[d]	19.6 mph	19.2 mph 20 mph[d]	17.8-19.6 mph[c] 19.6[d]
Average Idle Percent of Trip	18%	27%	18%	37%	18%
Average Percent VMT Cold Start	20.6%	14.3%	20.6%	14.3%	18.3-20.6%[c] 20.6[d]
Average Percent VMT Stabilized	52.1%	0%	52.1%	0%	52.1-57.5%[c] 52.1[d]
Average Percent VMT Hot Start	27.3%	86.7%	27.3%	86.7%	24.2-27.3%[c]

[a] LDGV = light duty gasoline vehicles, LDGT1 = light duty gasoline trucks less than 6001 pounds, LDGT2 - light duty gasoline trucks greater than 6000 pounds, HDGV = heavy duty gas vehicles, LDDV = light duty diesel vehicles, LDDT = light duty diesel trucks, HDDV = heavy duty diesel vehicles, MC = motorcycles.

[b] Optionally, this 12+ hour engine off time may be replaced by a forced cool down procedure, whereby cool water is circulated through the engine cooling system until the engine oil temperature is between 68°F and 75°F.

[c] Depending on engine size.

[d] Assumed in MOBILE2.

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(2) The success rate in identifying 1981 and later model year low altitude non-California LDGVs operating under rich failure conditions (the identification rate of Technology IV vehicles). Technology III is not defined in MOBILE2.

(3) The vehicle types affected by the program: LDGV; LDGV & LDGT1; LDGV & LDGT2; or LDGV, LDGT1, & LDGT2.

(4) The calendar year being analyzed and the calendar year an I/M program is implemented.

(5) The presence or absence of an adequate mechanic training program.

(6) The model years involved in the I/M program.

This report focuses on emissions for the 1983 Raspberry Road traffic (1983 vehicle inventory year). Since no I/M program was in effect at that time, no I/M credits are included. Note, however, that an I/M program was implemented during the preparation of this report. Since evaluations of future development projects will reflect this program, this report begins an investigation into the MOBILE2 credits for I/M programs.

2.2 MOBILE2.5

MOBILE2.5 was developed through modifications made to MOBILE2. These modifications involve the basic CO emission rates and I/M inspection credits. The basic CO emission rates are reduced from MOBILE2 to account for actual 1981 vehicle test results which were lower than previously expected.

2.3 AKMOBILE2.5

AKMOBILE2.5 was developed by Sierra Research, Inc. under contract to the Alaska Department of Environmental Conservation prior to October 1983. AKMOBILE2.5 is a modification to USEPA's MOBILE2.5 to reflect vehicle CO emissions data representative of: (1) low ambient temperature (20°F), (2) Fairbanks, Alaska vehicle distribution by age (rather than the national average as used in MOBILE2.5), and (3) Fairbanks, Alaska mileage accumulation rates. The 20°F CO emission factors for passenger cars (LDGV) and light-duty gas trucks (LDGT1-LDGT2) were substituted for the USEPA factors used in MOBILE2.5 for the 68 to 86°F temperature range. The correction for ambient temperatures other than 68 to 70°F was then disabled for these categories. With the above modifications, AKMOBILE2.5 can only be used to calculate CO emissions at 20°F (emissions of other pollutants, or at other temperature ranges, should be ignored). Further description on AKMOBILE2.5 is presented in the paper "Light Duty Vehicle CO Emissions During Cold Weather" (Society of Automotive Engineers Technical Paper Series No. 831698) presented at the Fuels and Lubricants Meeting, San Francisco, California, October 31 - November 3, 1983.

2.4 MOBILE3

MOBILE3 is a modified version of MOBILE2 based on USEPA emission factors and calculating procedures presented in the USEPA publication Compilation of Air Pollutant Emission Factors: Highway Mobile Sources, August 1984 (Publication No. EPA 460/3-84-005). Modifications include incorporation of several new options, calculating methodologies, emission factor estimates, emission control regulations, and internal program designs.

Two basic differences between MOBILE2 and MOBILE3 are: (1) changes in the basic emission rates for certain vehicle types and model years based on new data, and (2) changes in the emission rate calculating method that includes:

- tampering effects and anti-tampering programs (ATP),
- additive low temperature CO model for cold start engine mode for light duty gas vehicles and trucks,
- I/M test procedures and standards (for I/M credits),
- heavy duty diesel vehicle mileage accumulation reflecting new engine designs, and
- methane fraction of total hydrocarbon emissions.

Incorporation of tampering effect, anti-tampering program, and I/M program is optional but, when used, allows for significant detail in characterization of the program. MOBILE3 allows user specified (local) tampering rates, or defaults to national averages for non-I/M and I/M areas. Tampering includes modifications to: (1) misfueling, (2) fuel inlet disablement, (3) catalyst removal, (4) EGR, (5) evaporative canister, (6) positive crankcase ventilation (PCV) system, and (7) air pump. Characterization of anti-tampering programs include the following factors:

- frequency of inspection (annual, biannual, change-of-ownership, or random audits of 1%, 2%, and 5% of the fleet),

- equipment inspected (air pump, catalyst, fuel inlet, lead deposit, PCV, and evaporative canister),

- first year of ATP implementation,

- first and last vehicle model years included in ATP, and

- vehicle types covered by ATP (LDGV, LDGT1, LDGT2, HDGV).

The low temperature CO offset model used in MOBILE3 for cold start engine mode, calculates offset emissions at temperatures other than 75°F by the equation:

$$\text{Offset (g CO/mi)} = -1.3812\ \text{g/(mi-°F)} \times (T_a - 75°\text{F})$$

where Offset = CO emissions which are added to basic emission factors representative of 75°F

T_a = ambient temperature (°F).

75 = mid temperature of federal test procedure (FTP) range.

This compares with the log-linear correction factor used in MOBILE2 for all engine modes and used in MOBILE3 for hot start and hot stabilized modes by the equation:

$$\text{Correction Factor} = \exp\left[-k \times (T_a - 68°F)\right]$$

where k = positive constant dependent on vehicle type, pollutant, and engine mode (typically between 0.0485 and 0.0004)

T_a = ambient temperature (°F)

68 = lower end of FTP temperature range (86 was used at temperatures greater than 86°F).

Optional incorporation of I/M program credits in MOBILE3 is made through characterization of the I/M program by the following factors:

- first year of I/M program implementation,
- first and last vehicle model year included in I/M program,
- stringency level of I/M program (defined as a percent expected to fail),
- whether mechanic training is part of the I/M program,
- type of vehicles affected by I/M program,
- type of I/M test (idle, two-speed, or loaded),
- standards used in conjunction with I/M short test for 1981 and later light duty vehicles (0.5% CO/100 ppm HC, 1.2% CO/220 ppm HC, or 3.0% CO/300 ppm HC),
- whether alternative I/M credits are to be used (according to USEPA data on Alternative Technologies I, II, III, and IV).

The remaining modifications incorporated into MOBILE3 concerning heavy duty diesel vehicle mileage accumulation, elimination of California-specific emission rates, and methane fraction, are not pertinent or of sufficient magnitude to be discussed further in this report.

3.0 CO EMISSION CALCULATIONS

Mobile vehicle exhaust CO emissions have been calculated using each of the four previously described emissions models. Model results are presented in units of grams of CO per vehicle-mile traveled. Using these results, total emissions (in units of 103 grams per mile per hour) are calculated for 1983 traffic on Raspberry Road. These total emissions data will be used in the near future in the evaluation of mobile source pollutant dispersion models. In calculating CO emissions, sensitivity of the models to vehicle speed, engine mode (cold start, hot start, hot stabilized, FTP mix), ambient temperature, and inventory year is investigated. All calculated emissions use a vehicle type mix based on Alaska Department of Transportation Vehicle Registration Summaries for the Anchorage Census District for 1977 through 1981:

Light duty gas vehicles (LDGV)	68.9%
Light duty trucks less than 6001 pounds (LDGT1)	19.8%
Light duty trucks greater than 6000 pounds (LDGT2)	8.9%
Heavy duty gas vehicles (HDGV)	1.7%
Light duty diesel vehicles (LDDV)	0.2%
Light duty diesel trucks (LDDT)	0.1%
Heavy duty diesel vehicles (HDDV)	0.4%
Motorcycles (MC)	0.0%

3.1 VEHICLE SPEED AND ENGINE MODE DEPENDENCE

Tables 3-1 through 3-4 show model results for inventory year 1983 as a function of speed for 4 engine mode scenarios: (1) 100 percent cold start, (2) 100 percent hot start, (3) 100 percent hot stabilized, (4) FTP mix (20.6 percent cold start, 27.3 percent hot start, 52.1 percent hot stabilized), respectively.

TABLE 3-1

ALASKA DEPARTMENT OF TRANSPORTATION
MOBILE EMISSIONS MODEL RESULTS
(100% COLD START ENGINES - 1983)[a]

Vehicle Speed (MPH)	CO Emissions (Grams Per Vehicle-Mile)			
	MOBILE2	MOBILE2.5	AKMOBILE2.5	MOBILE3
10	383	383	302	501
15	273	273	215	357
20	221	221	173	277
25	182	182	142	220
30	149	149	117	176
35	124	124	98	143
40	109	109	86	121
45	104	104	82	107
50	103	103	81	98
55	94	94	74	87

[a] Based on an ambient temperature of 20 degrees F.

TABLE 3-2

ALASKA DEPARTMENT OF TRANSPORTATION
MOBILE EMISSIONS MODEL RESULTS
(100% HOT START ENGINES - 1983)[a]

Vehicle Speed (MPH)	CO Emissions (Grams Per Vehicle-Mile)			
	MOBILE2	MOBILE2.5	AKMOBILE2.5	MOBILE3
10	57	57	66	68
15	40	40	47	48
20	32	32	37	37
25	26	26	31	30
30	21	21	25	24
35	18	18	21	20
40	16	16	19	17
45	15	15	18	15
50	15	15	18	14
55	14	14	17	13

[a] Based on an ambient temperature of 20 degrees F.

TABLE 3-3

ALASKA DEPARTMENT OF TRANSPORTATION MOBILE EMISSIONS MODEL RESULTS (100% HOT STABILIZED ENGINES - 1983)[a]

Vehicle Speed (MPH)	CO Emissions (Grams Per Vehicle-Mile)			
	MOBILE2	MOBILE2.5	AKMOBILE2.5	MOBILE3
10	77	77	71	85
15	54	54	50	60
20	43	43	40	46
25	36	36	33	37
30	29	29	27	30
35	24	24	23	25
40	22	22	20	21
45	21	21	19	19
50	20	20	19	18
55	19	19	18	16

[a] Based on an ambient temperature of 20 degrees F.

TABLE 3-4

ALASKA DEPARTMENT OF TRANSPORTATION
MOBILE EMISSIONS MODEL RESULTS
(FTP MIX OF ENGINE MODES - 1983)[a,b]

Vehicle Speed (MPH)	CO Emissions (Grams Per Vehicle-Mile)			
	MOBILE2	MOBILE2.5	AKMOBILE2.5	MOBILE3
10	120	120	105	144
15	85	85	75	102
20	69	69	60	79
25	56	56	49	63
30	46	46	41	51
35	39	39	34	41
40	34	34	30	35
45	32	32	29	31
50	32	32	28	29
55	30	30	26	27

[a] Cold start (non-catalytic engines) = 20.6 percent
Hot start = 27.3 percent
Cold start (catalytic engines) = 20.6 percent
Hot stabilized = 52.1 percent

[b] Based on an ambient temperature of 20 degrees F.

All four tables show that the MOBILE2 and MOBILE2.5 results are identical. Further inspection of these tables show the following comparisons between the models:

(1) For cold start engines (Table 3-1), hot stabilized engines (Table 3-3), and FTP mix of engines (Table 3-4); the AKMOBILE2.5 model emissions are less than MOBILE2/2.5 emissions by from 5 to 21 percent (13 percent less with the FTP mix).

(2) For hot start engines (Table 3-2), AKMOBILE2.5 emissions are from 16 to 21 percent greater than MOBILE2/2.5 emissions depending on vehicle speed.

(3) MOBILE3 emissions are from 7 to 31 percent greater than MOBILE2/2.5 emissions for cold start engines (Table 3-1) and reflect MOBILE3's low temperature CO emissions model.

(4) MOBILE3 emissions for hot start, hot stabilized, and FTP mix range from 20 percent greater to 16 percent less than MOBILE2/2.5 emissions (the trend is for greater emissions at slower speeds, and lesser emissions at faster speeds).

(5) MOBILE3 emissions are greater than AKMOBILE2.5 emissions for hot start and hot stabilized modes at slower speeds.

These tables also show the dependence on vehicle speed. Results show that MOBILE2/2.5 and AKMOBILE2.5 emissions at 10 mph are 4.0 times greater than emissions at 55 mph, and that MOBILE3 emissions are 5.8 times greater at 10 mph for cold start, and 5.3 times greater at 10 mph for other modes.

3.2 AMBIENT TEMPERATURE DEPENDENCE

Table 3-5 presents model results at two ambient temperatures (0 and 20°F) for each engine mode to evaluate the sensitivity to temperature. These emissions reflect a 1983 inventory year, and a vehicle speed of 35 mph.

TABLE 3-5

ALASKA DEPARTMENT OF TRANSPORTATION
MOBILE EMISSIONS MODEL RESULTS
SENSITIVITY TO AMBIENT TEMPERATURE[a]

Mode/Temperature	CO Emissions (Grams Per Vehicle-Mile)			
	MOBILE2	MOBILE2.5	AKMOBILE2.5	MOBILE3
Cold Start/				
0 Degrees F	195	195	--[b]	219
20 Degrees F	124	124	98	143
Hot Start/				
0 Degrees F	18	18	--[b]	20
20 Degrees F	18	18	21	20
Hot Stabilized/				
0 Degrees F	28	28	--[b]	28
20 Degrees F	24	24	23	25
FTP Mix/				
0 Degrees F	52	52	--[b]	55
20 Degrees F	39	39	34	41

[a] Based on 1983 inventory year, and a vehicle speed of 35 mph.
[b] AKMOBILE2.5 does not allow calculation of emissions at other than 20°F.

Temperature sensitivity of the AKMOBILE2.5 is not possible since the model does not have the capability to calculate emissions at any temperature other than 20°F. As was seen in Tables 3-1 through 3-4, MOBILE2 emissions are seen here to be identical to MOBILE2.5 emissions. These MOBILE2/2.5 CO emissions are greater at 0°F than 20°F by from 17 percent to 57 percent (for hot stabilized and cold start modes respectively). MOBILE2/2.5 and MOBILE3 emissions for hot start mode are no different at the two temperatures. MOBILE3 emissions show a slightly lower increase from 20°F to 0°F ranging from a 12 percent increase to a 53 percent increase (for hot stabilized and cold start modes respectively).

AKMOBILE2.5 emissions at 20°F are shown to be less than MOBILE2/2.5 emissions for all modes except hot start (up to 21 percent less for cold start mode). For hot start mode, AKMOBILE2.5 emissions are greater by 11 percent. In comparison, MOBILE3 emissions are greater than MOBILE2/2.5 emissions by from four percent (hot stabilized) to 15 percent (cold start). Compared to AKMOBILE2.5 emissions, MOBILE3 emissions are 46, 21, and 9 percent greater for cold start, FTP mix, and hot stabilized modes, respectively; and five percent less for hot start mode.

3.3 INVENTORY YEAR DEPENDENCE

Table 3-6 presents results of model runs for inventory years 1983, 1990, and 2001. Emissions reflect an ambient temperature of 20°F, a vehicle speed of 35 mph, and do not include I/M program credits. MOBILE2 and MOBILE2.5 emissions are again found to be identical. Table 3-6 shows that MOBILE2/2.5 emissions in 1990 and 2001 for cold start mode are 45 and 61 percent less than 1983 emissions. Comparative AKMOBILE2.5 emissions are not reduced quite as much in future years (39 to 58 percent less in 1990 and 2001 respectively). In contrast, comparative MOBILE3 emissions are reduced more than MOBILE2/2.5 in future years (50 and 78 percent less in 1990 and 2001, respectively). Comparing the models for the FTP mix, AKMOBILE2.5 emissions are reduced in future years by about the same percent as MOBILE2/2.5 while MOBILE3 emissions are reduced by a lesser percentage than MOBILE2/2.5.

TABLE 3-6

ALASKA DEPARTMENT OF TRANSPORTATION
MOBILE EMISSIONS MODEL RESULTS
SENSITIVITY TO INVENTORY YEAR[a,b]

Inventory Year	CO Emissions (Grams Per Vehicle-Mile) MOBILE2	MOBILE2.5	AKMOBILE2.5	MOBILE3
100% Cold Start:				
1983	124	124	98	143
1990	68	68	60	93
2001	48	48	50	65
100% Hot Start:				
1983	18	18	21	20
1990	13	13	14	16
2001	12	12	12	15
100% Hot Stabilized:				
1983	24	24	23	25
1990	19	19	14	18
2001	17	17	11	16
FTP Mix:				
1983	39	39	34	41
1990	25	25	21	29
2001	20	20	17	23

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[a] Based on a vehicle speed of 35 mph, and an ambient temperature of 20 degrees F.
[b] No I/M program is included.

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In most cases, however, AKMOBILE2.5 CO emission rates are less than MOBILE2/2.5, while MOBILE3 CO emission rates are greater than both MOBILE2/2.5 and AKMOBILE2.5 rates.

The most accurate prediction of future emissions are not reflected in Table 3-6 since the effects of an I/M program are not included. The State of Alaska is scheduled to implement an I/M program in the near future (July 1985). Details of this I/M program including anti-tampering programs can be used in developing input data to be used in evaluating model results that incorporate I/M credits.

Preliminary model results incorporating I/M program credits indicate that 1990 inventory year emissions are reduced from 1983 levels by 35, 32, and 31 percent by MOBILE2/2.5, AKMOBILE2.5 and MOBILE3, respectively. For inventory year 2001, emissions are reduced from 1983 levels by 29, 28, and 28 percent by MOBILE2/2.5, AKMOBILE2.5, and MOBILE3, respectively. With the added credits taken for a full anti-tampering program, MOBILE3 emissions are further reduced by a small amount.

3.4 TOTAL EMISSION RATES

Table 3-7 presents total emissions for four engine mode scenarios (in units of 10^3 grams per hour-mile). These are calculated by multiplying the model emissions in units of grams per vehicle-mile by the average daily Raspberry Road traffic load (7800 vehicles per hour). This traffic load was provided by Alaska Department of Transportation and Public Facilities for 1983. These emissions are based on model results reflecting: a 1983 inventory year (no I/M program), a 35 mph vehicle speed, an FTP engine mode mix, and an ambient temperature of 20°F. This table shows that the greatest emissions are calculated by MOBILE3 for cold start, hot stabilized, and FTP mix modes, and by AKMOBILE2.5 for hot start mode. This table also shows that the smallest emissions are calculated by AKMOBILE2.5 for cold start, hot stabilized and FTP mix modes, and by MOBILE2/2.5 for hot start mode.

TABLE 3-7

ALASKA DEPARTMENT OF TRANSPORTATION
TOTAL MOBILE EMISSIONS FOR
1983 RASPBERRY ROAD TRAFFIC[a,b,c]

	CO Emissions (10^3 Grams Per Hour-Mile)			
Engine Mode	MOBILE2	MOBILE2.5	AKMOBILE2.5	MOBILE3
100% Cold Start	967	967	764	1115
100% Hot Start	140	140	164	156
100% Hot Stabilized	187	187	179	195
FTP Mix	304	304	265	320

[a] Based on a vehicle speed of 35 mph, and an ambient temperature of 20 degrees F.
[b] No I/M program is included for 1983 inventory year.
[c] Based on an average daily traffic load of 7800 vehicles per hour.

4.0 SUMMARY OF EMISSION MODEL EVALUATION

4.1 EMISSIONS MODEL FORMULATIONS

Initial modifications to MOBILE2 comprising MOBILE2.5 included adjustment to basic CO emission factors that reflect 1981 vehicle test data. However, as used in this study, no significant difference between MOBILE2 and MOBILE2.5 emissions is apparent. AKMOBILE2.5 was developed from MOBILE2.5 by Sierra Research, Inc. to account for cold start CO emissions from light duty vehicles at 20°F. As such, this model can only be used to calculate CO emissions at 20°F without I/M program credits. AKMOBILE2.5 emission results show smaller CO emissions rates for 1983 and 1990 cold start engines than MOBILE2/2.5.

MOBILE3 represents the most current mobile emissions model available. It was developed based on extensive revisions to MOBILE2 and incorporates basic emission factors and calculating methods published by EPA in 1984. The capability to include more sophisticated I/M programs and anti-tampering programs, has been added as well as other program options. A significant, new feature of MOBILE3 is the cold start, low temperature CO offset emissions model. MOBILE3 results show calculated emissions are generally higher (especially at lower vehicle speeds) than either MOBILE2/2.5 or AKMOBILE2.5 emissions.

In assessing future emissions, the use of these models should include credits for I/M programs. At present, the MOBILE3 model allows the greatest flexibility in describing I/M programs and has the added capability to account for anti-tampering programs.

In developing mobile source emissions for input into the dispersion model portion of this study, it is recommended that MOBILE2 and MOBILE2.5 be excluded from further consideration. MOBILE3 should be retained because it is the state-of-the-art model currently in used by EPA. AKMOBILE2.5 should be retained because it was based on emission source tests in the Alaska winter climate.

5.0 DESCRIPTION OF DISPERSION MODELS

Dispersion models estimate the amount of dilution a pollutant will undergo between an emissions source and the point at which pollutant concentrations are predicted. The models described in this report were developed specifically for assessing air quality impacts of emissions from motor vehicles operating on highways or streets.

There are various techniques for estimating dispersion, but the most widely used technique is the Gaussian modeling approach. The CALINE models use a form of the standard Gaussian technique. Both CALINE models modify the basic dispersion curves used in the model to account for initial pollutant dispersion due to the turbulence created by moving vehicles and their hot exhaust. Both the atmospheric dispersion curves and the initial pollutant dispersion calculations used in the CALINE models are based on previous field data.

ROADWAY, by comparison, is a numerical model which explicitly solves fundamental physical equations using finite difference techniques. The model solves these equations to develop wind and turbulence fields, from which pollutant impacts are predicted. ROADWAY does not require the empirical dispersion assumptions implicit in CALINE3 and CALINE4 (e.g. atmospheric dispersion curves and initial pollutant dispersion due to vehicle-induced turbulence).

CALINE3, CALINE4, and ROADWAY are described in the following sections.

5.1 CALINE3

The CALINE3 dispersion model was released by CALTRANS in 1979 (Benson, 1979). CALINE3 was developed from earlier CALTRANS models which were developed in response to requirements of the National Environmental Policy Act of 1969. CALINE3 is a line source Gaussian dispersion model applicable to modeling mobile source emissions associated with streets, roads, or highways. This model is primarily designed to assess air quality impacts within the microscale region (within approximately 150 meters of the road being modeled). However, in practice the model is used for calculating impacts up to distances of several kilometers.

CALINE3 treats each individual highway segment to be modeled as a series of individual road elements. Vehicular emissions within each element are distributed equitably across a line which runs through the element midpoint and is oriented perpendicular to the wind direction being modeled. These emissions are then modeled as an "equivalent" finite line source. It is for this reason that CALINE3 is considered to be a line-source model. Calculated concentrations from each element are summed to form a total concentration estimate for a particular receptor location.

CALINE3 treats the region directly over the highway as a zone of uniform turbulence. Within this mixing zone, there is a considerable amount of mechanical turbulence, created by the moving vehicles themselves, and thermal turbulence, created by the heat output of the vehicle engines. Initial horizontal dispersion due to the vehicle wakes is implicitly accounted for in CALINE3 by adding 3 meters to each side of the input roadway widths. Initial vertical dispersion is calculated by CALINE3 from the "residence time", which is an arbitrarily defined variable roughly proportional to the amount of time emissions spend within this region directly over the highway. The initial vertical dispersion is then adjusted based on averaging time but is independent of stability and surface roughness. The amount of vertical dispersion assigned to each element is calculated from algorithms developed from the General Motors (GM) Sulfate Experiment (Cadle et al, 1976). These algorithms are independent of traffic volume and speeds, which should be the main factors which determine the initial vehicle-induced turbulence. The GM data indicated that initial vertical dispersion of pollutants is insensitive to changes in traffic volume and speed within the ranges of 4000 to 8000 vehicles/hour and 30 to 60 mph. This may be due to offsetting effects of traffic speed to volume (higher volumes increase thermal turbulence but decrease traffic speed, thus reducing mechanical turbulence). Because CALINE3 calculations of initial dispersion are based on a heavily-used freeway, the model may not accurately reflect the lower traffic volumes found on many of Alaska's surface streets.

After approximating the initial vertical dispersion within the mixing zone, the model calculates total vertical dispersion at points outside the mixing zone by a logarithmic interpolation scheme based on the Pasquill-Gifford dispersion curves (Pasquill, 1974). These curves are a function of atmospheric stability class and provide estimates of vertical dispersion as a function of downwind distance. (Stability classes categorize levels of ambient atmospheric turbulence).

Horizontal dispersion is calculated in the model directly from the Pasquill-Gifford curves. (As discussed above, initial road-related horizontal turbulence was accounted for by increasing the effective road width.) Since both horizontal and vertical dispersion are calculated from dispersion curves, these values depend on the user-input value of the stability class. However, it should be noted that, in the vicinity of the roadway, the dispersion is fairly independent of stability class, except during near-parallel wind conditions, due to the methods chosen for calculating the initial road-induced turbulence. Adjustments to the horizontal and vertical dispersion terms are made by the model based on averaging time and surface roughness.

Basic inputs to CALINE3 include information about the roadway segments being modeled, locations at which air quality impacts are to be estimated, and meteorological conditions. Roadway segment information includes the following:

- number of vehicles passing a single point on the segment in an hour,
- vehicular emissions of the inert pollutant being modeled,
- average speed of vehicles,
- road width and road type (at-grade, bridge, elevated, or depressed),
- road locations and geometries (coordinates of road endpoints).

In CALINE3, roadways must be modeled as straight segments, not to exceed 10 kilometers in length. Therefore, irregularly shaped roads must be approximated by inputting them into the model as a series of shorter road segments. Also, all roadway parameters must be fairly constant for each road segment. Therefore, even straight roads must sometimes be modeled as a series of shorter road segments when road characteristics such as vehicle speeds or road widths change. Up to 20 road segments may be input to CALINE3.

Coordinates of the locations where air quality impacts are to be calculated, referred to as receptors, are also input to the model. By requiring input receptor locations, CALINE3 offers the user flexibility in choosing a modeling approach. Up to 20 receptors may be input to CALINE3. Meteorological inputs to the model include wind speed, wind direction, stability and mixing height. These are typically chosen in any modeling application to represent a realistic worst-case condition (maximum concentration). Other model inputs include pollutant deposition and settling velocities, surface roughness length, and averaging time.

5.2 CALINE4

CALINE4 is the most recent CALTRANS model. CALINE4 was released during late 1984 (Benson, 1984), primarily to other regulatory agencies. Dames & Moore was able to obtain an advanced copy of CALINE4 from DOT&PF. One model error was discovered in this CALINE4 version. This error was pointed out to CALTRANS, who determined the cause of the error and provided the necessary corrections to the model code. Although the model now appears to be running properly, Dames & Moore can assume no responsibility for errors and omissions in the current CALINE4 version being studied.

CALINE4, although similar to CALINE3 in appearance, has many significant differences. Most apparent are special options which can be used for modeling air quality near intersections, street canyons, and parking facilities by allowing for input modal emissions resulting from vehicle accelerations and decelerations. Also, the model can now predict NO_2 impacts, which is a secondary pollutant formed from vehicular NO_x emissions. None of these special options were considered in the modeling performed for this report. Instead, attention was focused on inputs to the model which affect calculated impacts from at-grade roads with steady vehicle flow.

CALINE4, when used without these special options, is very similar to CALINE3. Like CALINE3, CALINE4 treats each road segment as a series of finite line sources oriented perpendicular to the wind. Although there are some minor program modifications to algorithms calculating element size and vehicular emission distribution within each element, the models function similarly. Both models contain algorithms for calculating initial turbulence generated by traffic (mixing zone model). Both models require essentially the same input data: meteorological conditions, receptor locations, and link information such as traffic volume and speed, road width and type, vehicular emissions, and road endpoint coordinates.

Major program modifications in CALINE4 (as opposed to CALINE3) which significantly affect calculated concentrations from roadway segments are as follows:

- Horizontal dispersion is calculated from a user-input value of sigma-theta, which is a measure of horizontal wind direction variability. The specific method for calculating horizontal dispersion from sigma-theta was developed by Draxler (1976). Vertical dispersion is still calculated from stability class in CALINE4. Since sigma-theta implicity includes the effects of averaging time on horizontal dispersion, averaging time is no longer input to the model.

- The residence time of link segment element emissions within the mixing zone is calculated as a function of the angle between the wind direction and the road orientation up to 45°. In CALINE3, the initial vertical dispersion coefficient was adjusted for averaging time. In CALINE4, this adjustment was not done. The net effect on dispersion is relatively small and site-specific. (Residence time in CALINE3 was assumed to be independent of wind angle).

- Ambient vertical dispersion (within and near to the mixing zone) is increased to account for the thermal effects of vehicular emissions. After determining the amount of vehicle-generated heat, the stability class used for calculating initial vertical dispersion is adjusted using Smith's nomograph (1972). After some downwind distance, the vertical dispersion values are returned to their unadjusted values based on the original stability.

These modifications, especially the use of sigma-theta to calculate horizontal dispersion, make CALINE4 results much different from CALINE3 in similar applications of the models (even though the basic gaussian techniques are similar).

5.3 ROADWAY

The ROADWAY dispersion model was initially developed by the EPA in 1979. The current version was released in 1982. ROADWAY is a numerical model which combines surface layer similarity theory with a vehicle wake theory to assess air quality impacts from mobile sources along roads and highways. The vehicle wake theory was originally developed by Eskridge and Hunt (1979) with subsequent modifications by Eskridge and Thompson (1982) and Eskridge and Rao (1983). As a numerical dispersion model, ROADWAY is substantially different from gaussian line-source models like CALINE3 and CALINE4. Instead of estimating pollutant dispersion from empirically derived atmospheric dispersion curves (with relatively simple corrections for traffic-generated turbulence), ROADWAY calculates ambient and traffic-generated turbulence and velocity fields using finite difference techniques.

The vehicle wake theory incorporated into ROADWAY is based on the observation that turbulent mixing near highways is dominated by vehicle-generated turbulence. The model initially generates velocity and turbulence fields using surface layer similarity theory, based on a simple set of input meteorological conditions. The vehicle-generated fields are then determined from traffic speeds and volume, using a set of empirically derived eddy diffusion coefficients. The first version of ROADWAY relied on the General Motors Sulfate Experiment to derive these coefficients. The current version uses eddy-diffusion coefficents calculated from wind tunnel experiments (Eskridge and Thompson, 1982). This modification improved the accuracy of ROADWAY's predictions by about six percent (Rao et al., 1985). Pollutant concentrations are calculated from wind and turbulence fields to produce an output concentration profile.

As previously discussed, the ROADWAY model uses finite difference techniques to implement the vehicle wake theory. Finite difference models approximate continuous physical processes on a discrete grid. These models typically involve an iteration of computations through time, continuing until some set of conditions remain essentially unchanged. In ROADWAY, discrete grids are used for the velocity and turbulence fields. The vehicle-induced fields are then superimposed upon the ambient fields by an iterative finite difference technique until the field values reach a steady-state condition. In general, care must be taken when using numerical models; small changes in input values can sometimes cause excessive run times or result in program execution errors. Even with reasonable inputs, the costs associated with running ROADWAY are much greater than with the CALINE models (up to 1000 times more expensive). For this reason, ROADWAY must be considered a specialized, post-screening model, used to confirm or extend results from simpler highway models under particular vehicle and meteorological conditions.

The complexity and expense of ROADWAY lead to an input structure quite different from that employed by the CALINE models. The inputs required by ROADWAY are quite simple, though in general they give the model less flexibility than the gaussian highway models. The basic inputs to ROADWAY consist of road geometry, road and vehicle parameters, and meteorological conditions.

Road geometry is limited to a single road segment. ROADWAY cannot model road networks consisting of several links and intersections in a single run. Thus pollutant concentrations calculated by ROADWAY do not take into account contributions from other highways and roads, as is the case when the CALINE models are run with multiple links. The use of empirical dispersion curves by the CALINE models allows them to calculate pollutant concentrations at much greater downwind distances than ROADWAY. However contributions far from the source can be roughly approximated in ROADWAY by inputting an appropriate ambient concentration. The model simply adds this value to the concentrations calculated on the link modeled by ROADWAY.

Receptor locations are determined by the program. Receptors are placed in the X-Z plane (a vertical plane perpendicular to the road) as a function of road width; discrete receptors cannot be located by the user. This precludes the use of ROADWAY to estimate air quality impacts at points not immediately adjacent to the road (i.e. at distances greater about 100 meters).

Road and vehicle parameters input to ROADWAY include the number of vehicles per lane, vehicle speed, road orientation, lane width, number of lanes, median width, and average vehicle height and width. The computer algorithm used restricts these inputs in several important instances. ROADWAY was developed to model highways, and current input requirements call for at least four lanes of traffic and a substantial median width. Vehicle speed and traffic volumes are the major factors influencing the final dispersion results in ROADWAY. The model explicitly accounts for the changing turbulence that is created at various driving speeds and highway usages. This feature is perhaps the main practical difference between ROADWAY and the CALINE models, which use a single set of turbulence corrections independent of vehicle speeds and traffic volumes.

Meteorological inputs determine the initial turbulence and velocity fields in ROADWAY. These inputs consist of wind speed, wind direction, and temperature at two heights. The latter yields a vertical temperature gradient. It should be noted that ROADWAY does not account for horizontal wind direction variability during stable conditions (sigma-theta). This fact becomes important in near-parallel conditions, where wind meander has a large effect on pollutant concentrations, as will be seen in the CALINE analyses. Eskridge (1984) estimates that ROADWAY will overpredict concentrations when wind directions are within 30° of the link orientation.

6.0 DISPERSION MODEL SENSITIVITY ANALYSES

Sensitivity studies were performed to determine the impact of various input parameters on modeled air quality impacts. CALINE3 and CALINE4 performances are compared first under varying input conditions. The CALINE models are considered seperately from ROADWAY due to the dissimilar nature of these models. The CALINE sensitivity analyses focus on input meteorological data as it applies to a simplified Raspberry Road situation. This will allow a comparison of CALINE3 and CALINE4 results under similar conditions. Subsequently, ROADWAY impacts are studied for a smaller number of meteorological conditions.

6.1 CALINE SENSITIVITY ANALYSES

CALINE3 and CALINE4 sensitivity runs were made for various input parameters to quantify the impact of varying inputs to the models. Sensitivity runs were made for wind speed/stability, wind direction-link orientation, mixing height, and surface roughness. In order to facilitate model comparisons, Raspberry Road inputs were simplified as follows:

- only Raspberry Road was modeled (no cross-streets were considered),
- Raspberry Road was assumed to be a single at-grade link consisting of 2 twelve-foot lanes with constant traffic and emissions,
- vehicle loading of 780 vehicles/hour was assumed (estimate of peak-hour traffic as 10% of 1983 average daily traffic (DOT&PF, 1983)), and
- vehicular emissions rate of 219 grams/vehicle-mile assumed (MOBILE3 emission rate for 0° F ambient temperature, 100% cold start conditions, and vehicle speed of 35 miles/hour).

Receptors were placed at distances of 5, 10, 50, and 100 meters from the south edge of the Raspberry Road "mixing zone" near the middle of the link. All receptors were placed at ground level. Most sensitivity runs were made for wind directions both perpendicular and almost parallel to Raspberry Road. Since Raspberry Road runs east-west, the wind directions chosen were 0 deg. and 89 deg. respectively. An averaging time of 60 minutes was assumed.

<u>Wind Speed/Stability</u>

The first sensitivity analysis performed was to compare CALINE results for various combinations of wind speed and stability. Each model was run for Pasquill-Gifford stability classes D (neutral), E (slightly stable), and F (moderately stable). Wind speeds of 0.5, 1.0, 1.5, 2.0, 3.0, and 5.0 meters/sec were considered with each stability class. Note that the CALINE3 user's manual suggests that the model is not applicable (i.e., valid) for general use at wind speeds less than 1.0 meter per second. Since the objective of this report is to provide a model comparison rather than establishing general-use concentration levels, the model evaluation results for the 0.5 meter/sec wind speed scenario are presented for all models including CALINE3.

As discussed earlier, CALINE3 calculates horizontal and vertical dispersion on the basis of a single input stability class. However, CALINE4 uses the input stability class only to estimate vertical dispersion and the user is required to input the standard deviation of the horizontal wind direction (sigma-theta), which is used by the model to calculate the horizontal dispersion. Recent literature suggests that sigma-theta is relatively insensitive to stability class during stable conditions and can be best categorized as inversely proportional to wind speed (Hanna, 1983). For relatively flat terrain areas, it is estimated that sigma-theta (in deg.) is roughly equal to the arctangent of 0.5 meters/sec divided by the wind speed (in meters/sec). This relationship was used in the sensitivity analysis, giving sigma-theta equal to 45, 27, 18, 14, 9.5, and 5.7 degrees for wind speeds of 0.5, 1.0, 1.5, 2.0, 3.0, and 5.0 meters/sec, respectively. Other model inputs to both CALINE3 and CALINE4 were a surface roughness of 15 cm and a large mixing height value to simulate unlimited vertical mixing.

Results of the wind speed/stability sensitivity analysis are given in Table 6-1. Both models predict higher concentrations for near-parallel wind conditions as compared to perpendicular winds for the same wind speed and stability. This is due to the fact that only link segments in the immediate area of the receptors can affect ambient concentrations in the perpendicular wind case while most, if not all, upwind link segments can affect predicted receptor concentrations in the near-parallel wind case. Another comparison is that both models predict higher concentrations for lower wind speeds and higher (more stable) stability classes. However, CALINE4 is much less sensitive to stability class than is CALINE3 and depends strongly on the user-input wind speed. This is due to the fact that the user basically inputs the horizontal dispersion in the form of sigma-theta. Since sigma-theta was assumed to be independent of stability and strongly correlated to windspeed, the CALINE4 results show the same relationships. The slight differences between stability classes in CALINE4 for the perpendicular wind cases is due to the differences in the vertical dispersion. However, even the vertical dispersion in CALINE4 in the vicinity of the link is less sensitive to stability class than CALINE3 due to a modification in the mixing zone calculations (more emphasis is placed on road-generated turbulence). CALINE3 on the other hand is very sensitive to stability class since it is used for both the horizontal and vertical dispersion estimates. In general, CALINE3 predicts higher worst-case concentrations than CALINE4 due to the method of calculating sigma-theta. Highest concentrations for both models were predicted for near-parallel winds under stability class F and a wind speed of 0.5 meters/sec. Under these conditions, CALINE3 results are approximately 3 times higher than CALINE4.

Sigma-Theta

To quantify the effect of sigma-theta on CALINE4 results, a wind speed of 0.5 meters/sec was rerun with various combinations of stability class and sigma-theta. These CALINE4 predicted CO concentrations, given in Table 6-2, show increased concentrations for decreased sigma-theta in the near-parallel wind case and no dependence of concentrations on sigma-theta in the perpendicular wind case. The results can be explained by two CALINE4 assumptions. First, sigma-theta is a direct indication of the horizontal "plume" dimensions (a smaller sigma-theta indicates a narrower plume, which would necessarily have

TABLE 6-1

COMPARISON OF CALINE RESULTS[a] FOR VARIOUS WIND SPEED/STABILITY COMBINATIONS

Wind Direction	Stability/ Wind speed (m/s)	Model/Receptor Distance (m) CALINE3 5	10	50	100	CALINE4[b] 5	10	50	100
Near-Parallel to Road	D-0.5	11.6	8.6	2.9	1.3	8.9	6.7	2.6	1.5
	1.0	6.7	4.9	1.6	0.7	6.5	4.8	1.8	0.9
	1.5	4.7	3.5	1.1	0.5	5.2	3.8	1.3	0.6
	2.0	3.7	2.7	0.9	0.4	4.3	3.1	1.1	0.5
	3.0	2.5	1.8	0.6	0.3	3.3	2.4	0.7	0.3
	5.0	1.6	1.1	0.4	0.2	2.5	1.8	0.4	0.1
	E-0.5	16.3	12.3	4.2	1.8	9.4	7.2	3.0	1.7
	1.0	9.3	7.0	2.3	1.0	6.9	5.2	2.0	1.1
	1.5	6.6	4.9	1.6	0.7	5.6	4.1	1.5	0.8
	2.0	5.1	3.8	1.2	0.5	4.6	3.4	1.2	0.6
	3.0	3.5	2.6	0.8	0.3	3.5	2.6	0.8	0.3
	5.0	2.2	1.6	0.5	0.2	2.7	1.9	0.5	0.1
	F-0.5	28.8	22.2	6.9	2.2	10.1	7.9	3.6	2.1
	1.0	16.3	12.4	3.8	1.2	7.4	5.7	2.4	1.4
	1.5	11.4	8.7	2.6	0.8	6.0	4.6	1.9	1.0
	2.0	8.8	6.7	2.0	0.6	5.0	3.8	1.5	0.7
	3.0	6.1	4.6	1.4	0.4	3.9	2.9	1.0	0.4
	5.0	3.7	2.8	0.8	0.3	-[c]	-	-	-
Perpendicular to Road	D-0.5	7.7	6.1	2.8	1.9	8.5	6.7	3.0	2.0
	1.0	4.8	3.8	1.7	1.1	5.4	4.2	1.8	1.2
	1.5	3.5	2.8	1.2	0.8	4.0	3.1	1.3	0.9
	2.0	2.8	2.2	0.9	0.6	3.2	2.4	1.0	0.7
	3.0	2.0	1.5	0.6	0.4	2.2	1.7	0.7	0.5
	5.0	1.2	1.0	0.4	0.3	1.4	1.1	0.5	0.3
	E-0.5	8.0	6.5	3.3	2.3	8.5	6.8	3.2	2.2
	1.0	5.1	4.1	2.0	1.3	5.5	4.3	1.9	1.3
	1.5	3.7	3.0	1.4	1.0	4.0	3.1	1.4	0.9
	2.0	2.9	2.3	1.1	0.7	3.2	2.5	1.1	0.7
	3.0	2.1	1.6	0.8	0.5	2.3	1.8	0.8	0.5
	5.0	1.3	1.0	0.5	0.3	1.5	1.1	0.5	0.3
	F-0.5	8.5	7.2	4.1	3.1	8.6	6.9	3.5	2.5
	1.0	5.4	4.5	2.5	1.8	5.5	4.4	2.1	1.5
	1.5	3.9	3.3	1.8	1.3	4.1	3.2	1.5	1.1
	2.0	3.1	2.6	1.4	1.0	3.2	2.5	1.2	0.8
	3.0	2.2	1.8	1.0	0.7	2.3	1.8	0.8	0.6
	5.0	1.4	1.1	0.6	0.4	-	-	-	-

[a] Results are given in ppm of CO with no CO background added.
[b] Input sigma-theta set equal to arctangent (0.5/wind speed).
[c] - indicates CALINE4 will not consider a 5 meter/sec wind speed under F stability.

TABLE 6-2

COMPARISON OF CALINE4 RESULTS[a] FOR VARIOUS SIGMA-THETA/STABILITY COMBINATIONS[b]

Model	Stability/ Sigma-Theta (deg)	Wind Condition/Receptor Distance (m)							
		Near-Parallel Winds				Perpendicular Winds			
		5	10	50	100	5	10	50	100
CALINE3[c]	D-*[d]	10.1	7.4	2.3	1.0	7.7	6.1	2.8	1.9
	E-*	13.6	10.0	3.0	1.1	8.0	6.5	3.3	2.3
	F-*	21.4	15.7	3.7	0.8	8.5	7.2	4.1	3.1
CALINE4	D-45	8.9	6.7	2.6	1.5	8.5	6.7	3.0	2.0
	30	10.2	7.6	2.7	1.4	8.5	6.7	3.0	2.0
	20	11.5	8.5	2.7	1.3	8.5	6.7	3.0	2.0
	15	12.4	9.1	2.7	1.3	8.5	6.7	3.0	2.0
	10[e]	13.9	9.8	2.6	1.2	8.5	6.7	3.0	2.0
	5	16.5	10.9	2.4	0.7	8.5	6.7	3.0	2.0
	E-45	9.4	7.2	3.0	1.7	8.5	6.8	3.2	2.2
	30	10.8	8.2	3.1	1.7	8.5	6.8	3.2	2.2
	20	12.2	9.1	3.1	1.6	8.5	6.8	3.2	2.2
	15	13.2	9.8	3.1	1.5	8.5	6.8	3.2	2.2
	10	14.7	10.6	3.0	1.4	8.5	6.8	3.2	2.2
	5.6[e]	16.9	11.4	2.7	0.9	8.5	6.8	3.2	2.2
	5	17.4	11.6	2.7	0.8	8.5	6.8	3.2	2.2
	F-45	10.1	7.9	3.6	2.1	8.6	6.9	3.5	2.5
	30	11.7	9.0	3.7	2.1	8.6	6.9	3.5	2.5
	20	13.1	10.0	3.7	2.0	8.6	6.9	3.5	2.5
	15	14.0	10.5	3.5	1.9	8.6	6.9	3.5	2.5
	10	15.4	11.1	3.3	1.6	8.6	6.9	3.5	2.5
	5	17.8	11.9	2.8	0.8	8.6	6.9	3.5	2.5
	1.9[e]	23.7	14.9	1.5	0.0	8.6	6.9	3.5	2.5

[a] Results are given in ppm of CO with no background CO added.
[b] Windspeed set equal to 0.5 meters/sec.
[c] CALINE3 results from Table 6-1 given for comparison only.
[d] * indicates CALINE3 calculates horizontal dispersion from input stability class and therefore will not accept an input value for sigma-theta.
[e] Sigma-theta historically associated with given stability class from NRC Safety Guide 23 (February, 1972).

higher concentrations). Second, CALINE4 assumes a link to be composed of a series of finite link elements. In the near-parallel wind case, plumes formed by the atmospheric transport and dispersion of emissions from upwind link segments will generally overlap. If the plumes for each link segment are made narrower (smaller sigma-theta), then the total ambient concentration is increased. In the perpendicular wind case, enough link elements are used by the model to closely approximate the link itself as a line source. Concentrations downwind of an infinite line source become independent of horizontal dispersion as the wind flow becomes perpendicular to the line source modeled because it is assumed that lateral dispersion from one segment of the line is compensated by dispersion in the opposite direction from adjacent segments. It is interesting to note that, since concentrations during perpendicular wind conditions are insensitive to horizontal dispersion (sigma-theta), CALINE3 and CALINE4 calculate similar concentrations under these conditions (see wind speed/stability analysis in Table 6-1). For a wind speed of 0.5 meters/sec, the CALINE4 sigma-theta values which most nearly duplicate the CALINE3 near-parallel wind condition results are 30°, 15°, and 1.9° for stabilities D, E, and F, respectively.

Wind Direction

After determining the worst-case combination of stability and wind speed for each model, the models were rerun for a variety of wind directions to test the model sensitivity to link-wind angles. Each model was run for F stability and a wind speed of 0.5 meters/sec. All other inputs, including sigma-theta, were identical to those used in the wind speed/stability analysis. The results, given in Table 6-3, show that the models are relatively insensitive to small changes in wind direction for generally perpendicular winds and that concentrations generally increase as the wind direction becomes more parallel to the link (i.e., near 90°). The maximum concentration is generally close to, but not exactly, a parallel wind. This maximum concentration is greater in CALINE3 as compared to CALINE4 due to the use of a large sigma-theta (45°) in CALINE4 to characterize the horizontal dispersion under the assumed wind speed (0.5 meters/sec).

This same sensitivity analysis was performed with CALINE4 under the same conditions except that sigma-theta was input as 1.9 deg. These results, also

TABLE 6-3

COMPARISON OF CALINE RESULTS[a] FOR VARIOUS WIND DIRECTIONS DURING F STABILITY AND 0.5 M/S WIND SPEED

Wind Direction[b] (deg)	Model/Receptor Distance (m)											
	CALINE3				CALINE4 (45°)[c]				CALINE4 (1.9°)[d]			
	5	10	50	100	5	10	50	100	5	10	50	100
0	8.5	7.2	4.1	3.1	8.6	6.9	3.5	2.5	8.6	6.9	3.5	2.5
1	8.5	7.2	4.1	3.1	8.6	6.9	3.5	2.5	8.6	6.9	3.5	2.5
2	8.5	7.2	4.1	3.1	8.6	6.9	3.5	2.5	8.6	6.9	3.5	2.5
4	8.4	7.1	4.1	3.1	8.6	6.8	3.5	2.5	8.6	6.9	3.5	2.5
6	8.3	7.1	4.2	3.1	8.6	6.8	3.5	2.5	8.6	6.9	3.5	2.5
8	8.2	7.1	4.2	3.1	8.6	6.8	3.5	2.5	8.6	6.9	3.5	2.5
10	8.2	7.1	4.2	3.1	8.6	6.8	3.5	2.5	8.7	6.9	3.5	2.5
20	8.4	7.5	4.0	3.2	8.7	7.1	3.6	2.6	8.9	7.1	3.6	2.6
30	9.3	8.1	4.7	3.3	9.1	7.5	3.7	2.8	9.2	7.4	3.7	2.7
40	10.0	8.1	4.3	3.6	9.8	8.0	4.1	3.1	9.8	7.9	3.9	2.9
50	11.1	9.2	5.1	3.8	10.6	8.7	4.6	3.5	10.4	8.4	4.2	3.1
60	12.6	10.5	6.2	4.4	11.0	9.3	4.8	3.5	11.9	9.5	4.6	3.5
70	15.6	13.2	7.5	5.6	11.2	9.4	4.8	3.2	13.9	10.6	5.4	4.1
80	23.9	19.8	10.9	7.8	10.9	8.7	4.3	2.7	17.2	13.3	7.2	5.7
81	25.3	20.9	11.4	7.9	10.9	8.6	4.2	2.7	17.7	13.8	7.5	5.9
82	26.9	22.2	11.8	7.9	10.8	8.6	4.2	2.6	18.3	14.3	7.9	6.3
83	28.5	23.5	12.1	7.6	10.8	8.5	4.1	2.6	19.2	15.0	8.3	6.5
84	30.1	24.7	12.2	7.0	10.7	8.4	4.0	2.5	20.2	15.8	9.0	6.5
85	31.4	25.6	11.9	6.2	10.6	8.3	3.9	2.4	21.6	17.1	9.5	5.4
86	32.2	26.0	11.2	5.2	10.5	8.2	3.8	2.4	23.9	19.3	9.6	3.3
87	32.1	25.6	10.0	4.2	10.3	8.1	3.8	2.3	27.6	22.0	7.8	1.3
88	31.0	24.4	8.6	3.1	10.2	8.0	3.7	2.2	29.9	21.5	4.5	0.3
89	28.8	22.2	6.9	2.2	10.1	7.9	3.6	2.1	23.7	14.9	1.5	0.0
90	25.5	19.2	5.2	1.4	9.9	7.7	3.5	2.1	12.0	7.0	0.3	0.0

[a] Results are given in ppm of CO with no background CO added.

[b] Wind direction given such that 0° denotes a wind direction perpendicular to link, 90° denotes a parallel wind.

[c] Input sigma-theta set equal to arctangent (0.5/wind speed), or 45°.

[d] [illegible]

given in Table 6-3 show that CALINE4 gives comparable results to CALINE3 when the sigma-theta used in CALINE4 is comparable to horizontal dispersion assumed from the stability class by CALINE3.

Mixing Height

Mixing height, also referred to as the planetary boundary layer depth, or the depth of the well mixed layer, is usually defined as the height above the surface to which mechanical and convective produced turbulence extends. During neutral and unstable conditions, the mixing height is often capped by a temperature inversion which effectively acts as a lid to trap pollutants within the well mixed layer. In order to account for the effects of plume trapping during these conditions, most dispersion models include an algorithm that incorporates plume reflections between the surface and the inversion.

During nocturnal periods, radiative cooling in the absence of strong winds can result in a strong surface based temperature inversion. Mixing during these extremely stable periods is retarded and turbulence produced mechanically at the surface is often restricted to less than 100 meters. Bowling (no date) has suggested the use of very low mixing heights (approximately 10 meters) during nighttime stable conditions in high latitudes. Remsberg et. al. (1979) used a mixing depth of 25 meters for a study in Virginia during nighttime inversion conditions.

The mixing height values used in the CALINE series are intended for the simulations of plume trapping during unstable or neutral conditions, and the corresponding algorithms are not appropriate for stable conditions. Limited mixing during stable periods is inherently included in the formulation of the stable vertical dispersion curves and, as such, most conventional Gaussian models ignore mixing heights input during these conditions. However, CALINE models will incorrectly treat a low mixing height as a rigid lid to dispersion when input during stable conditions. It is suggested that an arbitrary large value of mixing height be used to bypass these algorithms during stable periods.

In order to demonstrate the consequences of using a low mixing height during stable conditions, the CALINE3 and CALINE4 models were applied to stable conditions with varying rigid lids. In all other aspects, the input data were the same as was used in the previous sensitivity analysis.

In the sensitivity analysis shown in Table 6-4, the modeled CO concentrations are relatively insensitive to mixing height for heights greater than about 50 meters. This is due to the very limited amount of vertical dispersion that can take place under F stability within the microscale area being modeled. This is most apparent in the perpendicular wind case where only link elements in the immediate receptor vicinity contribute to predicted concentrations.

Under extremely low mixing heights (mixing height $\leq$ 25 meters), CALINE3 is more sensitive to mixing height than CALINE4 for near-parallel wind conditions. This is due to the contribution from distant link elements which undergo less horizontal dispersion in CALINE3 (stability dependent) than CALINE4 (sigma-theta dependent). It should be emphasized that the low mixing heights were used for demonstration purposes only and should not normally be applied during stable conditions.

Surface Roughness

Mechanical turbulence is generated by any airflow over a non-smooth surface. As the mechanical turbulence increases, predicted CO concentrations will decrease since the amount of horizontal and vertical dispersion is enhanced. The amount of turbulence generated by a rough surface is calculated by the models from the input surface roughness length for the area being studied. The surface roughness length is typically 100 to 300 cm in forest and residential/urban areas, 10 to 100 cm in open rural/agricultural areas, and <1 cm in grassy or paved areas. This final sensitivity analysis was performed with the same input conditions as the wind speed/stability analysis under F stability and a 0.5 m/s wind speed. In the analysis shown in Table 6-5, both models are less sensitive to surface roughness as receptor distance increases. Near the modeled link, CALINE3 is more sensitive to surface roughness than CALINE4 due to the modification made in calculating mixing zone turbulence. Surface roughness primarily affects the horizontal and vertical dispersion, whose effects are minimized in the CALINE4 mixing zone model. This is most apparent in the CALINE4 results on Table 6-1 for perpendicular wind flows, where ambient concentrations are caused only by nearby link elements.

TABLE 6-4

COMPARISON OF CALINE RESULTS[a] FOR VARIOUS MIXING HEIGHTS DURING F STABILITY AND 0.5 M/S WIND SPEED

Wind Condition	Mixing Height (m)	Model/Receptor Distance (m)							
		CALINE3				CALINE4[b]			
		5	10	50	100	5	10	50	100
Near-Parallel	1000	28.8	22.2	6.9	2.2	10.1	7.9	3.6	2.1
	500	28.8	22.2	6.9	2.2	10.1	7.9	3.6	2.1
	250	28.8	22.2	6.9	2.2	10.1	7.9	3.6	2.1
	100	28.8	22.2	6.9	2.2	10.1	7.9	3.6	2.1
	50	29.1	22.5	7.2	2.3	10.1	7.9	3.6	2.2
	25	36.3	29.6	11.7	4.1	11.2	9.0	4.6	3.1
	10	80.0	68.9	29.2	10.3	18.8	16.4	10.6	7.6
	5	159.8	137.9	58.4	20.6	34.8	31.8	21.2	15.1
Perpendicular	1000	8.5	7.2	4.1	3.1	8.6	6.9	3.5	2.5
	500	8.5	7.2	4.1	3.1	8.6	6.9	3.5	2.5
	250	8.5	7.2	4.1	3.1	8.6	6.9	3.5	2.5
	100	8.5	7.2	4.1	3.1	8.6	6.9	3.5	2.5
	50	8.5	7.2	4.1	3.1	8.6	6.9	3.5	2.5
	25	8.5	7.2	4.1	3.1	8.6	6.9	3.5	2.5
	10	8.5	7.3	5.2	5.2	8.6	6.9	4.5	4.4
	5	10.5	10.3	10.3	10.3	9.5	8.9	8.8	8.8

[a] Results are given in ppm of CO with no background CO added.
[b] Input sigma-theta set equal to arctangent (0.5/wind speed).

TABLE 6-5

COMPARISON OF CALINE RESULTS[a] FOR VARIOUS SURFACE ROUGHNESS DURING F STABILITY AND 0.5 M/S WIND SPEED

Wind Condition	Surface Roughness (cm)	Model/Receptor Distance (m)							
		CALINE3				CALINE4[b]			
		5	10	50	100	5	10	50	100
Near-Parallel	3	33.1	25.3	7.2	2.5	10.4	8.2	3.8	2.3
	15	28.8	22.2	6.9	2.5	10.1	7.9	3.6	2.1
	30	27.2	21.0	6.7	2.4	10.0	7.8	3.5	2.1
	90	24.8	19.2	6.5	2.4	9.8	7.6	3.4	2.0
	150	23.7	18.5	6.4	2.3	9.7	7.5	3.3	2.0
	250	22.7	17.7	6.2	2.2	9.6	7.4	3.2	1.9
	350	22.1	17.3	6.1	1.9	9.5	7.3	3.2	1.9
Perpendicular	3	8.6	7.3	4.3	3.2	8.7	7.0	3.6	2.6
	15	8.5	7.2	4.1	3.1	8.6	6.9	3.5	2.5
	30	8.5	7.2	4.1	3.0	8.6	6.8	3.4	2.5
	90	8.4	7.1	4.0	3.0	8.5	6.8	3.3	2.4
	150	8.4	7.1	3.9	2.9	8.5	6.8	3.3	2.4
	250	8.4	7.1	3.9	2.9	8.5	6.7	3.3	2.3
	350	8.4	7.0	3.9	2.9	8.5	6.7	3.2	2.3

[a] Results are given in ppm of CO with no background CO added.
[b] Input sigma-theta set equal to arctangent (0.5/wind speed).

6.2 ROADWAY SENSITIVITY ANALYSES

ROADWAY sensitivity analyses were performed for a smaller number of cases than the CALINE models for two reasons. First, the model is quite expensive and, second, the ROADWAY model is not truly representative of Raspberry Road due to model input restrictions.

ROADWAY analyses were performed for two wind speeds (1.0 meters/sec and 5.0 meters/sec) under three different wind directions (perpendicular to Raspberry Road and 2 near-parallel wind conditions - 5° and 10° from parallel). An input surface roughness of 15 cm was used, similar to the CALINE sensitivity analyses. A vertical temperature gradient of 0.035 °C/meter was input to the model to simulate F stability with a near-ground-level ambient temperature of 0°F. Vehicle speeds were assumed to be 35 mph.

ROADWAY is only capable of modeling roads with 4 or more lanes with a median divider. Therefore, some simplifying assumptions were made to simulate the Raspberry Road CALINE analyses. The first analysis, shown in Table 6-6, used 4 lanes of traffic and an hourly vehicle flow of 390 vehicles/hour/lane. This value, twice the total traffic flow used in the CALINE analyses, was chosen so that each of the four traffic lanes in ROADWAY had identical traffic volumes to each of the two lanes used in CALINE3 and CALINE4, giving approximately the same area-averaged vehicle generated turbulence in ROADWAY. Vehicular emissions are halved from the CALINE analyses so that total link emissions are identical. A median of 3 meters was selected because smaller median widths caused excessive ROADWAY run times.

As shown in Table 6-6, ground-level concentrations decrease with increasing distance from Raspberry Road and increase as the wind flow becomes more parallel to Raspberry Road. These relationships are very similar to the CALINE results. It should be noted that the model chooses its own receptor locations so not all runs have results at the same locations and it was impossible to match the CALINE distances exactly. Receptor distances shown on Table 6-6 designate the distance from a point 3 meters off the edge of the road (the edge of the CALINE "mixing zone"). The MAX concentration for each run is the maximum ROADWAY concentration and normally occurs within the road itself or directly adjacent to it.

TABLE 6-6

ROADWAY RESULTS[a] FOR 4-LANE HIGHWAY
WITH 1560 VEHICLES/HOUR

Approximate Receptor Distance (m)	Wind speed/Wind-Road Angle[b]					
	1.0 m/s wind speed			5.0 m/s wind speed		
	90°	10°	5°	90°	10°	5°
-MAX-[c]	16.5	35.3	47.3	7.5	11.0	12.7
9	11.4	27.2	34.7	5.9	5.5	6.2
24	10.0	19.5	23.6	3.8	3.4	3.8
44	8.1	15.0	16.9	2.8	2.5	2.8
69	7.3	-[d]	-	1.8	-	-

[a] Results are given in ppm of CO with no CO background added.
[b] Wind-road angle given such that 90° equals a wind perpendicular to Raspberry Road, while 10° and 5° represent near-parallel wind flow conditions.
[c] MAXIMUM concentrations occurs within or directly adjacent to road itself.
[d] Receptor distances are determined by ROADWAY itself, so some receptor distances are not available for all conditions (denoted by -).

The ROADWAY results for a 1 meter/sec wind speed are greater than the corresponding CALINE3 and CALINE4 results. For example, at 9 and 44 meters, the ROADWAY concentrations under perpendicular conditions are 11.4 and 8.1 ppm. The corresponding CALINE results for F stability and 1 meter/sec at 10 and 50 meters are 5.4 and 2.5 ppm for CALINE3 and 5.5 and 2.1 ppm for CALINE4. For near-parallel wind conditions (5° from parallel for ROADWAY, 1° from parallel for CALINE3 and CALINE4), ROADWAY calculates concentrations of 34.7 and 16.9 ppm while CALINE3 predicts 16.3 and 3.8 ppm and CALINE4 predicts 7.4 and 2.4 ppm.

The fact that ROADWAY concentrations were greater than CALINE3 or CALINE4 concentrations suggests that the CALINE models may overestimate initial vehicle-induced dispersion. This observation comes by recalling that vehicle-induced dispersion in CALINE3 is not dependent on traffic volume and speeds. On the other hand, ROADWAY's treatment of vehicle-induced dispersion incorporates these effects based on theoretical principles. Therefore, the ROADWAY treatment is likely to be more accurate.

In order to examine the sensitivity of vehicle-induced dispersion on concentrations, a second set of ROADWAY runs were made with total traffic flow identical to the CALINE runs (half of the traffic in the first set of ROADWAY runs). Vehicular emissions were the same as the CALINE runs, so total link emissions were identical. ROADWAY concentrations, under those conditions, are shown in Table 6-7. In general, ROADWAY predictions increased by approximately 20%. These ROADWAY results suggest that, at the speeds (35 mph) and traffic volumes (approximately 1000 vehicles/hour) representative of Raspberry Road, initial vehicle-induced dispersion calculations may be sensitive to traffic volumes. They also imply that the CALINE assumptions based on GM data may not be appropriate under these conditions.

6.3 DISCUSSION OF SENSITIVITY ANALYSES CONCLUSIONS

Both CALINE models were tested for a variety of meteorological conditions. CALINE3 is relatively sensitive to wind speed, stability, wind-link orientations, and mixing height. CALINE4, on the other hand, is extremely sensitive to the method chosen for calculating an input sigma-theta (especially

TABLE 6-7

ROADWAY CONCENTRATIONS[a] FOR 4-LANE HIGHWAY
WITH 780 VEHICLES/HOUR

Approximate Receptor Distance (m)	Wind speed/Wind-Road Angle[b]					
	1.0 m/s wind speed			5.0 m/s wind speed		
	90°	10°	5°	90°	10°	5°
-MAX-[c]	20.3	43.5	57.8	8.6	12.4	14.2
2.5	-[d]	39.0	52.6	-	-	10.6
9	14.2	-	-	4.2	5.8	-
12.5	-	32.6	41.3	-	-	6.4
24	12.6	-	-	2.9	3.4	-
27.5	-	22.8	26.9	-	-	3.9
44.	9.8	-	-	1.9	2.5	-
47.5	-	17.0	18.7	-	-	2.8
69	8.5	-	-	1.4	-	-

[a] Results are given in ppm of CO with no CO background added.
[b] Wind-road angle given such that 90° equals a wind perpendicular to Raspberry road, while 10° and 5° represent near-parallel wind flow conditions.
[c] MAXIMUM concentrations occurs within or directly adjacent to road itself.
[d] Receptor distances are determined by ROADWAY itself, so some receptor distances are not available (denoted by -).

during near-parallel wind conditions). Based on current literature, a sigma-theta was assumed based on the wind speed to be modeled. Under this assumption, CALINE4 is very sensitive to the input wind speed and somewhat sensitive to mixing height, but much less so than is CALINE3. Also, with the sigma-theta assumptions, CALINE4 is much less sensitive to the wind-road angle under near-parallel conditions.

Other model inputs not studied which affect CALINE results are vehicle source strengths, highway width and length, averaging time (CALINE3 only), source type, and median width. For a discussion of model sensitivities to these input parameters as well as those already discussed, the reader is referred to the CALINE user's manuals (Benson, 1979 and 1984).

The most significant difference between CALINE3 and CALINE4 is the use of a split-stability approach in CALINE4, which calculates horizontal dispersion as a function of sigma-theta instead of the input stability class. This approach has been advocated by Dr. Bowling (1985), who has documented cases in Alaska of extreme variation in horizontal wind direction during stable, low wind speed conditions. This phenomenon has been noted by many authors. Draxler (1979) states that, in all field dispersion studies during stable, low wind speed conditions, observed concentrations were lower than gaussian model calculations (with horizontal and vertical dispersion taken from Pasquill-Gifford dispersion curves). Draxler goes on to state that when the gaussian model calculations accounted for the short-term wind direction fluctuations, concentration predictions were much closer to the observed values. Kristensen et al (1981) suggests that if plume meander is not accounted for, estimates of mean concentrations can easily be too high by a factor of 4 to 6.

The American Meteorological Society conducted a workshop of Stability Classification Schemes and Sigma Curves in June, 1977 (Hanna, et. al., 1977). One of the panel recommendations was that horizontal dispersion in gaussian models be calculated from input values of sigma-theta and the sigma-theta values should be estimated/measured as 1-hour averages. For these reasons, CALINE4, which does model horizontal dispersion as a function of sigma-theta, should be considered superior to CALINE3.

If sigma-theta is the preferred method for calculating horizontal dispersion, then sigma-theta values must be determined for input to CALINE4. The preferred method for obtaining input sigma-theta values would be to do a climatological study of measured sigma-theta values during stable, winter conditions. Unfortunately, no known sigma-theta data are available for the Anchorage area.

Hanna (1983) recently studied the subject of plume meander during stable conditions. Hanna concluded, based on field measurements, that the quantity wind speed x tangent(sigma-theta) is relatively constant during stable conditions, although some variation is noted for light wind speed cases. The value of this quantity ranged from 0.3 meters/sec (at Porton, England), to 0.5 meters/sec (offshore of California coast and Snake River Plateau, Idaho), to 1.0 meters/second (complex terrain in California). The value of this quantity is generally site specific and also depends strongly on the averaging time. A value of 0.5 meters/second was chosen for the analyses presented in this report. As more data measurement programs in the Anchorage area or general research studies are conducted, the relationship between sigma-theta and other meteorological parameters during stable conditions may be more completely understood.

ROADWAY results suggest that the CALINE models may overestimate initial vehicle-induced dispersion and therefore underestimate pollutant impacts for streets with moderate traffic volumes (about 1000 vehicles/hour). However, this inference is based on a limited set of modeling conditions and generally ignores possible errors introduced due to the basic computational differences between the CALINE models and ROADWAY. Also, ROADWAY is not strictly applicable to the Raspberry Road case being considered. Until more field data (like the GM data base) are obtained for traffic volumes similar to Raspberry Road, it is difficult to generalize about CALINE mixing zone calculations based on ROADWAY results. As with any model, the user should be aware of restrictions in applicability of the CALINE models.

Due to the expense and limited applicability of ROADWAY, it probably will not become a widely used model. However, ROADWAY may be useful to study localized impacts, which are predicted by CALINE4 to be of potential concern. Like CALINE3, ROADWAY estimates during stable near-parallel wind conditions should be viewed with a degree of caution since wind direction variability is not considered by the model.

7.0 FINAL DISPERSION MODELING ANALYSES

Since the simplified case applicable to Raspberry Road was modeled in the sensitivity studies, it is tempting to compare predicted concentrations to maximum concentrations measured at the Sand Lake monitoring site. Since the modeled concentrations were based on Raspberry Road traffic only, it is important to estimate "background" concentrations during high CO episodes due to CO emissions from other more distant sources such as roads, highways, and parking areas.

Background CO concentrations are discussed in the following section. Special emphasis has been placed on 2 extensive CO monitoring studies - one conducted in San Jose, California and the other in Anchorage, Alaska. Conclusions from the Anchorage study are used to estimate the best manner in which the models should determine worst-case concentrations at the Sand Lake Monitor.

Two sets of modeling runs were then performed with CALINE3 and CALINE4. The areas considered in these applications are shown in Figure 7-1. The first set included most major Anchorage Bowl transportation corridors north of International Airport Road and Tudor Road. The emphasis for this first modeling study was to determine model performance in calculating "background" CO levels due to distant sources under worst-case dispersion conditions.

In the second set of analyses, local CO sources are modeled -- including Raspberry Road -- under various meteorological conditions. Recent traffic volume information was included in this study based on the 1983 Anchorage

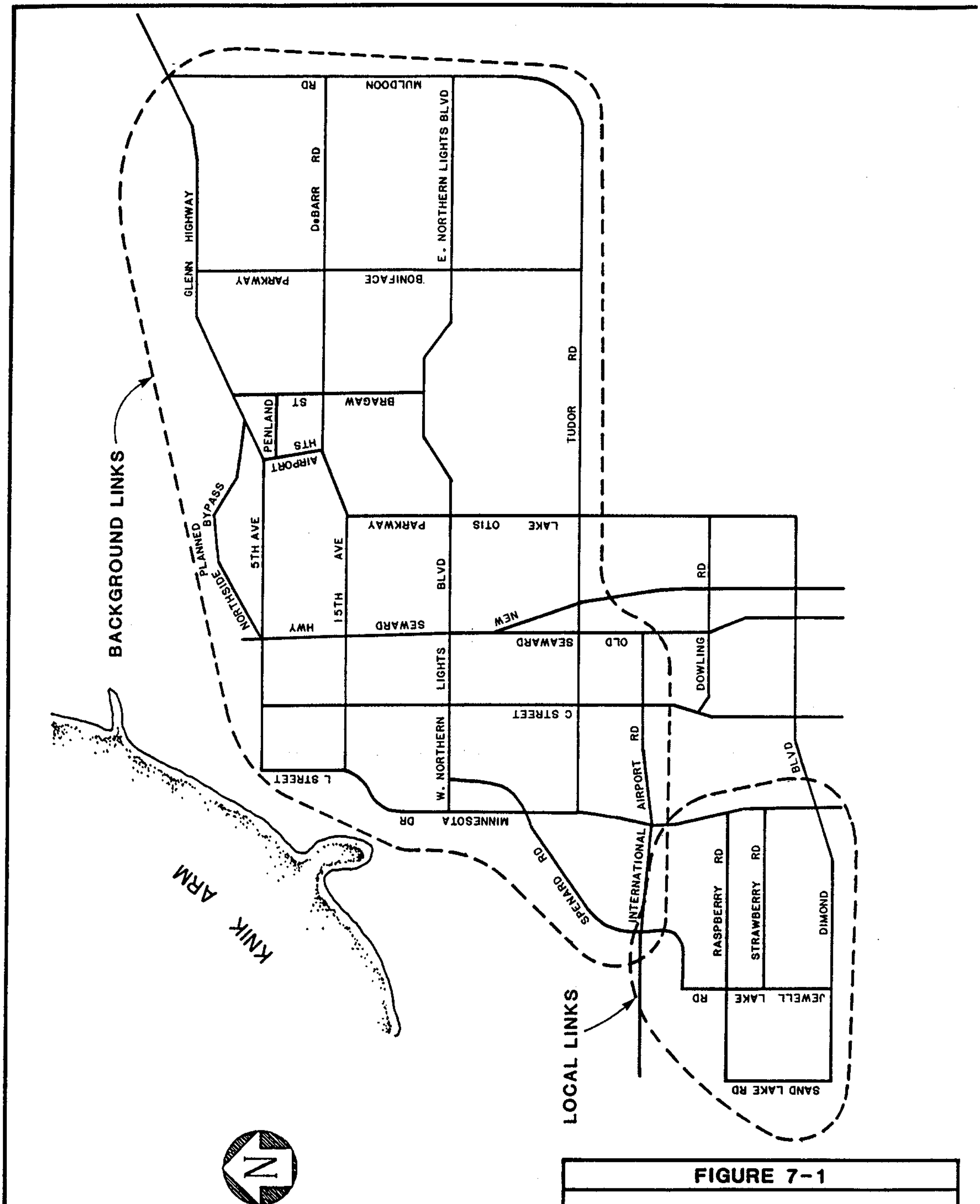

FIGURE 7-1

LOCATION OF LOCAL AND BACKGROUND LINKS

Dames & Moore

average weekday daily traffic (AWDT) estimates. The emphasis of this modeling is to determine model performance in modeling local CO contributions to concentrations measured at the Sand Lake monitor.

7.1 BACKGROUND CO STUDIES

An extensive study of CO concentrations in San Jose, California has been conducted by the Bay Area Air Quality Management District (BAAQMD) (Duker et. al., 1984). Highest CO concentrtions were observed to occur during cold, clear, windless nights. Since CO concentrations were measured at permanent sites near streets with AWDT volumes of approximately 10,000 vehicles/day, efforts were initiated to try to measure CO concentrations at localized "hot spots" (for example, near intersections with AWDT volume of 80,000). Surprisingly, measured CO hot-spot concentrations were not significantly greater than measured CO concentrations at the permanent sites and only slightly higher than CO concentrations measured at "cold spots" (locations with no local sources of CO). The researchers generally concluded that, in winter, during night-time, stable conditions with limited dispersion, CO concentrations were much more uniform than previously believed. During 8-hour CO violations, background CO comprised approximately 75% or more of the total measured CO concentration at hot-spot locations. This percentage was relatively insensitive to local traffic volumes or averaging time. This large background CO profile has been described as a CO "cloud" with a horizontal extent of several miles.

It is important to note that the conclusions of the San Jose study were applied only to high CO episodes under night-time, stagnation (low wind speed) conditions. The authors stated they believe that, during periods of relatively good dispersion, CO concentrations are probably similar to those based on historical assumptions -- relatively low background CO concentrations with localized hot-spots due to traffic-related emissions.

Implications of this study for the Anchorage area are important since many CO control strategies are based on reducing emissions at localized hot-spots (e.g., improved traffic flow). Also, CALINE-like models, such as those studied in this report, may not effectively treat these extremely high CO episodes as well as box-type models (for example, roll-back models).

A CO study was conducted in the Anchorage area during the 1982-83 winter season (Schweiss, 1983). The field measurement program was designed to relate CO measurements at Anchorage's four permanent monitoring stations to potential CO concentrations at "hot-spots". The CO "cloud" does not appear to be a significant factor in high Anchorage CO concentrations based on study conclusions. First, the 1982-83 Anchorage study showed consistently higher hot-spot CO concentrations than at the permanent sites. Second, the most severe CO impacts occurred within areas of high local traffic volumes. Third, there was typically a wide variability in CO concentrations at corresponding times. Finally, extreme winter CO concentrations in Anchorage during stable conditions sometimes occur during good dispersion conditions (higher wind speeds) (DOT&PF, 1982). These findings are opposite from the San Jose study conclusions where high CO concentrations were related primarily to stagnant meteorological conditions and not to traffic "hot-spots".

Although background contributions to local hot-spots may not be as significant in Anchorage as in San Jose study, this is not to say that the background contributions are negligible everywhere. The 1982-83 Anchorage study found that the Garden Street and Sand Lake monitors generally characterized CO concentrations in adjoining and nearby neighborhoods. At Garden Street, there were no significant local CO sources near the monitoring site. Since the Sand Lake monitoring site was found to be representative of nearby neighborhood CO levels, Raspberry Road may not be a significant local CO source, even under worst-case dispersion conditions.

Based on the 1982-83 Anchorage CO study, it is assumed that larger and more distant CO sources, as opposed to local links, are the major contributors to Sand Lake CO measurements. The maximum 1-hour CO concentration measured at the Sand Lake monitor was 23 ppm during the 1980-81, 1981-82, and 1982-83 winter seasons. Since air quality standards are referenced to maximum concentrations (i.e., standards are not to be exceeded more than once per year), the role of any regulatory model is to be able to estimate the worst-case concentration. The CALINE models were thus judged against the following:

- Ability of the models to properly determine contributions to maximum modeled concentrations. The models should show that non-local CO sources (e.g., the Anchorage bowl) determine the maximum modeled concentration at the Sand Lake monitoring site.

- Maximum modeled concentrations from local CO sources (especially Raspberry Road) should be significantly less than maximum modeled concentrations due to non-local sources.

- Finally, the ability of the models to predict a worst-case CO concentration near 23 ppm.

7.2 BACKGROUND CO SOURCE MODELING ANALYSES

Dames & Moore recently performed a transportation modeling study for the proposed Knik-Arm crossing (U.S. Department of Transportation and DOT&PF, 1984). Using traffic volumes, vehicle speeds, and road geometry information from this study, CALINE3 and CALINE4 were run with AKMOBILE2.5 emissions estimates for 20°F and 100% cold start. The Knik-Arm information was based on 1982 traffic estimates. Information for major roads and streets were available for the Anchorage bowl area bounded by Muldoon Road, Glenn Highway, Spenard Drive, International Airport Road, and Tudor Road. The links included in the background modeling are shown in Figure 7-1. The AKMOBILE2.5 1983 emissions (as a function of vehicle speed) were obtained from Section 3.

Both CALINE models were run with a surface roughness of 100 cm (typical value for residential area), 20°F ambient temperature, and a mixing height of 1000 meters (no mixing height restrictions to vertical dispersion). An averaging time of 60 minutes was assumed for CALINE3. CALINE3 was run for D, E, and F stabilities with a 1.0 meter/sec wind speed. CALINE4 was run with F stability and wind speeds of 0.5, 1.0, and 2.0 meters/sec. Input CALINE4 sigma-theta values were calculated from wind speed using the same algorithm described in the sensitivity analysis. In order to find the worst-case wind directions, runs were made with wind directions input in 10° increments. On the basis of these results, runs were subsequently made with 1° increments to determine the worst-case wind direction. Final CALINE results for AKMOBILE2.5 emissions estimates are shown in Table 7-1.

Since the model runs were made with AKMOBILE2.5 emissions estimates and varying vehicle speeds, some simplifying assumptions were necessary for modifying the results for emissions estimates from MOBILE3. In the earlier Dames & Moore emissions report, the average ratio of MOBILE3 emissions to AKMOBILE2.5 emissions was 1.45 for vehicle speeds of 10 to 55 mph under 20°F ambient temperature and 100% cold start assumptions. This is nearly identical to the MOBILE3 to AKMOBILE2.5 ratio of 1.46 at 35 mph. Therefore, this ratio (1.46) was used for calculating dispersion model concentrations emissions estimates at 20°F and a similarly calculated ratio of 2.23 was used for calculating concentrations for MOBILE3 emissions estimates at 0°F. These concentration estimates are also shown in Table 7-1.

For CALINE3, F stability, 1 meter/sec wind speed concentration estimates range from 7.4 to 16.5 ppm depending on the emissions estimate used. For CALINE4, F stability, 1 meter/sec wind speed concentration estimates range from 6.7 to 14.9 ppm. If the maximum CO Sand Lake concentration of 23 ppm is composed primarily of background, then AKMOBILE2.5 and MOBILE3 emissions estimates at 20°F may significantly underpredict worst-case CO concentrations when used with CALINE3 or CALINE4 under situations of large link-receptor distances. For the situation chosen, large MOBILE3 emissions estimates at 0°F combined with CALINE4 dispersion estimates under F stability and a wind speed of 0.5 meters/second appear to best model worst-case Sand Lake CO background concentrations. Additional verification runs at other sites are needed before any conclusions can be drawn.

7.3 LOCAL CO SOURCE MODELING STUDIES

The sensitivity analyses considered a simplified Raspberry Road situation (Raspberry Road as a single link) with MOBILE3 emission estimates for 0°F and 100% cold start. In this final analysis, Raspberry Road (from Sand Lake Road to Minnesota Drive) is divided into 5 separate links to more accurately reflect

TABLE 7-1

BACKGROUND MODELING RESULTS
FOR THE SAND LAKE MONITORING SITE

Dispersion Model/Conditions	Worst-case Wind Direction	Emissions Model		
		AKMOBILE2.5 @ 20°F	MOBILE3 @ 20°F[a]	MOBILE3 @ 0°F[b]
CALINE3[c] - Stability D	39	1.7	2.5	3.8
Stability E	41	3.4	5.0	7.6
Stability F	41	7.4	10.8	16.5
CALINE4[d] - 0.5 m/s	41	9.3	13.6	20.7
1.0 m/s	42-45	6.7	9.8	14.9
2.0 m/s	44	4.2	6.1	9.4

[a] AKMOBILE2.5 concentrations multiplied by 1.46.
[b] AKMOBILE2.5 concentrations multiplied by 2.23.
[c] Wind speed of 1.0 meter/second.
[d] F stability and sigma-theta set equal to arctangent (0.5/wind speed).

actual traffic volumes. Also, local roads not considered in the earlier background analysis were included here for completeness (see Figure 7-1). These roads were:

- ° Frontage Road (North Access Road to International Airport Road)
- ° Sand Lake Road (Frontage Road to Dimond Blvd.)
- ° Dimond Blvd. (Sand Lake Road to Minnesota Drive)
- ° Minnesota Drive (Dimond Blvd. to International Airport Road)
- ° Jewel Lake Road (Dimond Blvd. to Frontage Road)
- ° Strawberry Road (east of Jewel Lake Road)

Peak 1-hour hour traffic volumes were assumed to be 10% of the 1983 AWDT. Each road was divided into links to accurately reflect local traffic volumes. Emissions estimates were based on AKMOBILE2.5 for vehicle speeds of 35 mph and 100% cold start asumptions (Dames & Moore, 1985). Since all roads were assumed to have identical vehicle speeds, CALINE dispersion model estimates using emissions estimates from MOBILE3 were easily calculated.

All of these roads were assumed to be at-grade 2-lane roads with 12 foot lanes. Vehicle speeds were assumed to be 35 mph. Other CALINE inputs were identical to the background modeling runs. A receptor was placed 10 meters south of the Raspberry Road mixing zone (55 feet from the center of Raspberry Road) to represent the Sand Lake monitoring site.

Results of the local source modeling analyses are shown in Table 7-2. Results of this analysis are given for two wind directions. First, modeling estimates are shown for the worst-case wind direction for each dispersion/emissions model combination. Like the background analyses, worst-case wind directions were determined to the nearest 1° in a step-wise fashion. Since only local sources were modeled, these concentrations are not meant to reflect maximum Sand Lake measurements.

As shown in Table 7-2, CALINE3 calculates very large concentrations during near-parallel wind conditions. CALINE4 calculated much smaller local-source concentrations than CALINE3. As discussed in the sensitivity analyses, CALINE3

TABLE 7-2

LOCAL SOURCE MODELING RESULTS
FOR THE SAND LAKE MONITORING SITE

Dispersion Model/Conditions	Worst-case Wind Direction	Emissions Model: AKMOBILE2.5 @ 20°F	Emissions Model: MOBILE3 @ 20°F	Emissions Model: MOBILE3 @ 0°F
Worst-Case Wind Direction				
CALINE3[a] - Stability D	79-84	2.9	4.2	6.5
Stability E	84	4.2	6.1	9.4
Stability F	86	7.5	11.0	16.7
CALINE4[b] - 0.5 m/s	64-72	5.4	7.9	12.0
1.0 m/s	77-82	3.7	5.4	8.3
2.0 m/s	80	2.5	3.7	5.6
Wind Direction - 40°				
CALINE3[a] - Stability D	--[c]	1.9 (3.6)[d]	2.8 (5.3)	4.2 (8.0)
Stability E	--	2.1 (5.5)	3.1 (8.1)	4.7 (12.3)
Stability F	--	2.7 (10.1)	3.9 (14.7)	6.0 (22.5)
CALINE4[b] - 0.5 m/s	--	4.5 (13.8)	6.6 (20.2)	10.0 (30.7)
1.0 m/s	--	2.6 (9.3)	3.8 (13.6)	5.8 (20.7)
2.0 m/s	--	1.6 (5.8)	2.3 (8.4)	3.6 (13.0)

[a] Wind speed of 1.0 meter/second.
[b] F stability and sigma-theta set equal to arctangent (0.5/wind speed).
[c] Worst-case wind direction applies to top section only.
[d] Number in parenthesis reflects total concentration estimate (background sources and local sources) for worst-case wind direction from background analyses.

(and ROADWAY) probably overpredict concentrations during near-parallel winds since they do not account for small-scale fluctuations in wind direction (sigma-theta). CALINE4, which accounts for sigma-theta, probably more accurately reflects actual dispersion conditions during stable, light wind speed conditions.

For CALINE3, F stability, 1 meter/sec wind speed worst-case concentration estimates range from 7.5 to 16.7 ppm. For CALINE4, F stability, 1 meter/sec wind speed worst-case concentration estimates range from 3.7 to 8.3 ppm. Since, based on the Anchorage CO study, it was assumed that Raspberry Road and other local CO sources should have relatively small impacts at the Sand Lake monitor, CALINE4 would be judged to better estimate concentrations due to local CO sources.

The second set of results given in Table 7-2 is the dispersion model estimates for a wind direction of 40°. This wind direction roughly corresponds to the wind direction during worst-case background concentration estimates. Total CO concentrations due to both background and local CO sources are also shown. For CALINE3, F stability, 1 meter/sec wind speed estimates range from 10.1 to 22.5 ppm for combined background plus local CO emission sources. For the same conditions, CALINE4 estimates range from 9.3 to 20.7 ppm. For both CALINE3 and CALINE4, MOBILE3 emissions estimates at 0°F would most nearly model the maximum measured Sand Lake concentration of 23 ppm during conditions of F stability, 1 meter/second wind speed, and a wind direction of about 40°.

Maximum CALINE3 dispersion estimates for Raspberry Road emissions (during near-parallel wind conditions) are greater than the background CALINE3 results and only slightly less then the combined CALINE3 local and background concentration results for a wind direction near 40°. Conversely, CALINE4 dispersion estimates due to local sources are much less than either background source only and combined background and local source CALINE4 dispersion estimates. Both models therefore meet the performance criteria that worst-case concentration estimates result from background emissions. In other words, both models predicted a wind direction of about 40° as worst-case.

CALINE3 local-source concentration results are larger than CALINE3 results due to background sources only. This is opposite to the performance criteria than local-source impacts be significantly less than non-local source impacts. It should also be noted that, if the receptor distance from Raspberry Road were decreased, CALINE3 would predict a near-parallel wind direction to Raspberry Road as worst-case under all conditions, irrespective of background (non-local) sources. This would have caused CALINE3 to fail the one performance criteria discussed in Section 7.1 that it did meet. CALINE4, on the other hand, would have predicted a wind direction of about 40° as worst-case whenever non-local sources are considered irrespective of the receptor distance from Raspberry Road. Thus CALINE4 appears to more accurately estimate probable source contributions to the actual worst-case Sand Lake measurements.

7.4 DISCUSSION OF FINAL MODELING CONCLUSIONS

CALINE modeling analyses were conducted for two situations -- the first to estimate the models' ability to estimate maximum background concentrations and the second to estimate the models' ability to estimate local source contributions to the maximum measured Sand Lake concentrations. Based on the results of an earlier DOT&PF/EPA study (Schweiss, 1983), it was assumed in this report that maximum measured concentrations in the Raspberry Road area were caused primarily by non-local (e.g., background) sources.

Both CALINE3 and CALINE4 predicted similar background source concentrations under identical conditions (F stability and 1 meter/sec wind speed). If F stability and 1 meter/sec wind speeds are representative of worst-case meteorological conditions and the CALINE models are assumed to model distant sources correctly, then AKMOBILE2.5 (at 20°F and 100% cold start) would appear to underestimate background source emissions when modeling Sand Lake concentrations. Although the 100% cold start assumption for AKMOBILE2.5 may tend to overestimate emissions, the use of these emissions as input to the CALINE models may still reult in udnerestimated CO concentrations since many CO sources were not included in the background analyses. Some background CO sources not included are:

° minor streets in the Anchorage Bowl area.

° CO emissions in the Anchorage Bowl due to traffic accelerations and decelerations, intersections, parking facilities, etc.

° CO emissions at International Airport (passenger parking areas, plane and service vehicle emissions, etc.), which could significantly contribute to CO concentrations in the Raspberry Road area, and CO emissions from Elmendorf Air Force Base.

° other non-vehicular CO sources (most notably fireplaces and wood burning stoves).

If these emissions had been included with AKMOBILE2.5 estimates in the modeling analyses, then modeled concentrations due to background emissions may have more accurately reflected worst-case Sand Lake measurements. However, the complexity in quantifying these emissions for input to the models exceeds the scope of this study.

For local sources, CALINE3 and CALINE4 predicted very different worst-case concentrations. Under similar meteorological conditions, maximum CALINE3 concentrations were a factor of 2 greater than CALINE4 concentrations when modeling local sources alone. This is due to the fact that CALINE3 appears to overpredict concentrations due to Raspberry Road emissions during near-parallel wind directions. In fact, CALINE3 would predict a near-parallel wind as worst-case for local plus background sources for receptors closer to Raspberry Road than the Sand Lake monitor. CALINE4 would predict a near-parallel wind as worst-case only for local sources. CALINE4 would have chosen a wind direction which would transport emissions from Anchorage Bowl to Raspberry Road as worst-case whenever background emissions are included irrespective of receptor distance from Raspberry Road.

At the Sand Lake monitor, CALINE4 predicts maximum local source impacts of 3.7 to 8.3 ppm for F stability, 1 meter/sec wind speeds depending on the emissions model estimate used. Without historical data relating maximum Sand

Lake concentrations during periods without a potential for transport of emissions from Anchorage Bowl to the monitor, it is difficult to judge these impacts quantitatively. However, since Raspberry Road was considered fairly representative of nearby neighborhood concentrations in the Anchorage study, maximum impacts due to Raspberry Road emissions are probably less than predicted by MOBILE3 emissions estimates at 0°F and 100% cold start assumptions.

Maximum total (background plus local) concentration estimates for CALINE4 range from 9.3 ppm to 20.7 ppm for F stability, 1 meter/sec wind speed depending on emissions used. MOBILE3 estimates for 0°F and 100% cold start best predicts worst-case concentrations. However, this may be due to compensating errors. CO emissions impacts are probably underestimated in the background modeling analysis while overestimated in the local source modeling analysis using MOBILE3 (0°F) emissions estimates.

8.0 SUMMARY OF DISPERSION MODEL EVALUATION

Based on the sensitivity and final modeling studies, CALINE4 is considered to be superior to CALINE3. Both models require the same basic input data, but CALINE4 consideration of horizontal wind direction fluctuations significantly improved modeling results. ROADWAY, while it may become an important post-screening model, lacks certain features. This restricts its usefulness as a regulatory model. Like CALINE3, ROADWAY also appears to overestimate pollutant concentrations during near parallel wind directions typical of worst-case concentrations.

No firm conclusions on emissions models can be made from the modeling analyses since certain CO emissions were neglected.

CALINE4 appears to offer a significant improvement to modeling worst-case meteorological conditions as compared to CALINE3 and ROADWAY. As such, it could prove to be a useful tool in understanding CO exceedances in the Anchorage area. If future studies are performed, they should be focused on CALINE4. We recommend that the following be considered in future work:

- Establish meteorological sensors throughout the Anchorage Bowl with priority given to locations with existing CO monitoring stations. At a minimum, meteorological measurements should include wind speed and direction, horizontal wind direction standard deviation (sigma-theta), and temperature. Other useful measurements include standard deviation of vertical wind fluctuations (sigma-w) and vertical temperature gradients. The latter two give an indication of vertical dispersion potential.

- Establish temporary CO monitors during winter in areas considered representative of background air quality (i.e., not near "hot spots"). One such location would be on the north side of Raspberry Road to complement the existing monitor south of the road. Impacts from Raspberry Road emissions could be determined as the difference between the downwind monitor and the upwind monitor.

- Correlate air quality from existing and background monitors with meteorological conditions.

- Conduct surveys or other studies to determine percentages of vehicles in cold start, hot start and hot stabilized modes of operation. These surveys should be conducted at various locations throughout the Anchorage Bowl and used to better determine actual emission levels.

- Determine contributions to the regional CO emissions budget by minor traffic sources such as residential streets, parking structures, etc. and non-mobile sources such as residential wood burning.

- Perform further sensitivity analyses for CALINE4's special options not considered in this report. Especially useful would be an analysis of the modal portion of CALINE4 (which calculates impacts due to emissions caused by traffic accelerations and decelerations at intersections). This analysis may prove useful for more accurately modeling existing hot-spots.

° Examine the mixing-zone assumptions of CALINE4. ROADWAY could potentially be used as a part of this study if source and meteorological inputs are carefully chosen.

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