

Modeling of Future-Year Emissions Control Scenarios for the Lower Fraser Valley: Impacts of Natural Gas and Propane Vehicle Technologies

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ABSTRACT

The MC2-CALGRID photochemical modeling system is used to simulate the impact of two fuel substitution scenarios on ozone levels for a future year in the Lower Fraser Valley of British Columbia, Canada. The relative impacts of selected natural gas and propane vehicle technologies are compared for the year 2005. The chosen natural gas technology imposes large reductions in nonmethane hydrocarbon emissions with moderate reductions in nitrogen oxide emissions, while the propane technology greatly lowers nitrogen oxide emissions with only small changes to nonmethane hydrocarbon emissions.

The model results showed that replacing the entire light-duty gasoline car and truck fleet with the selected natural gas vehicle technology in the year 2005 in the Canadian portion of the Lower Fraser Valley yielded significant benefits in terms of reducing potential exposures to elevated ozone levels in suburban and rural areas. Sites closer to the urban core were less affected. For the propane fuel substitution, benefits were realized in terms of lowering ozone concentrations and ozone exposures in the rural areas. Within the urban and suburban areas, ozone exposures tended to increase. The exposures to peroxyacetyl nitrate were universally smaller in the alternative fuel scenarios.

The nature of an effective control strategy for the Lower Fraser Valley is discussed, and it is suggested that in addition to the propane fuel substitution, moderate controls on the primary NO_x sources in conjunction with moderate nonmethane hydrocarbon controls could be the preferred route to lower ozone exposures.

1. Introduction

Photochemical models provide an advanced tool for policy makers in developing scientifically based decisions for improving air quality. In principle, the models incorporate our current scientific knowledge of the complex processes that affect air quality, including chemical emissions, transport, and atmospheric reactions. By simulating different options for controlling emissions from various sectors, a strategy can be developed that achieves the air-quality objectives and, at the same time, minimizes the cost to the industrial sector. This will often involve selection of competing manufacturing, chemical processing, and other technologies.

In this paper, we describe the first application of a recently developed photochemical modeling system, MC2-CALGRID (Hedley and Singleton 1997; Hedley et al. 1997), to future-year emission control strategies for the Lower Fraser Valley (LFV) of British Columbia, based on transportation fuel substitution. The MC2-CALGRID modeling system is composed of several major modules that perform the meteorological, photo-

chemical, and emissions modeling required to simulate air quality on a regional scale. The meteorological model, MC2, is fully elastic and nonhydrostatic (Tanguay et al. 1990) and is capable of handling the flow generated by the strong thermal and topographic forcing that is typical of the Lower Fraser Valley of British Columbia, Canada. The CALGRID photochemical model (Yamartino et al. 1992) is designed for application to regional-scale air-quality problems over complex terrain and has the desirable feature of a flexible reaction mechanism that allows us to incorporate improvements very easily. In this study, we employ a condensed version of the SAPRC90 scheme (Carter 1990), including 129 reactions among 54 organic and inorganic species (Jiang et al. 1997). The anthropogenic emissions are treated using version 2 of the Emissions Preprocessing System, or EPS2 (EPA 1992). Biogenic emissions are modeled using a modified version of PC-BEIS (Pierce and Waldruff 1991).

The control strategy evaluation is a two-step process in this type of application. Because of the time lag for significant application of a control strategy, the modeling is done for a future year. First, the base case inventory is projected to the future year without the emission controls to produce a set of future base emission files to be used as input by the photochemical model. The second step in the control strategy evaluation is to

TABLE 1. Emission scenarios.

Scenario	Description
B85	1985 Base case (Hedley et al. 1997)
FB05	2005 Future-year base case
FNO _x	30% reduction in Canadian tailpipe NO _x emissions relative to FB05
FNMO _C	30% reduction in Canadian tailpipe NMOC emissions relative to FB05
FCNG05	Canadian light-duty gasoline vehicles in FB05 replaced with CNG
FLPG05	Canadian light-duty gasoline vehicles in FB05 replaced with LPG

impose the emission controls of interest on the future base case emissions and then to run the model using these modified emissions.

The results of photochemical simulations based on a future-year projection of the Lower Fraser Valley emission inventory and two fuel substitution scenarios are presented in this paper. In the fuel substitution experiments, all light-duty gasoline vehicles are assumed to be replaced by natural gas and propane-burning vehicles, respectively. The assumption of 100% replacement of light-duty gasoline vehicles with the alternatively fueled vehicles in the year 2005 is clearly unrealistic but was adopted as a limiting condition. It maximizes the impacts and facilitates analysis and interpretation of the results. Several measures of ozone changes are presented that are relevant to assessing exposure impacts.

2. The emissions scenarios

Table 1 identifies the six emissions scenarios that are discussed in this paper. The scenarios include the 1985 base case, a projection to the year 2005, two sensitivity tests, and two fuel substitution scenarios. Detailed descriptions of the processing for each scenario are given below.

a. The 1985 base inventory

A moderate ozone episode occurred in the Lower Fraser Valley during 17–21 July 1985. This episode was simulated and analyzed by Hedley et al. (1997), and the experiment was named B85. The details of the day-specific emissions inventory processing and validation for this episode have been described previously (McLaren et al. 1996), but we present an overview of the emissions inventory here for clarity. The emissions inventory was processed using EPS2 to produce a gridded emissions dataset with a 5-km resolution horizontal grid that straddles the Canadian–U.S. border, covering a portion of southwestern British Columbia and north-eastern Washington State, shown as box c in Fig. 1. The emissions processing for this large inventory domain is broken down into two parts: a central region identified by the inner box a and a surrounding region represented

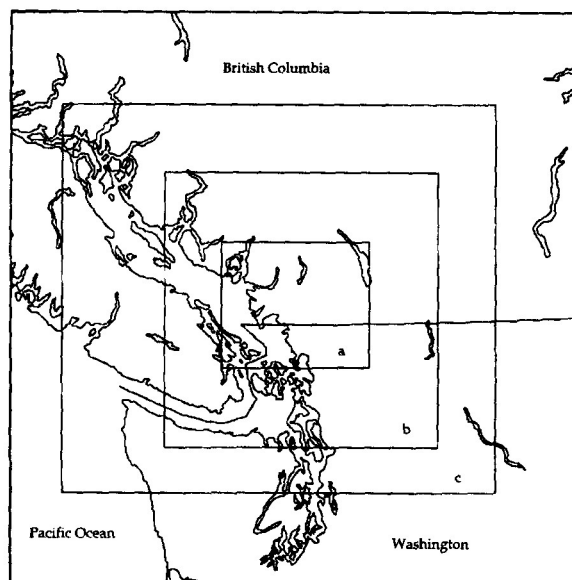


FIG. 1. Map of the emissions regions and the modeling domain. Box a is the central inventory region, box b is the photochemical modeling domain, and box c outlines the extent of the surrounding inventory region.

by the area between the inner box a and the outermost box c.

The processed emissions inventory for the central region is based on updated annual emissions inventories for the portions of British Columbia (GVRD 1988) and Whatcom County, Washington (Wilkin and Dunlop 1993), in the Lower Fraser Valley. The most significant updates we applied to the inventory involved the use of the MOBILE5a and MOBILE5C models for the mobile emissions (McLaren et al. 1996).

The emissions inventory for the less populated surrounding region includes industrial point sources taken from the 1985 Canadian inventory (Kolsteltz and DesLauriers 1990) and the U.S. Interim Inventory (Pechan 1993), as well as biogenic emissions modeled using a modified version of PC-BEIS.

b. The 2005 projected inventory

To generate the projected future-year emissions inventory for the future base case, FB05, forecast factors that take into account projections in activity as well as anticipated controls were generated by extrapolation of data from the Greater Vancouver Regional District (GVRD) Air Quality Management Plan (GVRD 1994a,b). The data were provided with the 1990 inventory in electronic format and are described in the report by Levelton (1993). The forecast factors were developed by extraction of growth surrogate data for each area source code or source classification code (ASC/SCC) for 1985 and 2005, and the relevant expected control factors (where applicable) for 2005. The projection fac-

TABLE 2. Emissions from the photochemical modeling inventories for Wednesday, 17 July for the base case (B85) and projection to the year 2005 (FB05). Units of emissions are tons per day.

	B85				FB05			
	NMOC	CH ₄	NO _x	CO	NMOC	CH ₄	NO _x	CO
Central region emissions inventory								
<i>Canadian sources</i>								
Area	99.2	479.9	6.9	23.9	65.0	759.9	8.0	29.1
Gas distribution	21.3	0.0	0.0	0.0	5.0	0.0	0.0	0.0
Mobile	211.6	14.0	141.3	1547.4	128.8	11.2	122.4	1065.0
Point	35.3	2.9	24.6	39.5	17.7	2.2	20.3	33.6
Canadian total	367.4	496.9	172.7	1610.7	216.5	773.3	150.8	1127.7
<i>U.S. sources</i>								
Area	25.7	18.3	4.4	44.3	29.8	18.5	6.9	66.1
Mobile	18.0	1.1	15.6	119.8	8.5	0.9	12.8	78.2
Point	21.2	1.0	13.3	131.1	22.0	1.1	13.8	136.6
U.S. total	64.9	20.4	33.2	295.2	60.2	20.5	33.5	280.9
Biogenics	292.5	0.0	0.0	0.0	292.5	0.0	0.0	0.0
Inner total	724.8	517.3	206.0	1905.9	569.3	793.7	184.3	1408.5
Surrounding region emissions inventory								
Point	97.8	9.4	70.5	346.1	81.4	8.8	67.5	347.0
Biogenics	2620.6	0.0	0.0	0.0	2620.6	0.0	0.0	0.0
Outer total	2718.4	9.4	70.5	346.1	2702.0	8.8	67.5	347.0

tor for a given ASC/SCC category was then calculated as

$$P_{\text{factor}}^{2005} = \frac{S^{2005}}{S^{1985}} \times (1 - C^{2005}), \quad (1)$$

where S is the growth surrogate (population, GDPs, energy consumption, etc.) and C is the anticipated control efficiency. To a large extent, the control efficiencies are consistent with those in GVRD (1994a), which included the best estimate of the effects of the Phase I NO_x/VOC (volatile organic compound) Management Plan Initiatives (CCME 1990), and included several measures that are already in place in the Lower Fraser Valley. Some controls that were thought to be missing or unrealistic were modified based upon good judgment; for example, effects of reduced gasoline volatility, already a reality in the Lower Fraser Valley, were added since they were missing in the files, while the effects of AirCare were removed due to the uncertainty of AirCare's effectiveness in reducing emissions from future-year vehicles in its current format. The projection factors created were then incorporated into EPS2 in order to scale the emissions for the future year.

On-road mobile sources were forecast using two separate pieces of information: changes in vehicle miles traveled and changes in emission factors. The vehicle miles traveled were projected for each of the eight vehicle types based upon data in the GVRD Air Quality Management Plan. The episodic emission factors for eight vehicle classes were calculated with the MOBILE5C model for the year 2005 using relevant local data, gasoline volatility, by-model-year distributions, etc. The EPS2 software incorporates these new emission factors into the inventory by directly reading the output files of the MOBILE model.

Emissions from point sources in the GVRD were forecast by processing the latest version of the point source inventory (valid for 1990) available from the GVRD and projecting to the year 2005, including all the emission-reduction measures identified in the GVRD Air Quality Management Plan. The reprocessing of the point-source inventory was necessary to take into account the many new sources that have appeared since 1985 as well as those that are no longer operational. Due to lack of information and resources, point sources in regions outside the GVRD, including British Columbia and Washington, were assumed to operate at their 1985 levels.

A forecast was not available for the inventory for Whatcom County, Washington. As a preliminary estimate, it was assumed that growth factors for area and on-road mobile sources would be the same as those in the GVRD. Some control factors were incorporated, which were equivalent to those in the GVRD. Only those controls of a nonregulatory nature expected to affect both sides of the international border were included in the Whatcom County forecast. An example is the reduction of solvent emissions for paint and architectural coatings due to product reformulation. A control efficiency of 25% was added for fuel marketing emissions in Whatcom County due to the reduction in gasoline volatility (Reid vapor pressure) from 11.0 to 8.0 psi. Other regulatory controls in the GVRD, such as vapor recovery at terminals, were not assumed for Whatcom County.

A breakdown of the emissions by source sector and region is given in Table 2 for experiments B85 and FB05 on 17 July 1985. The total emissions of NO_x, CO, and nonmethane organic compounds (NMOCs) are actually

lower in the projected inventory, while emissions of CH_4 are higher.

c. The NO_x -NMOC sensitivity experiments

The purpose of the two sensitivity experiments is to determine the sensitivity of ozone formation in the future-year scenario to incremental changes in NO_x and NMOC emissions from the light-duty gasoline vehicle fleet. This information is useful in terms of deciding upon an effective emissions control strategy. We modified tailpipe emissions from the Canadian light-duty gasoline vehicle fleet only since this source category is the largest contributor to pollutant emissions in the Lower Fraser Valley and is the most likely candidate for regulated emissions control in the future.

In experiments FNO_x and FNMOC, the tailpipe emissions of NO_x and NMOCs from the Canadian light-duty gasoline vehicle fleet were reduced by 30%, respectively, compared to FB05. These reductions are intentionally small compared to the total emissions, and we expect the absolute impact of the changes on the ozone forecast to be small.

d. Alternative fuels scenarios

The projected emissions inventory for the year 2005 is used as a base case from which to evaluate changes in ozone concentrations caused by replacing gasoline with either natural gas or propane-burning vehicles. For each fuel substitution, the 2005 base case was adjusted for the mass and chemical speciation of the mobile source emissions and gas distribution emissions that are expected to be affected by the fuel substitution. Emissions from other sources are assumed to remain the same.

1) SELECTION OF VEHICLE TECHNOLOGIES

The CleanFleet demonstration program in the south coast air basin of California (Battelle 1995) was selected because it met a number of selection criteria. The program involved in-use testing of a fleet of panel vans that were used by Federal Express over a period of two years beginning in 1992. The vehicles represented are comparable to 1992 technology from Ford, General Motors (GM), and Chrysler for gasoline, natural gas, and propane. Multiple emission measurements were made on three vehicles for each fuel at nominal odometer readings of 5000, 15 000, and 25 000 miles.

Table 3 summarizes the emissions of nonmethane hydrocarbons (NMHC), CH_4 , NO_x , and CO for three types of natural gas vehicles and two types of propane vehicles tested during the CleanFleet Program. The data were obtained from the Alternative Fuels Data Center in Colorado.

We judged the Dodge OEM natural gas technology as being closest to the natural gas technology that would

TABLE 3. Emission factors (g mi^{-1}) for natural gas and propane vehicles from the CleanFleet program.

Vehicle	Fuel	NMHC (g mi^{-1})	CH_4 (g mi^{-1})	NO_x (g mi^{-1})	CO (g mi^{-1})
1992 Dodge van	CNG	0.01	0.90	0.56	1.29
1992 GM van	CNG	0.10	3.00	1.59	4.99
1992 Ford van	CNG	0.11	3.42	1.70	0.86
1992 GM van	LPG	0.68	0.11	1.08	5.98
1992 Ford van	LPG	0.41	0.18	0.83	1.54

exist in the future year and selected the emission data from these vehicles for the modeling study. In particular, the Dodge natural gas vehicles were production model B350 vans dedicated for natural gas, used a three-way catalyst tailored to natural gas emissions, and were certified to California's 1992 medium-duty vehicle emission standards. The same natural gas technology in model year 1993 was certified to California's low-emission vehicle (LEV) standards. The gasoline vehicle technology selected for the modeling was a Dodge B350 van certified to model year 1992 California emission standards. Both types of vans were V8, with displacement of 5.2 L, compression ratio of 9.08, sequential multiport fuel injection, and three-way catalysts tailored to the specific fuel. Technical specifications of the vehicles are provided in a CleanFleet report (Battelle 1992).

The propane vehicles included in the CleanFleet program were gasoline vans that were modified to run on propane. The Ford vans had 4.9-L inline six-cylinder engines with a compression ratio of 8.8. The emissions control systems were tailored for gasoline. The General Motors vehicles had 5.7-L V8 engines with a compression ratio of 8.6 and an Engelhard propane emission control system. We decided that the GM vehicles represented more closely the technology that would exist in the future year. The gasoline technology selected for comparison in this case was the gasoline-burning version of the GM van.

As described in the CleanFleet reports, it should be noted that these comparisons represent a snapshot of technologies in 1992. We can expect further developments in each fuel technology in the future.

2) PROCESSING OF FUEL SUBSTITUTION CONTROL STRATEGIES

The replacement scenarios that are being modeled involve complete replacements of all emissions from light-duty gasoline vehicles and light-duty gasoline trucks (classifications LDGV, LDGT1 and LDGT2 in the inventory) in the Canadian portion of the Lower Fraser Valley in the year 2005 with emissions anticipated from a corresponding fleet of natural gas or propane vehicles.

The adjustment of emissions for the alternative fuel fleet is done by applying a control factor in the EPS2 software for each on-road SCC and pollutant. This in-

TABLE 4. Control factors, $F = e_{AF}/e_{gasoline}$ for natural gas- and propane-fueled vehicles from the CleanFleet program.

Vehicle	Fuel	NMHC	CH ₄	NO _x	CO
1992 Dodge van	CNG	0.08	12.50	0.59	0.15
1992 GM van	CNG	0.14	27.30	0.32	0.35
1992 Ford van	CNG	0.38	38.00	2.12	0.35
1992 GM van	LPG	1.11	1.65	0.26	0.46
1992 Ford van	LPG	1.44	1.65	1.01	0.54

cludes exhaust, evaporative, refueling, and other fuel marketing emissions. The speciation of the organic emissions is also modified. The control factor, F , is estimated for each emission mode, m (exhaust, evaporative), and pollutant, p (organic compounds, NO_x, CO), from vehicle emission test data:

$$F_{AF,p,m} = \frac{e_{AF,p,m}}{e_{gasoline,p,m}}, \quad (2)$$

where e_{AF} is the emission factor measured or estimated for the alternative fuel (AF, either natural gas or propane) test data and $e_{gasoline}$ is the emission factor measured for the gasoline test data. The control factor adjusts the baseline conventional fuel emissions present in the inventory for the future year:

$$E_{AF,p,m} = F_{AF,p,m} \times E_{gasoline,p,m}, \quad (3)$$

where E_{AF} is the emissions from the future fleet of natural gas or propane vehicles and $E_{gasoline}$ is the emissions from the conventional fleet in the future base inventory.

The evaporative emissions from natural gas and propane vehicles were taken to be zero, and hence the control factor for evaporative emissions was zero. This is a reasonable assumption since the fuel systems for these vehicle types are closed. Emissions from refueling and other marketing sources were also taken as zero. There are no data available for probable emissions from the natural gas or propane marketing sector, but simple estimates indicate that they could be small. This resulted in a value of the control factor for fuel marketing of 0.25, based on the fraction of gasoline vehicles displaced by alternative fuel vehicles in the scenarios. (Only light-duty gasoline cars and trucks were replaced in the scenario.)

To calculate the control factors listed in Table 4, the regulated emissions data for CO, total organic gases, and NO_x were regressed as a function of vehicle mileage

for both the alternative fuel vehicles and the control vehicles and then interpolated at 40 000 km. Data are presented for all of the natural gas and propane van types in the CleanFleet program, although only the Dodge natural gas and GM propane vans were used in this study.

The low control factors for all GM propane vehicle emissions and for the natural gas Dodge NMHC and CO emissions probably reflect the tuning of the emissions control technology to the specific fuel.

e. Comparison of emission scenarios

The emissions from each sector within the Canadian portion of the central region for the two fuel substitution scenarios FCNG05 and FLPG05 are shown in Table 5 for 17 July. The central region emissions inventory in the tables is identified by the central box a in Fig. 1. The emissions from U.S. sources and from the surrounding region are unchanged from FB05. Biogenic emissions are the same for all of the emission scenarios.

The natural gas vehicle scenario, compared to FB05 (Table 2), shows reductions for NO_x, NMOCs, and CO, and an increase in methane emissions from Canadian mobile sources. Canadian NMOC emissions from gas distribution also decrease. Emissions from all other sectors remain the same. These features are consistent with the replacement of gasoline with natural gas vehicles only in the Canadian portion of the LFV.

In the propane scenario, the NO_x emissions from the Canadian mobile sector were reduced by about one-third compared to FB05, resulting in lower NO_x emissions than the natural gas scenario. The NMOC emissions were only marginally reduced. Canadian mobile sector methane emissions in the propane case are less than one-tenth of those from the natural gas scenario.

3. Domain, chemical mechanism, and boundary conditions

The MC2-CALGRID photochemical modeling domain used here is 240 km on a side, composed of a 48 × 48 horizontal grid mesh with 5-km grid spacing (box b in Fig. 1), and is identical to the domain described in Hedley et al. (1997). The simulations presented below use the entire central region inventory but only a portion of the surrounding region inven-

TABLE 5. Canadian emissions in the central region on Wednesday, 17 July for the natural gas vehicle scenario (FCNG05) and the propane scenario (FLPG05). Units of emissions are tons per day.

	FCNG05				FLPG05			
	NMOC	CH ₄	NO _x	CO	NMOC	CH ₄	NO _x	CO
Area	65.0	759.9	8.0	29.1	65.0	759.9	8.0	29.1
Gas distribution	1.3	0.0	0.0	0.0	1.9	0.0	0.0	0.0
Mobile	51.7	135.6	99.7	335.1	114.6	12.7	81.4	600.2
Point	17.7	2.2	20.3	33.6	17.7	2.2	20.3	33.6
Canadian total	135.7	897.7	128.1	397.8	199.2	774.8	109.8	662.9

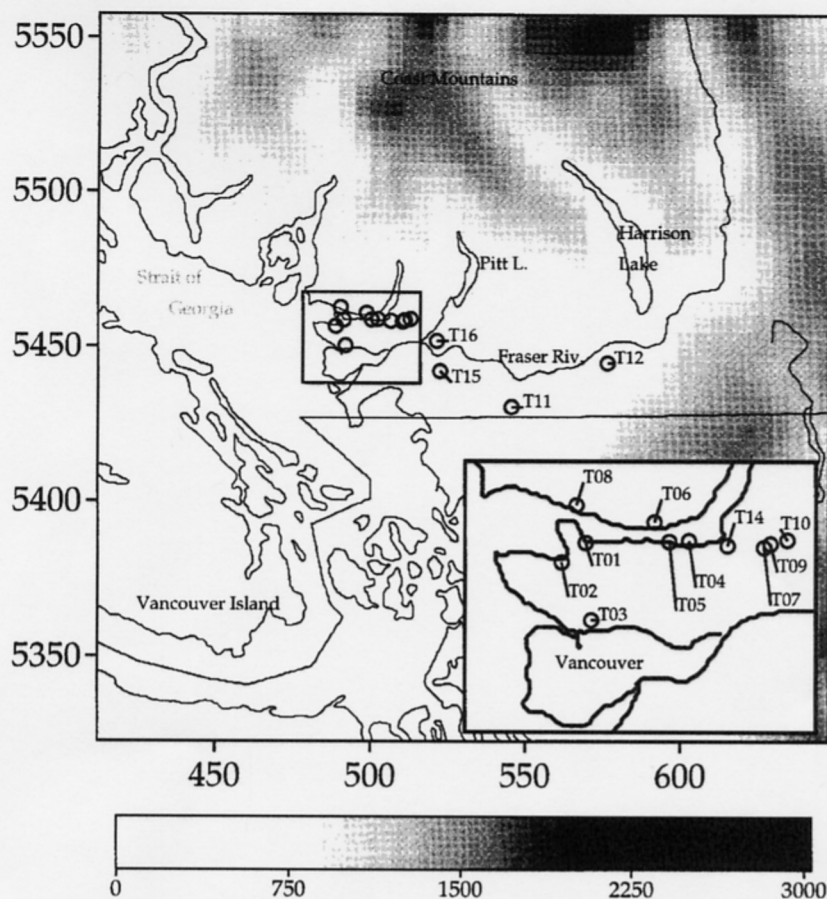


FIG. 2. Map of the Lower Fraser Valley and surrounding area. The shading corresponds to the height of the topography (m) according to the gray scale shown. The open circles show the location of the air-quality monitoring stations. The inset provides an expanded view of the Vancouver area. The top of the map is north. The Canadian-U.S. border is shown as the thin line running just south of T11. The scales along the axes show the UTM coordinates in kilometers.

tory. Figure 2 shows the topography of the region within the modeling domain, along with the locations of the monitoring stations that were active during the July 1985 ozone episode.

As described previously (Hedley et al. 1997; Jiang et al. 1997), a modified and lumped version of the SAPRC90 chemical mechanism (Carter 1990) is implemented in our modeling system. The basic version of the mechanism used in this study is named COND2243. For all three simulations, rate constants and product yields of the lumped NMOC reactions as well as carbon numbers and molecular weights of lumped NMOC model species in the mechanism are recalculated based on the emissions profile for each scenario.

The COND2243 mechanism treats methane as a species with constant concentration. Reactions of methane with other species are included in the mechanism, but these do not change its concentration. Therefore, emissions of methane are ignored in the photochemical simulations presented below. Parallel with this study, a

mechanism with a more detailed treatment of NMOC compounds that also includes methane as a variable species has been developed and is currently being implemented into MC2-CALGRID.

The initial concentrations are as follows: O_3 , NO_x , and CO concentrations are set to 15, 2, and 200 ppb, respectively, and the total NMOC concentration is initialized at 17 ppbC. Inflow boundary values of all pollutants are assumed to be the same as the initial concentrations. The initial conditions and boundary conditions for the concentrations of all species remained the same for each scenario. This is justified for the boundary conditions because activity levels were assumed not to change outside the modeling domain. This assumption would leave the concentrations of species originating outside the domain unchanged at the boundaries. The concentrations of species for the initial conditions in the modeling domain are quite low to begin with, so that the initial conditions are effectively a source of very clean air compared to subsequent emis-

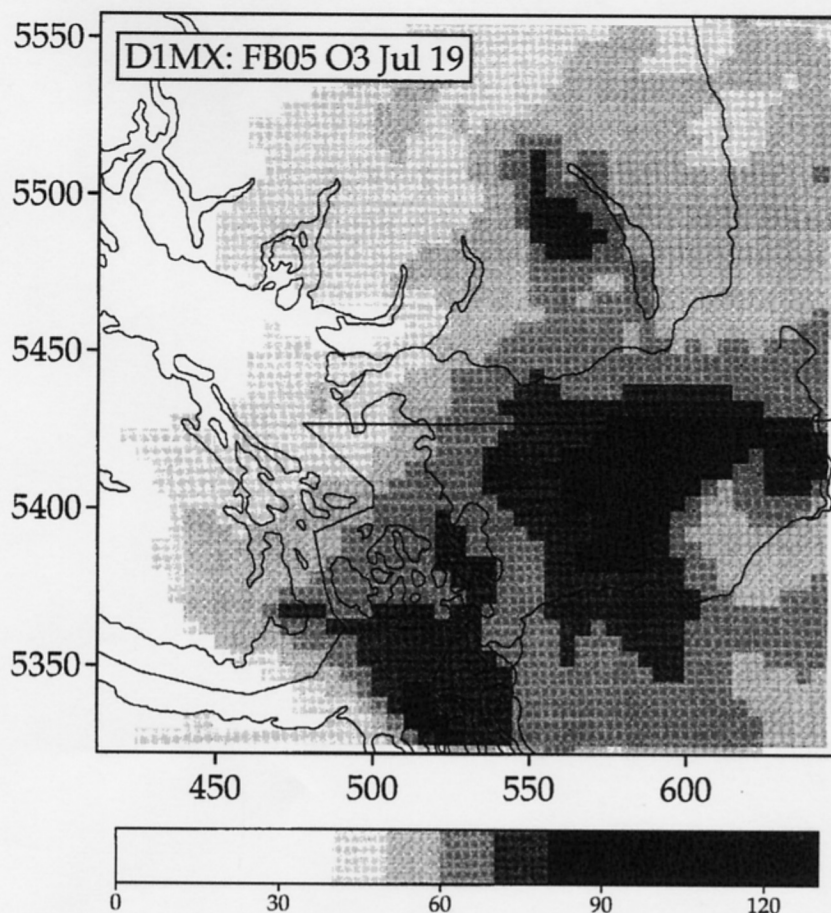


FIG. 3. Surface map of 1-h daily maximum ozone concentrations for the FB05 scenario on 19 July 2005. The gray scale shows the concentrations in parts per billion.

sions, and further reduction in the initial concentrations has little effect on the results.

4. Results

The following exposure-related measures are used to illustrate the severity of the modeled ozone episode and to evaluate the impact of the various emissions scenarios.

- 1) DIMX, D4MX, AND D8MX: the maximum daily 1-, 4-, and 8-h running averages of the ozone concentration.
- 2) N40, N50, N82: the number of hours per day that the ozone concentration exceeded 40, 50, and 82 ppb, respectively.

a. Domain-wide impacts of emission scenarios

The surface plot of D1MX for 19 July of the future-year projection, FB05, is shown in Fig. 3. There are three main areas that experienced relatively large 1-h

ozone exposures on this day, with values exceeding 70 ppb in the southern part of the Strait of Georgia and just west of Harrison Lake, and values above 100 ppb in the eastern part of the domain just south of the border.

In Fig. 4 the differences between the 19 July D1MX fields for FB05 and B85 are shown. There are three branches of the urban plume that have been most strongly affected by the differences between the 1985 and 2005 emissions, one traveling to the northeast, the second along the Fraser River, and the third tracking southward into the waters of the United States. The largest decrease in maximum daily ozone over the entire domain was 26 ppb on this day.

The sensitivity of FB05 to small decreases in NO_x is demonstrated by the surface map of the differences between D1MX for FNO $_x$ and FB05 in Fig. 5, again for 19 July. The dominant feature of the field is the plume of increased ozone concentrations extending many kilometers to the east and north of the urban core. In experiment FNMOC, where tailpipe emissions of NMOCs were reduced by 30% relative to FB05, the

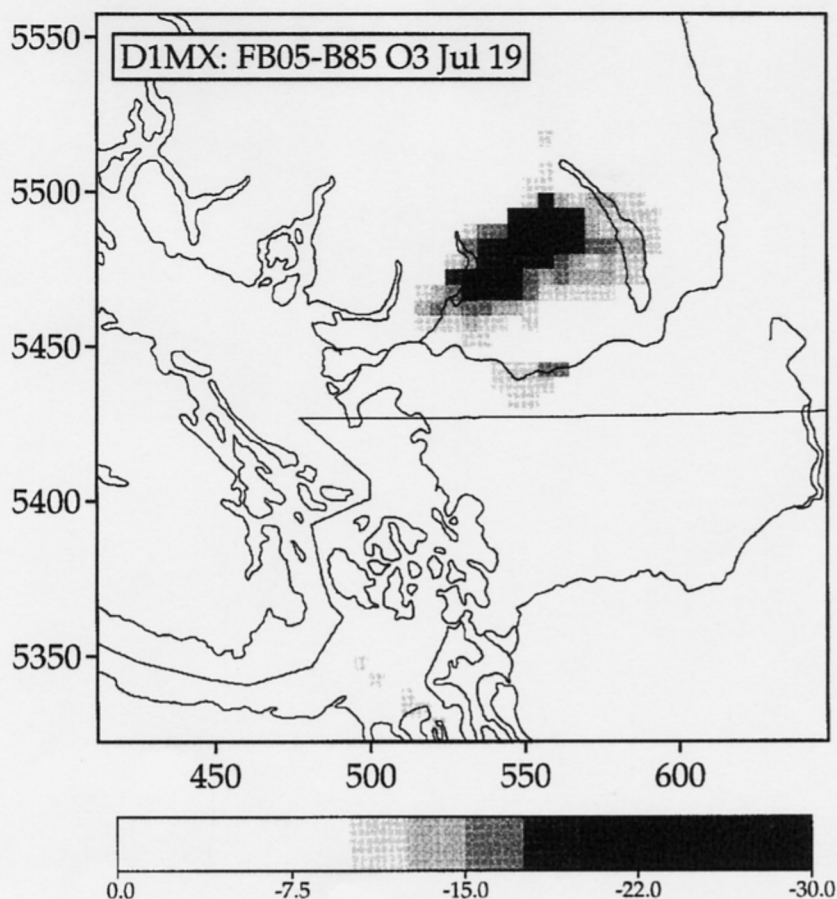


FIG. 4. Surface map showing the difference between the 1-h daily maximum ozone concentrations for FB05 and B85 on 19 July. The gray scale shows the concentration differences in parts per billion.

difference field for D1MX (Fig. 6) shows ozone decreases of up to 4 ppb along the same plume discussed above. One must conclude that the formation of ozone along this part of the plume is limited by the availability of NMOCs.

The differences between the natural gas scenario and FB05 D1MX fields (Fig. 7) shows that the natural gas vehicle scenario results in significant net decreases in ozone. Decreases of up to 13 ppb are realized in the urban plume. It is interesting that some of the larger differences occurred quite far to the south on the American side of the border. Since the only difference between the two experiments is the Canadian light-duty vehicle emissions, it is clear that the Canadian emissions have a significant impact on ozone levels on the American side of the border in this case.

The propane fuel substitution scenario results in moderate reductions in D1MX (Fig. 8) with a reduction of approximately 8.5 ppb in the southern part of the domain. In the vicinity of the urban plume, increases of up to 4 ppb were experienced due to the significant

reduction of NO_x emissions from the light-duty vehicle fleet. The reductions in ozone produced in FCNG05 were more substantial.

It is clear from the surface plots of the D1MX differences for the fuel substitution runs in Figs. 7 and 8 that the locations of the maximum modeled benefits may not occur in the areas of high population or economically important agriculture in this particular simulation. Additional simulations for other case studies are required in order to determine whether similar benefits could occur closer to the more populated areas during episodes with slightly different meteorological conditions.

b. Impacts at urban, suburban, and rural sites

It is important to analyze the effects of the emission scenarios on ozone levels in the urban, suburban, and rural areas independently since the model response to changes in emissions tends to be very different for these three types of locations. In the urban regions, NO_x emis-

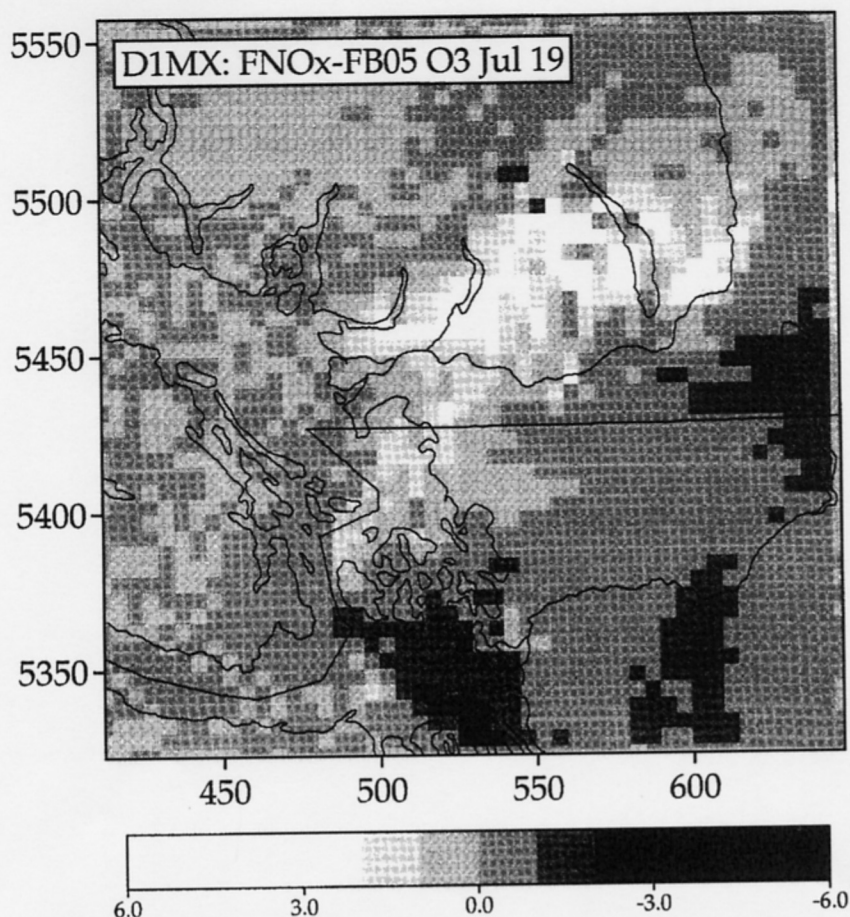


FIG. 5. Surface map showing the difference between the 1-h daily maximum ozone concentrations for FNO and FB05 on 19 July 2005. The gray scale shows the concentration differences in parts per billion.

sions tend to be very high, and the local ozone concentration is very much controlled by the titration of ozone by fresh NO emissions, while in rural regions, ozone formation processes dominate. In the suburban regions, neither mode dominates. The stations shown in Fig. 2 are grouped as follows: the urban stations are T01–T06, and T14; the suburban stations are T07, T09, T10, T15, and T16; and the rural stations are T11 and T12.

We know from our statistical validation of B85 in Hedley et al. (1997) that there are systematic errors in the model forecasts. Therefore, to obtain a more accurate estimation or of the actual impacts of the projected emission inventory on ozone exposures, the model data is calibrated to remove the reported systematic errors.

The model forecast of ozone (or any other variable) P at a given station can be assumed to be composed of a part that is linearly related to the actual observed value O plus a component that behaves nonlinearly with observations. The linear relationship is calculated from the least squares linear fit of P as a function of O and is

called P^* . Thus, we have $P^* = m \times O + b$, where m and b are the slope and intercept derived from the least squares fit. The model forecast P can be simply calibrated by calculating $P_c = (P - b)/m$ using the values of m and b for each station as presented in Hedley et al. (1997). It is important to note that the calibration method described here can be applied to model results at the station locations only and not to other parts of the domain.

Tables 6a–c summarize the modeled exposure metrics for ozone at the three station categories. The observed values of the exposure metrics from 17–21 July 1985 have been included for comparison against the modeled values. The average impact of the projected emissions inventory in FB05 relative to B85 was to lower ozone exposures in all three station categories. The average ozone exposures at rural stations were affected the most, with decreases from 8.1% for N40 to 51.4% in N82. The projected inventory also results in substantial reductions in the maximum exposure values for the rural stations. At urban locations, the maximum values of

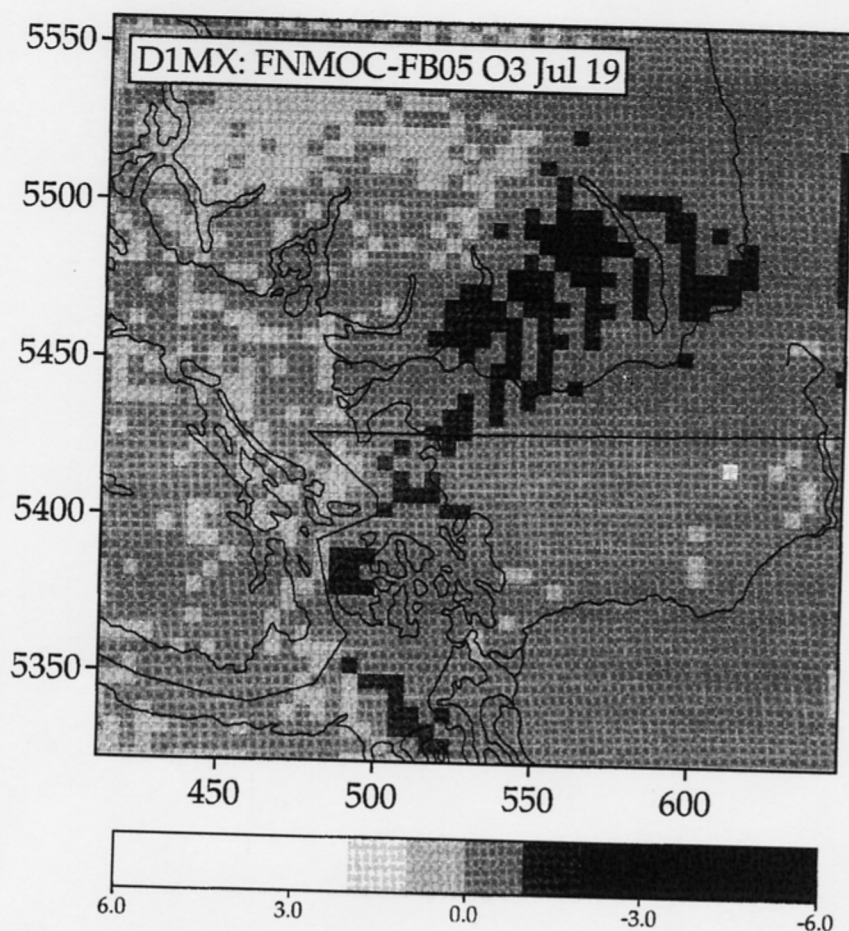


FIG. 6. Surface map showing the difference between the 1-h daily maximum ozone concentrations for FNMOC and FB05 on 19 July 2005. The gray scale shows the concentration differences in parts per billion.

D1MX, D4MX, N40, and N82 increased in comparison with the 1985 base case due to overall reduction of NO_x emissions in the future projection, which results in less titration of ozone by fresh NO emissions.

The reduction in tailpipe NO_x emissions from light-duty gasoline vehicles caused increases in the ozone exposures for all station categories in experiment FNO $_x$. In experiment FNMOC, the ozone exposures all decreased in response to the reduction in tailpipe NMOC emissions.

Of the three station categories, rural stations were the least sensitive to tailpipe NO_x reductions. The rural sites were equally or more sensitive than the urban or suburban stations were to the NMOC reductions, indicating that the rural areas are still strongly influenced by the urban plume. The rural ozone levels are less sensitive than urban or suburban ozone levels are to the NO_x reductions because as air parcels are transported from the urban core to the outlying areas, they move away from any significant NO_x sources, while still accumulating biogenic NMOCs. At a certain downwind loca-

tion, the air parcels reach the crossover point between where the peak ozone levels are limited by available NMOCs or by available NO_x ; at this transition point, the ozone levels become insensitive to incremental NO_x changes. The rural sites in this analysis are still upwind of this transition point and thus do show sensitivity to the NO_x reductions. However, we can expect that with more substantial NO_x emission reductions that the transition point would move closer to the urban core.

It is clear from the two sensitivity experiments that the NMOC limited portion of the urban plume extends a rather long way into the rural region of the Lower Fraser Valley. In an NMOC-limited air parcel, the ratio of available NO_x to NMOC is high, and one must ask what major pollutant sources contributed to this high ratio. An inspection of the detailed projected anthropogenic emissions inventory reveals that on the Canadian side of the domain, the top contributor to NMOC and NO_x emissions is the light-duty gasoline vehicle fleet. The next largest sources of NO_x are industrial point sources, marine activity, and heavy-duty diesel trucks.

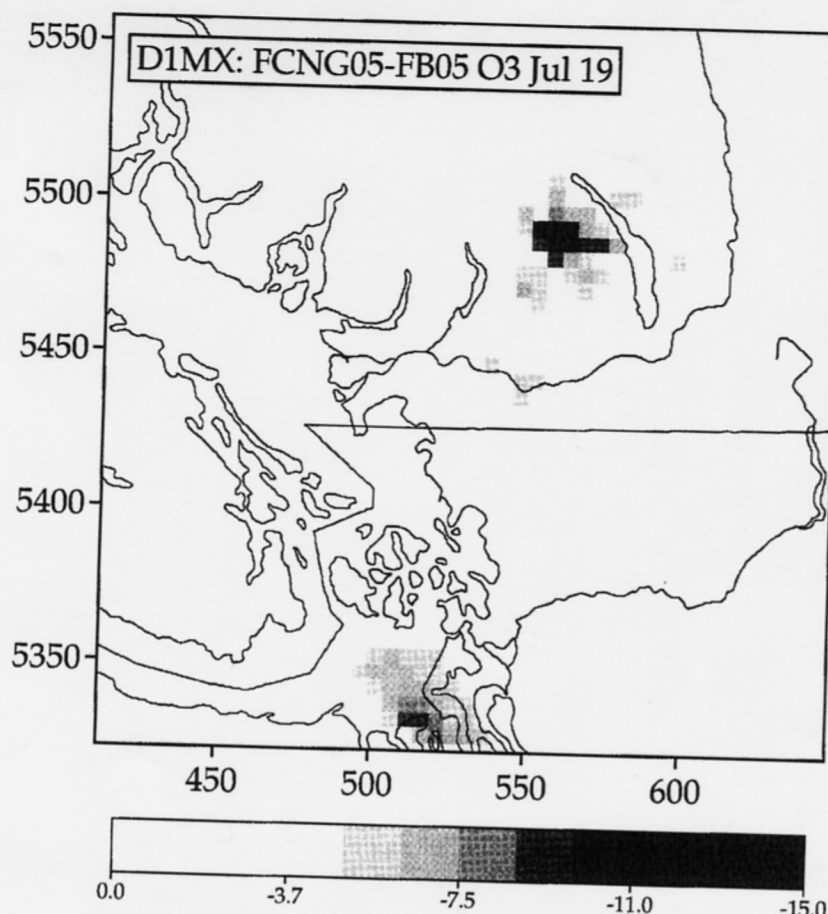


FIG. 7. Surface map showing the difference between the 1-h daily maximum ozone concentrations for FCNG05 and FB05 on 19 July 2005. The gray scale shows the concentration differences in parts per billion.

The marine activity source is mostly composed of emissions from large diesel engines. Each of these source sectors has very low NMOC to NO_x ratios, from 1.2 for marine activity to 0.4 for heavy-duty diesel trucks. These large, NO_x -rich sectors obviously have a profound impact on the character of the simulated ozone fields.

The natural gas vehicle simulation results in small changes in the ozone concentrations at the urban stations. The changes in maximum values of D1MX, D4MX, and D8MX were no greater than 2 ppb, and no changes were noted in the maximum N40, N50, or N82 values. Similarly, there were only slight alterations to the averaged values, with changes of no more than 3.9% in any case. Thus, in terms of ozone, the net effect of the natural gas controls was a very slight worsening of air quality at urban stations.

At suburban and rural stations, the natural gas substitution provided significant reductions in all of the averaged ozone exposure measures and most of the maximum values. At the suburban stations, the average value of N82 was lowered by 39%, while at the rural sta-

tions a decrease of 82.4% was obtained. The range of improvements for the other measures went from a 2.4% decrease in N40 at the suburban stations to a 14.5% decrease in N50 at rural stations.

The propane fuel substitution caused a larger degrading of air quality at urban stations than the natural gas scenario due to the greater reductions in NO_x emissions and the subsequent lessening of the rate of ozone titration by NO .

At suburban stations, the response of air quality to the propane substitution is opposite from the natural gas case. All of the six average exposure measures experienced increases, ranging from a 4.1% increase in D1MX to a 36.1% increase in N82. Experiments FNO $_x$ and FNMOC demonstrated that the ozone formation at the urban and suburban station locations in the future base case simulation was negatively correlated with incremental changes in tailpipe emissions of NO_x from light-duty gasoline vehicles. Therefore, it is understandable why an emissions control strategy that involves greater reductions in tailpipe NO_x emissions than

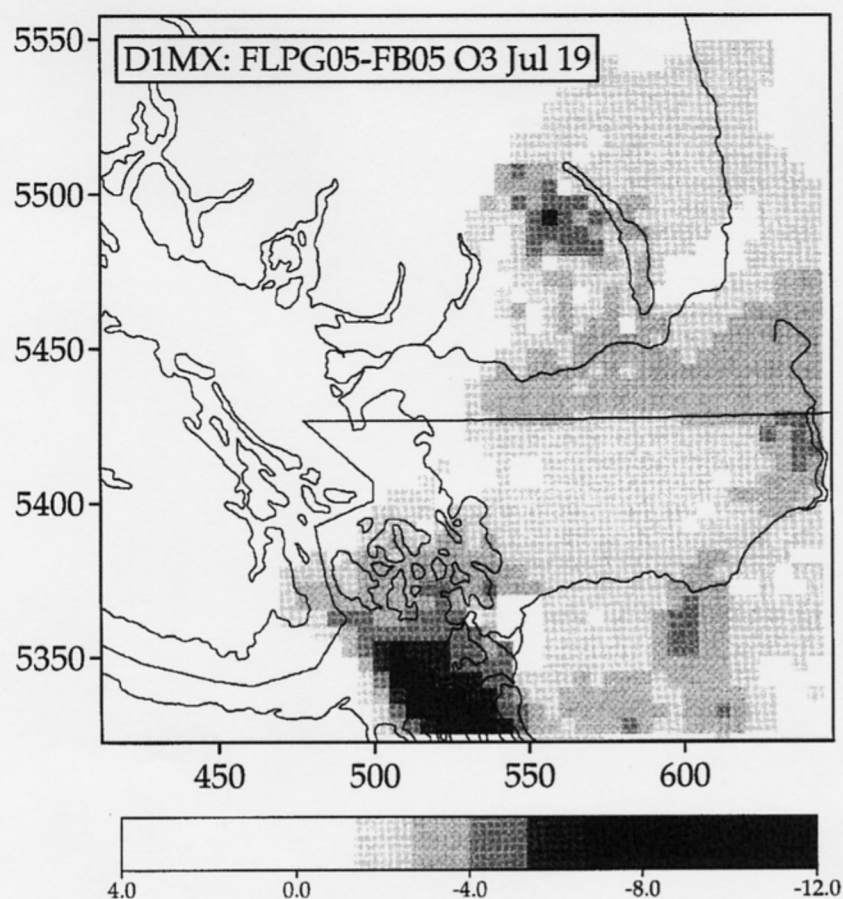


FIG. 8. Surface map showing the difference between the 1-h daily maximum ozone concentrations for FLP05 and FB05 on 19 July 2005. The gray scale shows the concentration differences in parts per billion.

TABLE 6a. Summary of ozone metrics for the urban stations.

Scenario	D1MX	D4MX	D8MX	N40	N50	N82
Maximum values	(ppb)	(ppb)	(ppb)	(h)	(h)	(h)
Observed	91.0	85.8	78.1	12.0	10.0	3.0
B85	85.9	77.2	63.7	9.0	8.0	1.0
FB05	87.4	80.5	62.2	10.0	7.0	2.0
Average values ^a	(ppb)	(ppb)	(ppb)	(h)	(h)	(h)
Observed	51.3	47.1	40.4	3.8	2.3	0.1
B85	61.9	57.5	48.5	5.7	3.7	0.0
FB05	61.1	56.5	46.8	5.0	3.5	0.1
Average relative impact ^a	(%)	(%)	(%)	(%)	(%)	(%)
FB05 ^b	-1.2	-1.6	-3.6	-12.3	-5.4	n.a.
FNO _x ^c	4.4	5.8	7.7	18.5	15.4	150.0
FNMO _C ^c	-1.2	-1.4	-1.7	-3.8	-6.6	0.0
FCNG05 ^c	0.4	0.8	1.4	3.9	3.3	0.0
FLPG05 ^c	7.4	9.1	12.9	29.2	24.2	300.0

^a Averages are over the five days of simulations for each station class.

^b Changes are relative to B85.

^c Changes are relative to FB05.

TABLE 6b. Summary of ozone metrics for the suburban stations.

Scenario	D1MX	D4MX	D8MX	N40	N50	N82
Maximum values	(ppb)	(ppb)	(ppb)	(h)	(h)	(h)
Observed	110.0	98.8	89.8	17.0	14.0	6.0
B85	118.3	108.1	101.7	19.0	18.0	8.0
FB05	118.3	98.1	91.0	20.0	17.0	8.0
Average values ^a	(ppb)	(ppb)	(ppb)	(h)	(h)	(h)
Observed	82.7	75.8	67.7	9.8	7.9	1.7
B85	90.6	84.8	76.0	12.0	10.0	3.1
FB05	86.1	77.8	68.6	11.7	9.4	2.0
Average relative impact ^a	(%)	(%)	(%)	(%)	(%)	(%)
FB05 ^b	-5.0	-8.2	-9.7	-2.5	-6.0	-35.5
FNO _x ^c	5.2	6.7	8.3	8.5	10.1	47.2
FNMOCC ^c	-2.4	-2.8	-3.7	-0.5	-7.1	-16.7
FCNG05 ^c	-4.4	-4.6	-7.2	-2.4	-9.5	-39.0
FLPG05 ^c	4.1	5.4	6.1	12.3	14.8	36.1

^a Averages are over the five days of simulations for each station class.

^b Changes are relative to B85.

^c Changes are relative to FB05.

NMOC emissions, as in the propane scenario, would result in higher ozone levels.

The propane fuel substitution produced benefits at rural stations ranging from a 0.7% decrease in D8MX to a 29.4% decrease in N82. The maximum values of D1MX, D4MX, and D8MX were also reduced. On average, the impact of the propane substitution on air quality at rural stations was beneficial, although not to the same degree caused by the natural gas substitution.

In Table 7, the largest negative changes in the calibrated ozone exposure metrics over all stations and all days are listed for the two fuel substitution scenarios. Both scenarios result in substantial peak reductions with natural gas substitution giving the greatest reductions.

c. Effect of fuel substitutions on PAN exposures

The peak values of the daily 1-h peak peroxyacetyl nitrate (PAN) concentrations (not shown) are roughly

collocated with the peak ozone values shown in Fig. 3. The largest modeled PAN concentrations were approximately 2.5 ppb. The values of HNO₃ in the regions of maximum PAN concentrations were in the range of 8–9 ppb (not shown), resulting in a PAN/HNO₃ ratio of about 0.3, which is typical of the distribution of NO_x oxidation products for air with relatively low initial NMOC/NO_x ratio (Finlayson-Pitts and Pitts 1986).

The peak 1-h PAN concentrations are generally lower in the fuel substitution scenarios with maximum reductions of about 0.7 ppb in the southern part of the domain. The largest reductions within the Canadian portion of the Lower Fraser Valley are closer to 0.3 ppb. Although the absolute reductions in PAN levels are rather small, their relative reductions of 10%–20% are significant. The results from the FCNG05 simulation were very similar to the FLPG05 results with differences of no more than ± 0.25 ppb in the 1-h maximum PAN concentration.

TABLE 6c. Summary of ozone metrics for the rural stations.

Scenario	D1MX	D4MX	D8MX	N40	N50	N82
Maximum values	(ppb)	(ppb)	(ppb)	(h)	(h)	(h)
Observed	107.2	99.4	87.9	11.0	10.0	6.0
B85	140.1	130.5	101.5	14.0	12.0	9.0
FB05	113.9	100.1	82.0	12.0	11.0	6.0
Average values ^a	(ppb)	(ppb)	(ppb)	(h)	(h)	(h)
Observed	83.3	77.1	66.6	8.8	7.4	1.9
B85	87.7	81.7	67.5	8.6	6.9	3.5
FB05	74.6	68.7	59.1	7.9	6.2	1.7
Average relative impact ^a	(%)	(%)	(%)	(%)	(%)	(%)
FB05 ^b	-14.9	-15.9	-12.4	-8.1	-10.1	-51.4
FNO _x ^c	2.5	4.4	4.8	6.3	6.5	35.3
FNMOCC ^c	-3.1	-3.9	-3.6	-5.1	-4.8	-17.6
FCNG05 ^c	-11.8	-12.9	-10.8	-11.4	-14.5	-82.4
FLPG05 ^c	-5.6	-3.9	-0.7	1.3	1.6	-29.4

^a Averages are over the five days of simulations for each station class.

^b Changes are relative to B85.

^c Changes are relative to FB05.

TABLE 7. Largest negative changes in ozone concentration metrics for the natural gas and propane vehicle scenarios compared to the future base case.*

Measure	Natural gas	Propane
D1MX (ppb)	-15.0	-11.5
D4MX (ppb)	-18.4	-9.0
D8MX (ppb)	-13.5	-6.1
N40 (h)	-2	-1
N50 (h)	-3	0
N82 (h)	-5	-3

* The maximum benefits are calculated over all stations and all days using the difference between the calibrated control scenario (FCNG05 or FLPG05) and FB05 model output.

5. Discussion

a. Modeling assumptions and uncertainties

It is difficult to quantify the uncertainties in the modeling results. Uncertainties in vehicle emission measurements, the emissions inventory, the meteorological data, the chemical mechanism in the photochemical model, and the initial and boundary conditions in the photochemical model can all contribute to the overall uncertainty. Any errors in the 1985 base inventory will be propagated to the projected inventory and the control scenario. It has been suggested by other researchers that emissions of nonmethane organic compounds, particularly from biogenic sources, tend to be underestimated. This could be an important factor in the heavily forested Lower Fraser Valley, and the results of the control scenarios could be sensitive to this kind of error. In developing the projected inventory, assumptions were made about growth rates and anticipated regulatory controls. We also made no effort to predict the future land use distribution of the area.

In the alternative fuel scenarios, we assumed 100% penetration of the alternative fuel vehicles in three vehicle classes. The ozone reductions for smaller penetration rates could be estimated by linear scaling of the reductions in the present scenario by the penetration rate. Further detailed modeling studies could be performed to assess the validity of this approach. In addition, future modeling studies should include other vehicle classes when comparable data are available. Further simulations are also required to evaluate the impact of changes in emissions of NMOC, NO_x , and CO from other sources in the future-year scenario.

Uncertainties in the vehicle emission measurements (test-to-test and vehicle-to-vehicle reproducibility) were reported as part of the CleanFleet program. The 95% confidence bounds reported for the Dodge van data in the CleanFleet study (Battelle 1995) lead to the following range of control factors for the natural gas case: NMOC 0.055–0.152, CO 0.10–0.45, and NO_x 0.29–1.29. For the GM propane vans, the control factor ranges were NMOC 0.60–2.04, CO 0.27–1.0, and NO_x 0.14–0.60. There is a large range of values for each control factor, particularly the value of the upper bound of the

control factor for NO_x from natural gas vehicles. Based on previous sensitivity studies involving changes in NMOC or NO_x emissions, both globally and by sector, a control factor of unity for NO_x in the natural gas vehicle substitution scenario would result in larger reductions of ozone in the urban areas. Further sensitivity runs would be required to evaluate more fully the effects of the vehicle emission uncertainties on the results.

The evaluation of the MC2-CALGRID modeling system is still under way, and sensitivities of the system to changes in meteorology, emissions, and reaction mechanism are continually being explored. One of the potentially largest sources of uncertainty in the emission inventory is the magnitude and speciation of the biogenic emissions. If biogenic emissions are underestimated, the model would overestimate reductions in ozone caused by any reductions in anthropogenic NMOCs. An important step in the validation of the modeling system will be made when it is applied to the rich chemical and meteorological data collected during the Pacific '93 field study (Steyn et al. 1997).

b. Effective emission controls for the Lower Fraser Valley

The results of the two sensitivity experiments and the two alternative fuel scenario simulations shown here would initially suggest that reducing the emissions of nonmethane organic compounds is the highest priority in any control strategy for the Lower Fraser Valley. A shift from gasoline-burning vehicles to natural gas vehicles would be an effective component of such a strategy.

The following factors should also be considered in developing a control strategy. First, the Lower Fraser Valley is characterized by very large biogenic emissions of organic compounds, which are impossible to regulate. Therefore, there is a significant lower bound to the NMOC emissions. Secondly, there are huge sources of NO_x other than light-duty gasoline vehicles, such as heavy-duty diesel trucks, marine activity, and other industrial sources, and these additional sources also have high NO_x -to-NMOC emissions ratios. The urban plume maintains a high NO_x -to-NMOC ratio for a long distance downwind of the primary emissions, and therefore, there is a long stretch of the plume that could be thought of as NMOC limited; under these conditions, we expect to see incremental reductions (increases) in ozone in the NMOC limited part of the plume for incremental reductions in NMOC (NO_x) emissions. With larger reductions in NO_x emissions, the NMOC limited segment of the plume shortens, while the downwind portion of the plume becomes NO_x limited due to loss of NO_x through chemistry and increase of NMOC from biogenic emissions.

Therefore, it is reasonable to expect that with moderate controls on the emissions of NO_x from these other major sources, in addition to the propane fuel substi-

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Therefore, it is reasonable to expect that with moderate controls on the emissions of NO_x from these other major sources, in addition to the propane fuel substi-

tution, the area of the domain covered by the NMOC-limited part of the plume could be significantly reduced. Further decreases in NO_x or NMOC emissions from other source sectors would then result in ozone reductions in the rest of the domain.

In addition, NO_x reductions would lower exposures to nitrogen-containing compounds, such as peroxyacetyl nitrate, reduce acid deposition, and improve visibility through reduction of nitrate aerosol.

This study is an initial attempt to forecast and evaluate a future-year emissions control scenario. A number of assumptions and limitations have been described, and further evaluation of the model is essential. Nonetheless, it is clear that the photochemical modeling system can provide an effective tool for selection of industrial processes and technology to achieve air-quality objectives as well as for developing an optimum growth plan for the region. Further applications of the modeling system are likely to include evaluation of other alternative fuels and reformulated gasolines, assessment of emissions trading propositions, and evaluation of potential growth scenarios.

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