REGIONAL GROUND-LEVEL OZONE STRATEGY

For the Canadian Lower Fraser Valley Region

April 2014

Fraser Valley Regional District | Metro Vancouver | BC Ministry of Environment | Environment Canada | Port Metro Vancouver

Authors

This Strategy has been produced jointly by:

- Fraser Valley Regional District (FVRD)
- Metro Vancouver
- BC Ministry of Environment (BC MOE)
- Environment Canada (EC)
- Port Metro Vancouver (PMV)

Members from each of these organizations sit on a Regional Ground-Level Ozone Strategy Steering Committee (RGLOSSC), which is chaired by the FVRD and supported by Metro Vancouver staff.

Purpose

To develop a plain-language document that provides a foundation for policies to control ozone precursors in the Canadian Lower Fraser Valley.

The objectives of this document are: (1) to present the state of scientific understanding about ground-level ozone formation in this region, (2) to establish broad policy directions based on the current scientific understanding, and (3) to identify areas for further study.

This Strategy will be a living document that is updated as needed by the RGLOSSC to reflect new research and policy initiatives.

Responsibility for implementing this Strategy rests in the hands of each managing authority - the Greater Vancouver Regional District within the boundaries of the Metro Vancouver region and the Province of BC within the confines of the FVRD.

Figure 1: Lower Fraser Valley airshed.

Geographic Scope

Although this document describes the state of scientific knowledge in the entire Lower Fraser Valley (LFV) airshed (see Figure 1), the policy recommendations are limited to the Canadian portion of the LFV region (Metro Vancouver and the southwestern portion of the Fraser Valley Regional District). This geographic scope is consistent with the approach taken by Canadian agencies to inventory and model emissions and air quality in the region.

The science supporting this document are based on observations of actual emissions monitored throughout our region over the last twenty years ("trends"), and, to a lesser extent, computer modelling. Both of these techniques involve some degree of uncertainty, especially with more detailed analysis. To combat uncertainty, we looked at a wide range of trends, from many stations and in various duration combinations. As well, modelling results were compared with trends and found to be consistent. This provides greater confidence in the findings.

What is Ground-Level Ozone?

The term “ozone” can be confusing. We have been told that the “ozone layer” is critical to life on Earth and in need of protection. However, while ozone in the upper atmosphere plays an important role protecting life on the planet from harmful ultraviolet radiation, ozone produced near the surface of the earth has environmental, health and economic impacts. The latter is referred to as ground-level ozone.

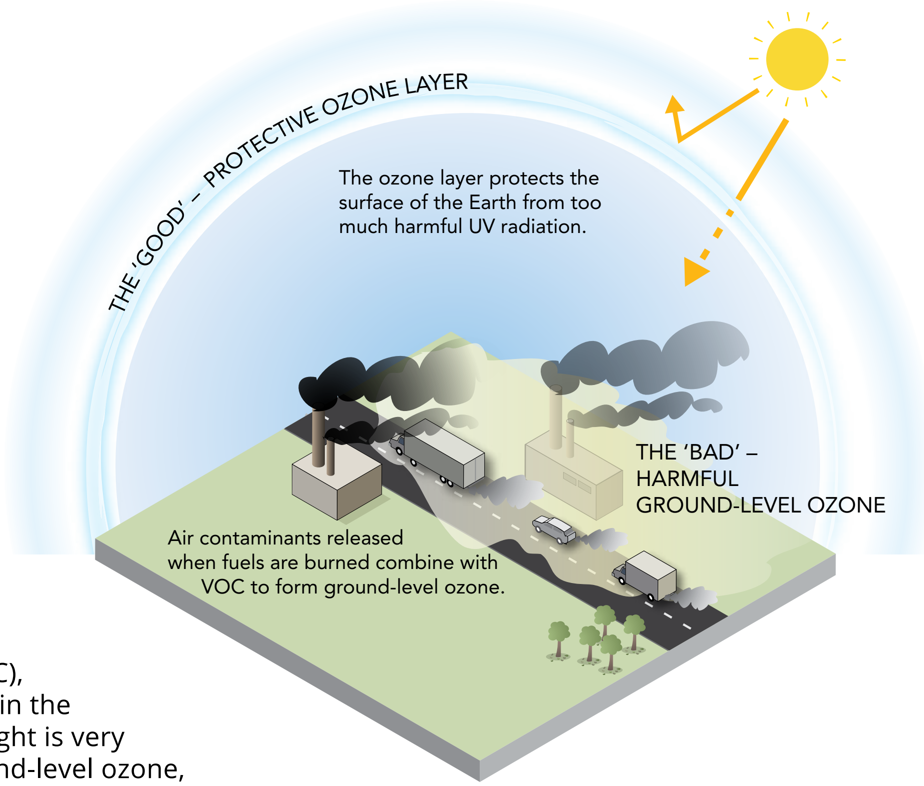
Ground-level ozone forms when nitrogen oxides (NO_X) and volatile organic compounds (VOC), the “precursor” chemicals, react in the presence of sunlight. Since sunlight is very important in production of ground-level ozone, the highest levels are often observed during the summer. Ozone levels typically peak during the late afternoons of hot, sunny summer days with stagnant weather conditions.

For more information about ground-level ozone, please see:

"The Good, The Bad ... And the Ozone"

metrovancouver.org/services/air/Documents/GLOFactsheet.pdf

Figure 2: Ground-level ozone versus the ozone layer.
Source: *Caring for the Air 2012*



‘...elevated ground-level ozone concentrations sometimes occur in the eastern portion of the region on hot summer days.’

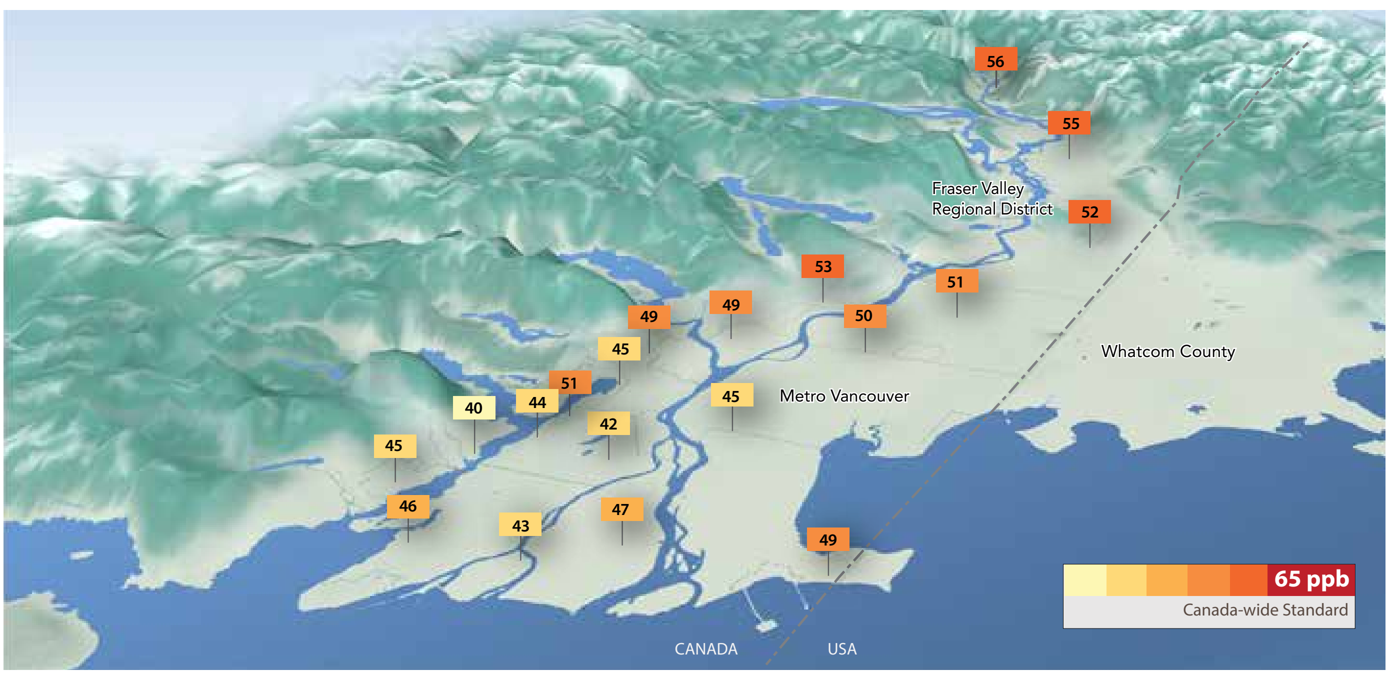
Ground-Level Ozone Formation in the Lower Fraser Valley

Summertime Peak Ozone

Although this region generally experiences good air quality, elevated ground-level ozone concentrations sometimes occur in the eastern portion of the region on hot summer days. Figure 3 shows that air quality stations in the eastern portion of the region (eastern Metro Vancouver and southwestern FVRD) record higher peak ozone concentrations than in western parts of the region. This is due in part to the weather conditions in the eastern portion of the valley, where temperatures are warmer and air circulation is more restricted due to the surrounding mountains.

Summertime ozone episodes occur under hot summer days with light winds. On fair weather days thermal (temperature-driven) inversions often occur, setting the stage for the formation of smog. During an inversion, a layer of warm air settles over and traps a layer of cooler air near the ground. With the region’s mountains limiting pollutants from dispersing horizontally and a thermal inversion

Figure 3: Ground-level ozone levels based on the Canada-wide standard metric for 2012.
The Canada-wide standard is a measure of highest sustained level of ozone occurring during the year.



limiting pollutants from mixing vertically, the conditions become ideal for sun-driven chemical reactions that convert VOC and NO_x emissions into ozone and other by-products typically found in smog.

With higher population density in Metro Vancouver, the main ozone precursor emissions tend to be released in the western part of the valley, primarily from the morning commute. These morning emissions tend to be carried inland by light winds. Exactly where these emissions (and hence smog) end up is governed by a delicate balance between the strength of the slope flow, sea breeze, and valleys flow (see Figures 4a-c).

Three potential paths are:

1) Up the slope of the North Shore mountains;

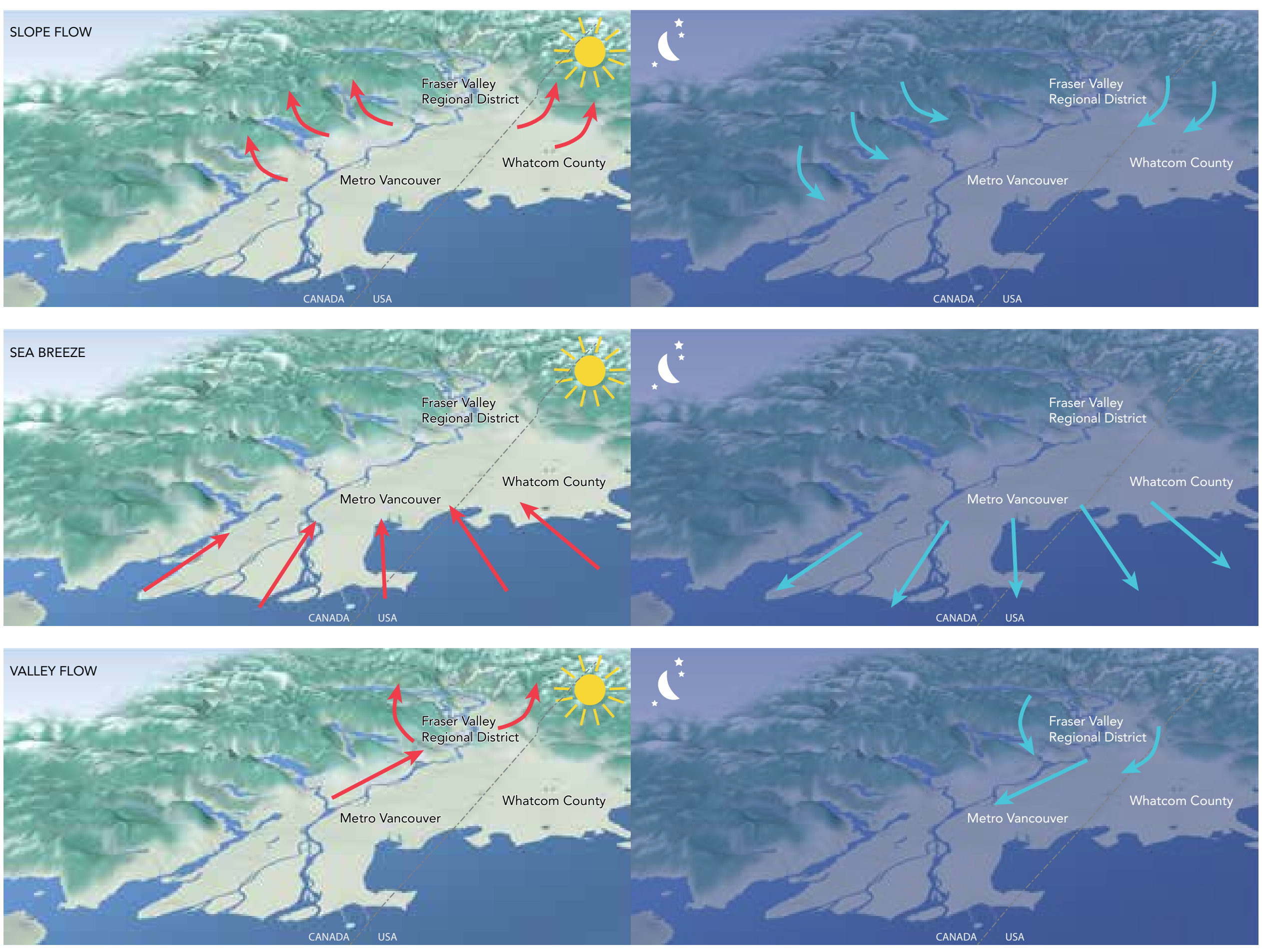
2) Towards Abbotsford;

3) Towards Chilliwack and beyond to Hope or up Harrison Lake.

At night the wind flows typically reverse direction leading to the merging of weak outflows from the tributary valleys, drainage flows from the mountains and the land breeze blowing down the valley. These nocturnal winds tend to push whatever ozone that was produced during the day and any left-over precursor emissions toward the coast. These may be either vented into Georgia Strait (sometimes ending up over the Gulf Islands) or re-circulated by the next day's sea breeze.

Figure 4 a-c:
Summertime peak ozone season day and nighttime airflow patterns in the Canadian Lower Fraser Valley, showing slope flow, sea breeze and valley flow.

4a



‘peak ozone levels are coming down’

‘non-peak ozone levels have been rising’

Springtime Moderate-to-High Ozone

Fortunately, summertime peak ozone levels are coming down – there are fewer extremely high ozone days over time. This is good news, especially for areas in eastern parts of the region which tend to host these peak ozone occurrences. However, non-peak ozone levels have been rising over time in both the western and eastern portions of our region. This trend is of concern because of the health effects associated with chronic exposure to ozone. The average ozone level is rising over time, which runs the risks associated with chronic exposure. This is of concern because there are no known safe levels of ozone exposure. See the box on page 14 for more information on the impacts of ground-level ozone.

Contributing to rising annual average ozone levels are increases in ozone levels in the spring. There are several explanations for the elevated springtime ozone phenomenon:

1) Rapid photochemical reactions in the springtime due to higher UV as daylight hours extend.
2) Ozone transport from Asia due to faster jet stream in the springtime.
3) Tropospheric mixing in the springtime.
4) Stratospheric intrusions – transport of air rich in ozone from the stratosphere.

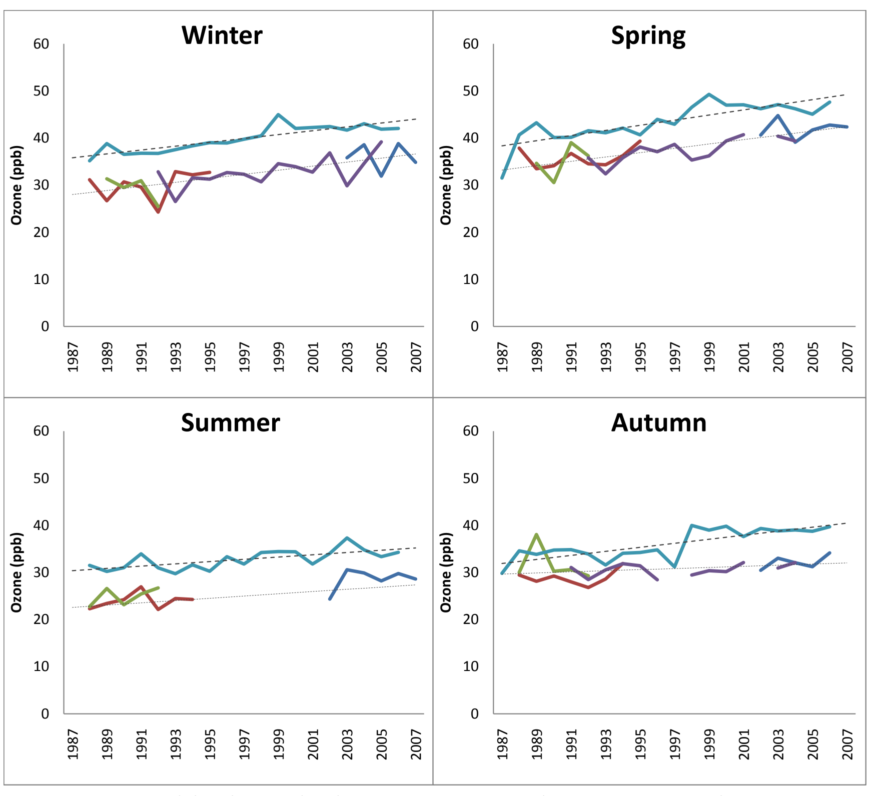
All of these phenomena result from natural meteorological forces and cannot be addressed by this Strategy.

'... rise of background ozone levels.'

Monitoring Background Ozone in Ucluelet

In partnership with the BC Ministry of Environment and Environment Canada, Metro Vancouver continues to provide support for the West Coast Marine Boundary Layer Background Station located in Ucluelet on Vancouver Island. The background station, located at the Amphitrite lighthouse, is a remote station positioned to monitor background air quality in the lower atmosphere on the west coast of BC.

The background station, established in 2010, will allow a more complete understanding to be developed of the effect of background air masses transported into BC on local and regional air quality.



Background Ozone Levels

Another key concern in the region is the rise of background ozone levels. Until fairly recently, air pollution in the LFV was thought to originate entirely within the region. With intensifying use of fossil fuels globally, particularly in Asia, medium and long range transport of pollutants from human activity is creating an impact on background ozone levels in the LFV. Background ozone is the level of ozone that is present even without local contributing emissions. When ground-level ozone is measured as an annual average, we find a slight upward global trend of about 1 to 5 parts per billion per decade. We have limited ability to control this global trend, but we need to prepare for it.

Figure 5: Background Ozone Levels by season as measured at a number of remote sites along the Pacific coast and at Mace Head, Ireland. North American sites are based on 1-hr average ozone concentrations during the presence of high (>3m/s, except > 2m/s at Olympic NP) northwesterly wind (225 deg <wind direction <360deg). For Mace Head, monthly mean ozone data from the Derwent et al. (2007) study was used and 3-month seasonal averages were calculated based on those numbers. (Source: Parrish et al., 2012)

Emission Sources

Air pollution results from an interaction of meteorology, chemistry and emissions. The LFV is an urbanized area with relatively few industrial sources. Most of the region's 2.5 million inhabitants are concentrated in Metro Vancouver. Moving eastward from Metro Vancouver, the region becomes increasingly rural, with agricultural activity dominating. Towards the south, an industrial area extends along the western portion of Whatcom County, ending in the city of Bellingham.

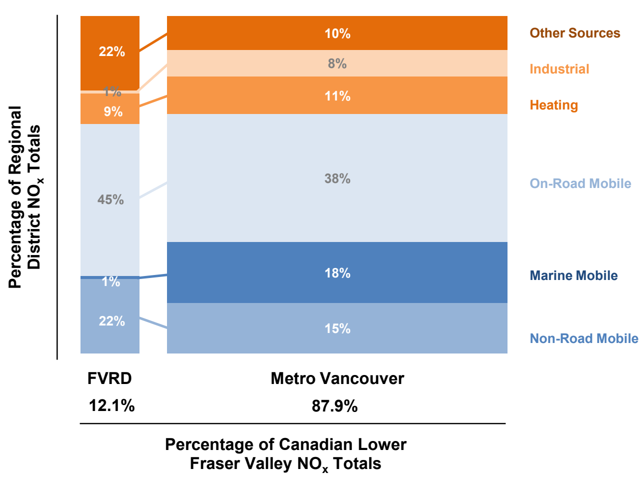


Figure 6: 2010 NOx emissions for the LFV by geographic location and source sector. Note that the width of the bars represents the relative amount of emissions from the two regional districts.

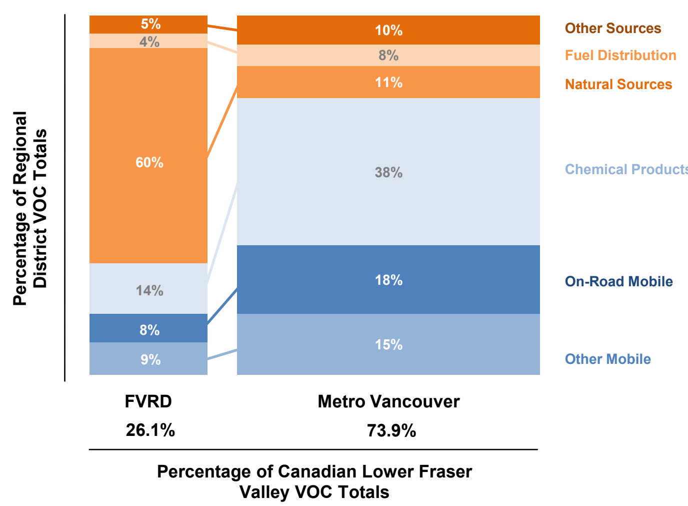


Figure 7: 2010 VOC emissions for the LFV by geographic location and source sector. Note that the width of the bars represents the relative amount of emissions from the two regional districts.

In 2010, NO_x emissions were dominated by mobile sources, namely, cars and trucks (onroad), nonroad equipment and ships (as illustrated in Figure 6). Natural gas use in homes, offices and industry also plays a role in NOx emissions. In 2010, the chemical products sector (e.g. industrial, commercial, and consumer products like paints, stains, varnishes, solvents, and thinners) became the main anthropogenic source of VOC, overtaking cars and light trucks (as shown in Figure 7).

NO_x emissions are projected to decrease continuously over the 20-year forecast period, primarily due to strict engine emission standards (see Figure 8). VOC emissions show a declining trend until 2020, after which emissions are projected to increase due to increase in chemical products use (see Figure 9).

The amount of ozone that forms is dependent on both the absolute and relative amounts of NO_x and VOC; therefore the future emissions trends and location of the emissions are important to consider. The relative amount of NO_x-to-VOC appears to be decreasing. This concept will be explored in detail in the next section.

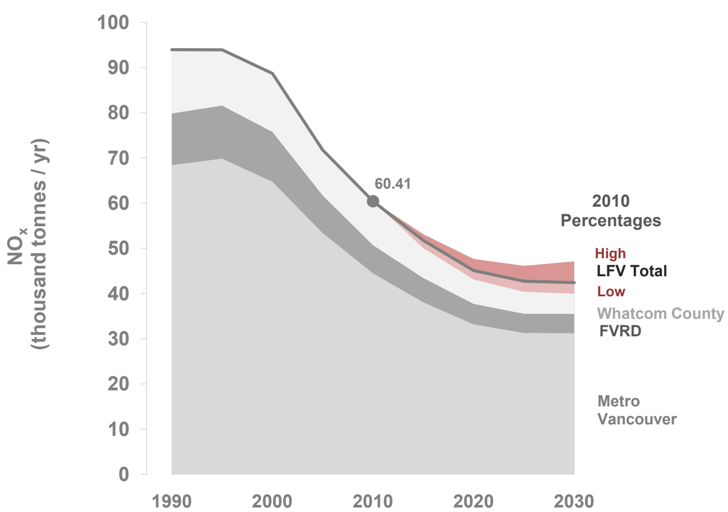


Figure 8: NO_x emissions trend for the LFV by location, including a low, moderate and high forecast for the LFV Total.

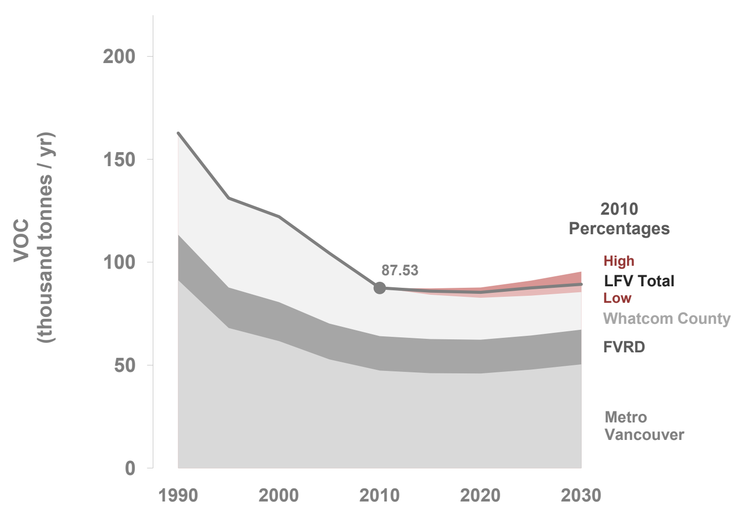


Figure 9: VOC emissions trend for the LFV by location, including a low, moderate and high forecast for the LFV Total.

VOC versus NO_x Limitation

> 'The western part of the region is consistently VOC-limited.'

Ground-level ozone is created when NO_x and VOC interact in the presence of sunlight. The amount of ground-level ozone produced depends on the absolute and relative amounts of NO_x to VOC. At an optimal ratio, we get lots of ozone.

When there is insufficient NOx to form ozone, an area or neighbourhood can be called "NO_x limited". When VOC are lacking, an area can be called "VOC limited". Reducing the wrong pollutant can either produce no reduction in ozone concentration or worse, inadvertently increase ground-level ozone. It is critical, therefore to understand whether an area is NOx limited or VOC limited. See page 11 for an analogy that compares ground-level ozone to noisy drumming.

Atmospheric scientists studying the LFV now understand that the region can be both NO_x and VOC limited and that the ratio varies both geographically and over time.

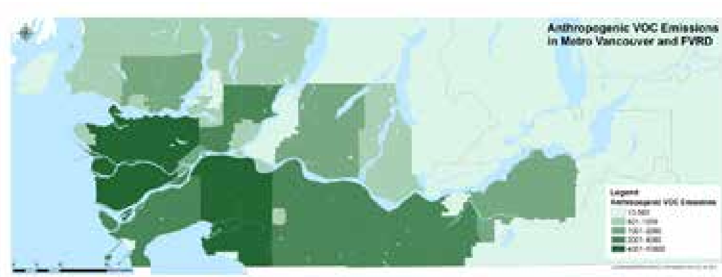
In order to develop a Ground-Level Ozone Strategy, it is important to understand and anticipate the changes in the relationships between the precursors.

The western part of the region is consistently VOC limited. This means that in order to reduce ozone production, VOC should be reduced in this region. This geographic area is roughly defined as the parts of Metro Vancouver west and south of Port Coquitlam, Langley and Pitt Meadows. With a dense population and high traffic volumes, the western part of the region produces a significant amount of NO_x emissions. Additionally, there are fewer natural sources of VOC (e.g., vegetation) in the western portion of Metro Vancouver. Figure 10 shows the annual NO_x emissions and Figure 11 shows the annual VOC emissions by municipality. This clearly shows that NO_x emissions are highest in the west and progressively decrease as you move eastward. Studies confirm that the western portion of the region is VOC limited on all days, irrespective of temperature.

Figure 10: Total NO_x emissions in 2010 by municipality

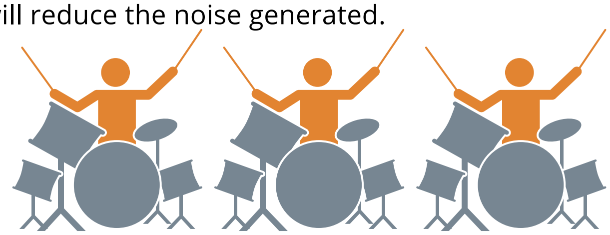
Figure 11: Total VOC emissions in 2010 by municipality

Figure 12: Human-induced VOC emissions in 2010 by municipality



Ground-Level Ozone as Noisy Drumming?

The formation of ground-level ozone could be compared to unpleasant, noisy drumming. Creation of this ear-offending situation (which is analogous to creation of ground-level ozone) requires a ratio of drummers to drum sets (or, VOC to NOx); in this case, the ratio is one-to-one. When one drummer is combined with one drum set, noisy drumming ensues. The more drummers and drum set combinations, the greater the racket. In a situation where there are exactly the same number of drummers and drum sets (for example, 3 and 3 in the image below), removing either drum set or drummer will reduce the noise generated.



In many cases, however, the number of drummers and drum sets is mismatched. When this occurs, to quiet the room, you need to be more strategic. For example when there are more drum sets than drummers, to stop the noise, getting rid of drum sets is ineffective. In this scenario, if you remove a drum set, the drummer will just move to an empty drum set and continue to make noise. To reduce noise, you need to get rid of drummers.

Alternately, if there are more drummers than drum set, getting rid of drummers is ineffective in reducing the decibel level in the room, as for every drummer you remove; a standby drummer is available to take-over the noise-making. In this case, you need to get rid of drum-sets.

Keep in mind that this is a simplified illustration only which cannot capture the full complexity of the chemistry.

‘The eastern part of the region is VOC limited on most days but NO_x limited on the hottest summer days.’

‘A transition zone delineates the VOC and NO_x limited regions.’

The eastern part of the region is VOC limited on most days but NO_x limited on the hottest summer days. On the hottest summer days, more VOC are released from natural (e.g. trees) and human-made sources (e.g., evaporation of fuels and chemicals). These VOC combine with the available NO_x emissions to form ozone, leaving an excess of VOC in the air. The limiting factor to ozone formation on these days is therefore NO_x, not VOC. If NO_x can be reduced in the eastern portion of the region on the hottest days, ozone production should also be reduced.

A transition zone delineates the VOC and NO_x limited regions. On hot summer days the transition zone separates the region into a VOC limited region in the southwest and NO_x limited region in the northeast. The exact location of the transition zone is influenced by emissions and meteorology moving geographically over time and space. This “zone” is depicted in Figure 13 as a shaded area. This depiction is estimated from air quality modelling and historic ambient air quality measurements.

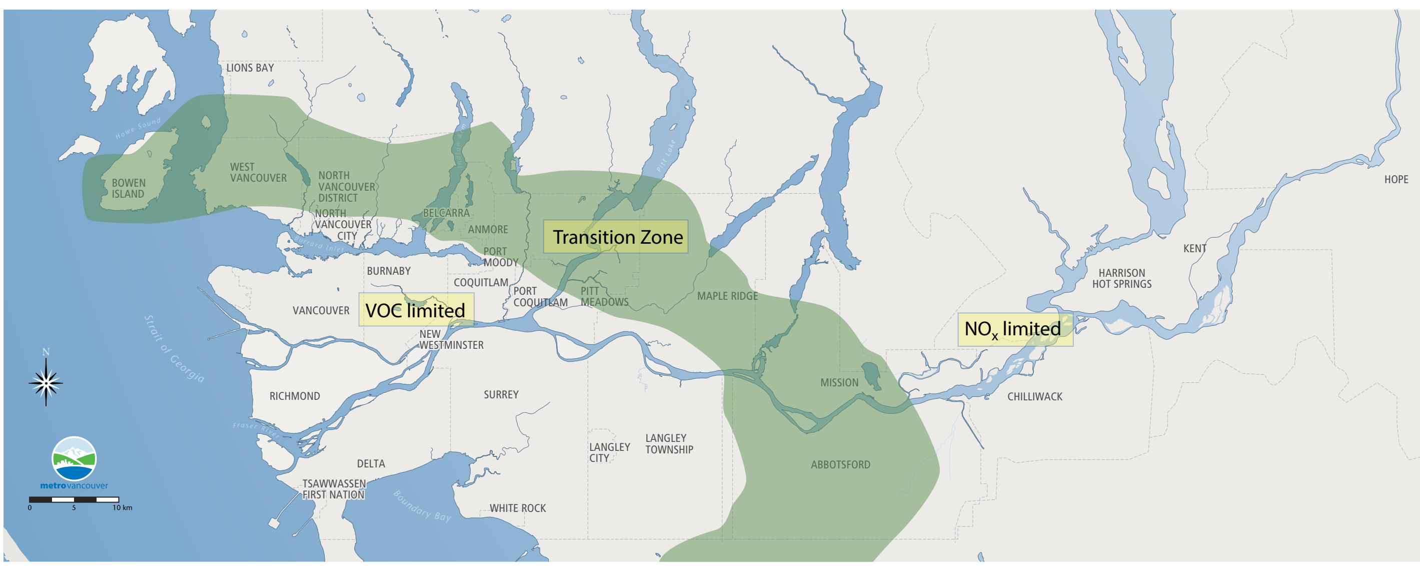


Figure 13: VOC and NO_x limited areas on the hottest summer days, based on CMAQ computer models using 2005 emissions. The shaded region, or Transition Zone, indicates the extent of the boundary between these two regions, due to meteorological variability.

Goals

This Strategy has the following goals:

- Minimize chronic exposure to ground-level ozone.
- Minimize the frequency and severity of acute exposure to “peak ground-level ozone”.
- Minimize impact on ecosystems, plant life and agricultural crops to ground-level ozone.
- Maximize co-benefits (e.g., reduced air toxics or improved visibility).

Impacts of Ground-Level Ozone

HEALTH IMPACTS

Evidence from numerous studies over several decades indicates that exposure to ozone causes health effects. There is currently more evidence for acute ozone exposure impacts than chronic exposure impacts.

ACUTE EXPOSURE HEALTH EFFECTS	CHRONIC EXPOSURE HEALTH EFFECTS
• Respiratory impacts - reduced lung function, respiratory tract inflammation, respiratory effects (e.g. coughing, wheezing), exacerbation of pre-existing respiratory conditions (e.g. asthma) - impaired immune response, increased susceptibility to respiratory infections - increased emergency room visits, hospital admissions, use of respiratory medication • Cardiovascular impacts - heart rate variability, elevated biomarker counts indicating oxidative stress • Central nervous system impacts - neurological effects, including short- and long-term memory impairment and sleep impacts • Mortality - increased number of cardiopulmonary-related deaths	• Respiratory impacts - reduced lung function, asthma onset in children, aggravated pre-existing respiratory conditions - structural airway changes and lung tissue damage in animal toxicology studies - increased emergency room visits, hospital admissions, use of respiratory medication • Reproductive and developmental impacts - some evidence for increased pre-term births, low birth weights • Mortality - increased number of respiratory deaths

Scientists have not been able to determine a “safe” level for ozone. This means that health benefits can also be achieved by reducing exposure in areas where ozone levels are already relatively low. This is in contrast with pollutants such as sulphur dioxide which have lowest observable adverse effects levels, below which no impacts are found. Environment Canada and Health Canada have determined the ozone dose-response curve to be approximately linear above concentrations of 10 ppb. Beyond that level, negative health effects increase in proportion to the rise in concentration. To put this in context, background ozone concentrations are about 25-35 ppb across Canada, and are exhibiting an increasing trend.

ENVIRONMENTAL IMPACTS

Plants and crops can also be damaged by ground-level ozone.

Plant exposure to ground-level ozone can result in visible injury, reduced growth and yield, and alternation of competitive patterns within plant communities and ecosystems (Environment Canada and Health Canada, 1999; Guderian et al., 1985). Studies conducted in the 1990s found that ground-level ozone was contributing to agricultural losses of up 4%, with a value of tens of millions of dollars each year in the Canadian Lower Fraser Valley.

Strategic Policy Directions

The following are guiding statements which are intended to advance policy and program development based on the strategy's goals and the state of the science. These directions emphasize the different influences of VOC and NOx during peak and non-peak periods.

Peak Ozone Periods

Peak ozone periods refer to the hottest summer days, most conducive to high ozone concentrations. A more scientific definition of peak ozone periods are the top 2% of days with the highest ozone readings.

A1. **Region-wide, continue current actions for ozone episodes**. Trends have shown a reduction in intensity and frequency of peak ozone episodes in the region over the past decade. This situation will continue to be monitored regularly. In the meantime, it is recommended that existing programs and actions during high ozone days (such as ozone advisories) are continued.

A2. **East of the transition zone, enhance NOx reductions.** As this sub-region is NOx limited on peak ozone days, measures to reduce NOx emissions on these days will have the most benefit. These measures could be short-term and connected to ozone advisories.

A3. **West of the transition zone, reduce VOC emissions during peak (and non-peak) periods.** The western part of the region is VOC limited at all times; therefore reducing VOC emissions at all times will reduce ground-level ozone production. Researchers confirm that reducing VOC in the western part of the region will not adversely affect the eastern part of the region.

Non-Peak Ozone Periods

Aside from the 2% of days considered peak ozone days, the rest of the year is considered a non-peak period. Sometimes non-peak periods are referred to as "days contributing to the annual average".

B1. **Region-wide, reduce VOCs to reduce ground-level ozone.** Focus on VOC emitted during non-peak periods or that contribute to average emissions levels through policy measures that reduce VOC emitted constantly across all seasons throughout the year.

B2. **Region-wide, reduce VOC emissions that are most reactive in the presence of sunlight and which lead to other co-benefits,** such as reduced air toxics, improved visual air quality, greenhouse gases and reduced particulate matter formation.

B3. **West of the transition zone, any NOx reductions need to be accompanied by equal or greater VOC reductions.** As the western part of the region is clearly VOC limited, a reduction in NOx emissions, without a corresponding reduction in VOC emissions, could inadvertently increase ozone levels.

Further Research

This Strategy will be a living document that is updated as needed to reflect new scientific understanding. Below are some areas in which research will be focused:

- Compiling data on the most reactive VOCs, including quantities, location and toxicity, in order to prioritize emission reduction efforts.
- Continual monitoring to track how current patterns shift over time and re-evaluating progress regularly (every decade).
- Modelling studies to understand the impact of NOx emissions in the western part of the LFV on ground-level formation both west and east of the transition zone.
- Modelling studies to understand the impact of NOx emissions in the transition zone.
- The impact of changing meteorology: climate change is expected to generate further unpredictability in the existing system. One of the likely effects is more frequent and severe "hot spells", which enhance ground-level ozone formation.
- Understanding trends and levels of background ozone transported to the region through monitoring at the Ucluelet station and accessing information from other West Coast background monitoring sites.

Glossary

Acute Exposure .... Exposure to a pollutant for a relatively short amount of time (e.g., minutes or hours), typically at a relatively high concentration.

Air Toxics .... Pollutants that are known or suspected to cause cancer or other serious health effects, such as reproductive effects or birth defects, or adverse environmental effects. Examples include dioxin, asbestos, toluene, and metals such as cadmium, mercury, chromium, and lead compounds.

Canada Wide Stds .... The Canada-wide standard is a measure of highest sustained level of ozone occurring during the year. It is based on the average of values from the three most recent years. The concentrations that are used in this averaging calculation are the fourth highest daily maximum 8-hour-average ozone concentration for each of the three calendar years.

Chronic Exposure .... Exposure to a pollutant for a relatively long period of time (e.g., months or years), typically at a moderate concentration.

Co-Benefits .... Secondary, or "side", benefits achieved from reducing ozone or precursors to ozone. Examples of co-benefits include reduced particulate matter, air toxics, greenhouse gases and visual air quality improvement.

Dose-Response .... The change in health effects caused by different levels (concentrations and durations) of exposure.

High Levels .... Elevated ozone concentrations that are persistent in duration lasting from several hours to several days.

Moderate Levels .... Slightly elevated ozone concentrations in the long term (based on the annual average).

Ppb .... Parts per billion – expression of concentration, based on the proportion of a substance in 1,000,000,000 parts of air.

Peak Levels .... Short spikes in ozone concentrations lasting about an hour or so. These occur typically in the summertime.

Precursors .... A substance that participates in a chemical reaction that produces another compound. NO_x and VOC are precursors to ground-level ozone.

Stratosphere .... The layer of the earth's atmosphere above the troposphere, extending to about 50 km above the earth's surface (the lower boundary of the mesosphere).

Stratospheric Intrusion .... Irreversible downward transport of stratospheric air into the troposphere.

Troposphere .... The lowest region of the atmosphere, extending from the earth's surface to a height of about 6–10 km, below the stratosphere.

References

- Ainslie, B and D. G. Steyn, 2007: Spatiotemporal Trends in Episodic Ozone Pollution in the Lower Fraser Valley, B.C. in Relation to Meso-scale Atmospheric Circulation Patterns and Emissions. Journal of Applied Meteorology. 46 (10), 1631-1644
- Ainslie, B. D., 2004: A photochemical model based on a scaling analysis of ozone photochemistry. Ph.D. thesis, University of British Columbia, Vancouver, B.C., Canada, 311 pp.
- Ashmore, M. R., 2005, Assessing the future global impacts of ozone on vegetation, Plant, Cell and Environment,
- Bovis, P.E. 2003. Stratosphere troposphere exchange and its influence on surface ozone concentrations in the lower Fraser Valley. M.Sc. thesis, Atmospheric Science Programme, University of British Columbia.
- Environment Canada and U.S. EPA, 2004, "Characterization of the Georgia Basin/Puget Sound Airshed". *http://www.ec.gc.ca/Publications/BFA49636-3310-4AAA-BB55-8054B1791178/02AirshedGBPSreporte.pdf*
- Fiscus, E. L., Booker, F. L. and Burkey, K. O., 2005, Crop responses to ozone: uptake, modes of action, carbon assimilation and partitioning, Plant, Cell and Environment, 28, 997-1011.
- Finlayson-Pitts, B. J. and Pitts, J. N. Jr, 1993, Atmospheric chemistry of tropospheric ozone formation: scientific and regulatory implications, Journal of the Air and Waste Management Association, 43 (8), 1091-1100.
- Health Canada. Canadian Smog Science Assessment Volume 2: Health Effects. 2013.
- Hedley, M. and D. L. Singleton, 1997: Evaluation of an air quality simulation of the Lower Fraser Valley - I. Meteorology. Atmospheric Environment, 31, 1605--1615.
- Hedley, M., R. McLaren, W. Jiang, and D. L. Singleton, 1997: Evaluation of an air quality simulation of the Lower Fraser Valley - II. Photochemistry Atmospheric Environment, 31, 1617--1630.
- Hedley, M., W. Jiang, R. McLaren, and D. L. Singleton, 1998: Modelling of future-year emissions control scenarios for the Lower Fraser Valley: Impacts of natural gas and propane vehicle technologies. Journal of Applied Meteorology, 37, 1190--1204.
- Hemispheric Transport of Air Pollution 2010. *http://www.htap.org/*
- Jaffe, Daniel, Heather Price, David Parrish, Allen Goldstein, Joyce Harris. 2003. Increasing background ozone during spring on the west coast of North America. GEOPHYSICAL RESEARCH LETTERS, VOL. 30, NO. 12, 1613, doi:10.1029/2003GL017024, 2003
- Jiang, W., Singleton, D. L., Hedley, M. and McLaren, R., 1997, Sensitivity of ozone concentrations to VOC and NO_x emissions in the Canadian Lower Fraser Valley, Atmospheric Environment, 31 (4), 627-638.
- Joe, H., D. G. Steyn, and E. Susko, 1996: Analysis of trends in tropospheric ozone in the Lower Fraser Valley, British Columbia. Atmospheric Environment, 30, 3413--3421.
- Krzyzanowski, K., I.G. Mckendry, J.L. Innes, 2006: Evidence of elevated ozone concentrations on forested slopes of the Lower Fraser Valley, British Columbia, Canada. Water, Air and Soil Pollution, 173, 273-287.
- Metro Vancouver 2012, 2011 Lower Fraser Valley Air Quality Monitoring Report Summary. *http://www.metrovancouver.org/about/publications/Publications/AmbientAirQuality2011.pdf*
- McKendry, I. G., Steyn, D. G., Lundgren, J., Hoff, R. M., Strapp, W., Anlauf, K., Froude, F., Martin, J. B., Banta, R. M. and Oliver, L. D.: 1997, 'Elevated ozone layers and vertical down-mixing over the Lower Fraser Valley BC', Atmos. Environ. 31, 2135–2146.
- McKendry, I.G. 2006. Background Concentrations of PM2.5 and Ozone in British Columbia, Canada. Prepared for the British Columbia Ministry of Environment, March 2006.
- D. D. Parrish, K. S. Law, J. Staehelin, R. Derwent, O. R. Cooper, H. Tanimoto, A. Volz-Thomas, S. Gilge, H.-E. Scheel, M. Steinbacher, and E. Chan, 2012: Long-term changes in lower tropospheric baseline ozone concentrations at northern mid-latitudes. Atmospheric Chemistry and Physics, 12, 11485-11504.

- Pottier, J. L., H. P. Deuel, and S. C. Pryor, 2000: Application of the UAM-V and use of indicator species to assess control strategies for ozone reductions in the Lower Fraser Valley of British Columbia. Environmental Monitoring and Assessment, 65, 459--467.
- Pryor, S. C., I. G. McKendry, and D. G. Steyn, 1995: Synoptic scale meteorological variability and surface ozone concentrations in Vancouver, British Columbia. Journal of Applied Meteorology, 34, 1824--1833.
- Pryor, S. C. and D. G. Steyn, 1995: Hebdomadal and diurnal cycles in ozone time series from the Lower Fraser Valley, B. C. Atmospheric Environment, 29, 1007--1019.
- Pryor, S. C., 1998: A case study of emission changes and ozone responses. Atmospheric Environment 32, 123--131.
- Reuten et al. 2012. Based on abstract only. Impact of Climate Change on Ozone Pollution in the Lower Fraser Valley, Canada in Atmosphere-Ocean, 50(1), 42-53. NB meteorological considerations only, emission and background were assumed to be same as at present.
- Statistics Canada. The Canadian Environmental Sustainability Indicators: On population-weighted ground-level ozone. 2008. Available from: *http://www.statcan.gc.ca/pub/16-002-x/2008002/article/10624-eng.htm#a2*
- Steyn, D. G., M. Baldi, and K. Stephens, 1996: Observation based analysis of photochemical smog in the Lower Fraser Valley using two analytical schemes Tech. Rep. Occasional Paper no. 41, Department of Geography, The University of British Columbia.
- Steyn, D.G., B. Ainslie, C. Reuten and P . L. Jackson. 2013. A retrospective analysis of ozone formation in the Lower Fraser Valley, British Columbia, Canada. Part I: Dynamical Model E valuation. Atmosphere-Ocean. 51 (2), 153-169.
- Suzuki, N. M., 1997: Application of the Urban Airshed Model in the Lower Fraser Valley, British Columbia, M.S. thesis, University of British Columbia, Vancouver, B.C., Canada, 111 pp.
- Tonnesen, G. S. and R. L. Dennis, 2000: Analysis of radical propagation efficiency to assess ozone sensitivity to hydrocarbons and NO_x 2: Long-lived species as indicators of ozone concentration sensitivity. Journal of Geophysical Research, 105, 9227--9241.
- United States Environmental Protection Agency. Integrated Science Assessment for Ozone and Related Photochemical Oxidants. 2013. Available from: *http://www.epa.gov/ncea/isa/ozone.htm*
- Vingarzan, R. and B. Taylor, 2003: Trend analysis of ground-level ozone in the Greater Vancouver/Fraser Valley area of British Columbia. Atmospheric Environment, 37, 2159--2171. Vingarzan, R. (2004). A review of surface ozone background levels and trends. Atmospheric Environment, 38; 3431-3442.
- Vingarzan, R. and P. Schwarzhoff, DRAFT 2008, 'Ozone Trends and Reactivity in the Lower Fraser Valley'.
- Vingarzan et al. 2012. Air Quality Observations at the Amphitrite Point Marine Boundary Layer Site. UBC Create Symposium. December 2012.
- World Health Organization. "Review of evidence on health aspects of air pollution – REVIHAAP." 2013. Available from: *http://www.euro.who.int/en/health-topics/environment-and-health/air-quality/publications/2013/review-of-evidence-on-health-aspects-of-air-pollution-revihaap-project-final-technical-report*
- World Health Organization. Health risks of ozone from long-range transboundary air pollution. 2008. Available from: *http://www.euro.who.int/__data/assets/pdf_file/0005/78647/E91843.pdf*
- Wu, S., Mickley, L. J. Leibensperger, E. M., Jacob, D. J., Rind, D., and Streets, D. G., 2008, Effects of 2000-2050 global change ozone air quality in the United States, Journal of Geophysical Research, 113 (D06302), doi: 10.1029/2007JD008917.

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