Optimization of Mechanical Ventilation Operations for State Route 99 Tunnel

Yunlong Liu, PhD, PE
HNTB Corporation

Sean Cassady, PE, FPE
HNTB Corporation

Susan Everett, PE
Washington State Department of Transportation

ABSTRACT

Ventilation operations optimization provides safe tunnel facilities while introducing environmentally sustainable energy cost savings. This research considers normal operation scenarios of the SR99 Tunnel ventilation system that is designed to maintain acceptable air quality and mitigate fire hazards.

Acceptable air quality criteria are considered for the atmosphere within the tunnel and the nearby neighbourhood in proximity to the tunnel portals. Ventilation air demand is based on vehicle emissions calculated from traffic distribution and number of vehicles inside the tunnel as per PIARC guidelines and admissible SR99 project air quality standards. Analysis utilizing predicted traffic volume for 2015 and SES simulations showed that mechanical ventilation would not be required for free flow traffic conditions and exit portal emission concentration below a minimum threshold. However, zero exit portal emission criteria would require almost continuous mechanical ventilation.

KEY WORDS: Tunnel ventilation, air quality, traffic speed, traffic volume, mechanical ventilation, emissions

1 INTRODUCTION

Tunnel ventilation systems must provide safe tunnel environments while maintaining acceptable tunnel portal air quality and operating cost effectively. This paper explains the methods used to meet these three ventilation requirements for the SR 99 Alaskan Way Tunnel (the SR 99 Tunnel).

The SR 99 Tunnel is a major part of the Alaskan Way Viaduct Replacement Program which replaces an elevated section of State Route 99 in downtown Seattle. In addition to replacing the viaduct, the program includes projects that meet the local and regional traffic needs and allow the City of Seattle to reimagine the downtown waterfront.

The SR 99 Tunnel is approximately 3 km with uni-directional traffic on each level of the tunnel. The tunnel ventilation system includes eight extraction or exhaust fans (four at each end of the tunnel) and 17 jet fans. The jet fans at the exit portals can reverse flow. There is a dedicated air duct to exhaust the pollutants with the vertical exhaust dampers of 9.29 m^2 spaced at every 33 m along the tunnel side wall. By default, all dampers are closed. For free-flowing or traffic congested modes, polluted air can be exhausted at any location along the length of tunnel as required. The egress passage with egress doors spaced at every 650 feet allows occupants to evacuate when fire emergency condition develops. Ventilation scheme is illustrated in Figure 1.

Inhalation of emissions discharged from vehicles in a road tunnel can be harmful to the health of tunnel users, maintenance staff and the neighbourhood near the tunnel portals. Effective control of tunnel environment demands operating the mechanical ventilation system to exhaust and dilute the pollutants from inside the tunnel when there is heavy traffic density traveling at low speeds. Effective dispersion of the tunnel emissions by the ventilation system through ventilation stacks and the tunnel portals will maintain acceptable air quality in the neighbourhood near the tunnel. In order to efficiently operate the tunnel and minimize power consumption, operation of jet fans and exhaust fans should be optimized based acceptable environment criteria and parameters. Parameters influencing the tunnel environment include the following:

- Type and number of vehicles inside the tunnel;
- Traffic speed of the vehicle passing through the tunnel;
- Ambient air quality and acceptance environment criteria;
- Operation of tunnel mechanical ventilation system;
- Portal wind conditions;
- Tunnel length and grades, etc.

For the tunnel owner and users, it is expected that tunnel condition should remain beneath allowable pollutants concentration limits, and the emissions discharged from the tunnel portal should remain within acceptance criteria of the air quality requirements.

Many countries have road tunnel portal emission requirements. For example, Sydney Australia's M5 East tunnel has zero emissions at the tunnel portals [5]. This requires continuous operation of an extensive ventilation fan system. The SR 99 Tunnel must meet the Clean Air Act, Environmental Protection Agency (EPA) National Ambient Air Quality Standards (NAAQS), which specify maximum allowable concentrations for criteria pollutants. This standard can be met while a limited amount of vehicle emissions exit the tunnel through the portals thereby allowing for tunnel ventilation system optimization.

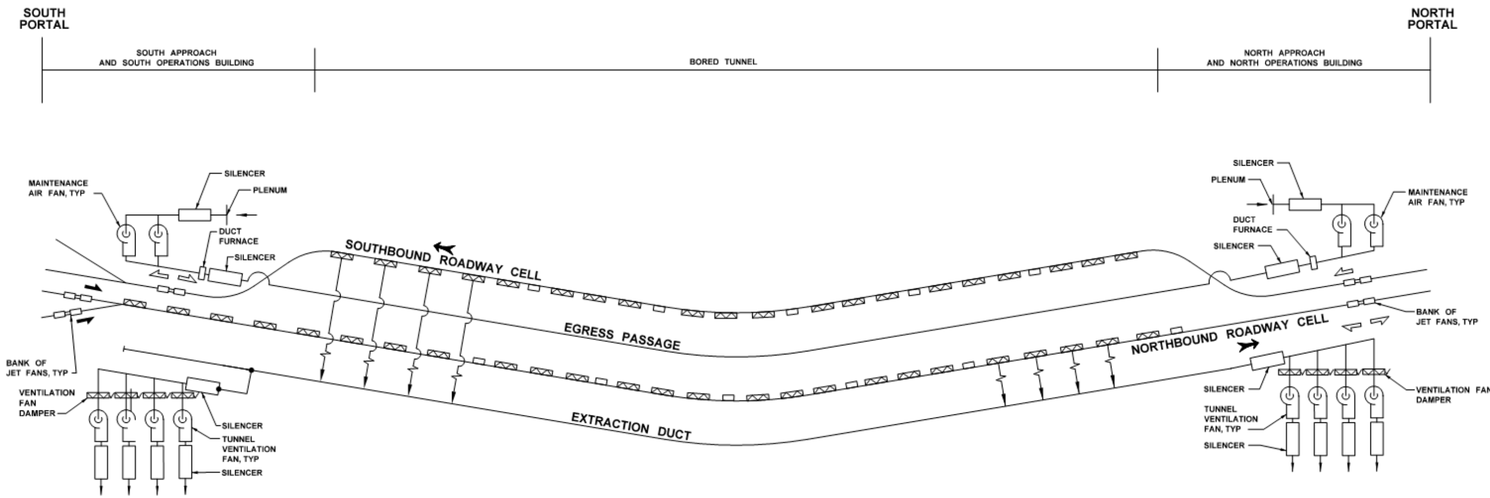

Figure 1: Ventilation Scheme for Normal Operations

2 AIR QUALITY CRITERIA

Background air quality used for modelling is summarized in Appendix B, Table-B1. This is the measure and modelled criteria pollutants in the SR 99 Tunnel area without the construction of the SR 99 Tunnel.
For the SR99 Tunnel, WSDOT based the air quality criteria for inside the SR 99 Tunnel on the OASHA air quality standards. The tunnel air quality acceptance criteria for CO, NO, NO_2 and PM_{10} are summarised in Appendix B, Table-B2.
The portal emission discharge could be prevented by exhausting all the tunnel emissions through tunnel ventilation discharge stacks, while imposing a reverse flow of 1.0 m/s into the exit portal with the jet fans. However, the energy cost for tunnel ventilation operations to exhaust all tunnel emissions through the ventilation stacks was approximately $2 million per year. Therefore, based on the SR 99 Tunnel's *Air Discipline Report Final EIS*[6] , an acceptable portal discharge criterion has been summarized in Table-1 below.

Table-1: Air Quality CO Acceptance Criteria for Portal Discharge

Peak hour time	Traffic speed	Vehicle/hr	Discharge location	Pollutant discharge limit
5:00PM	45 mph	3890	2015 mainline SB Jet	7.29 g/sec
			2015 South Portal VB	5.70 g/sec
8:00AM	46 mph	3430	2015 mainline SB Jet	6.46 g/sec
			2015 South Portal VB	5.05 g/sec

3 EMISSION CALCULATION

For a given tunnel, the controlling parameters that contribute to the tunnel air quality are the total emissions generated by the vehicles inside the tunnel, ambient air quality, vehicle generated piston effects, mechanical ventilation operation and portal wind conditions.

3.1 Vehicle Emissions
Vehicle emission inside tunnel is related to the vehicles type, traffic fleet, traffic speed, tunnel length, road grade, etc. Engine emission from an old vehicle is much higher because of lower combustion efficiency of earlier technology. At low speeds, for example, less than 5km per hour, more pollutants are generated than when vehicles travel at higher vehicle speeds. When a tunnel only has longitudinal ventilation, or no mechanical ventilation, pollutants will accumulate at the downstream (in direction of travel) portal.

3.2 Ambient Air Quality
Ambient, or background air quality, is added to the vehicle emissions to determine the tunnel emission pollution concentrations. The design is based on the predicted background concentration of CO, NOx and PM for 2015, which has been summarized in Appendix B, Table-B1, background concentration of CO, NO_2 and $PM_{10.}$

If the traffic density is high, traffic speed will reduce, and the total number of vehicles inside tunnel will increase due to a reduction in vehicle spacing. At high traffic speeds, over 35 mph for example, vehicle generated piston effects will induce airflow into/out of the tunnel and help dilute the emission concentration. Whether mechanical ventilation is required depends on whether the required fresh air supply can be generated with natural ventilation or the piston effects to sufficiently dilute the emissions.

3.3 Mechanical Ventilation

Mechanical ventilation operation includes running jet fans, exhaust fans or both types of fans to generate longitudinal ventilation flow and exhaust vitiated air out of the tunnel. Whether any fans are required or how many fans are required to operate depends on the traffic condition, traffic fleet and metrological condition, etc.

3.4 Portal Wind Conditions

Portal wind conditions can influence the airflow in the tunnel. Wind blowing into the entry or exit portals assists with the dilution of the vehicle emissions. Therefore, in this analysis, no wind condition is considered the worst scenario in terms of dilution of pollutants inside tunnel.

4 TUNNEL AIR QUALITY CONTROL ANALYSIS AND RESULTS

Based on the Seattle area vehicle fleet and data from the SR 99 Tunnel's *Transportation Discipline Report Final EIS* [7], emissions for selected traffic speeds were developed using MOBILE 6.2 (an EPA Vehicle Emission Modeling Software). The purpose is to optimize the fan operation schedule for traffic speeds between 3 mph to 65 mph.

The MOBILE 6.2 modelled CO, NOx and fine particulate matter (PM_{10}) emissions. With acceptance criteria for PM_{10} based on haze light extinction coefficient, a conversion factor of 1 $mg/m^3 = 0.0047\ m^{-1}$ was utilized to determine air demand.

The emission calculation results for the three km long SR99 Alaskan way tunnel have been summarized in Appendix B, Table-B3, B4 and B5. MOBILE 6.2 modelling concluded that CO was the driving pollutant and the air flow required to dilute CO to meet the tunnel air quality criteria ranges from 141 kcfm at 65mph to 549 kcfm at 3 mph.

The air flow requirement is calculated based on the ambient condition given in Table-B1, and the acceptance criteria given in Table-B2. Vehicle number is estimated based on the spacing between vehicles at certain traffic speeds as recommended by PIARC 2005[2]. Table-B3, B4 and B5 summarize air flow required to dilute CO, NO_2 and PM_{10} for traffic speed from 3 to 65 mph to meet tunnel air quality criteria.

When calculating the air flow requirement, the 30-minute CO exposure criteria of 65ppm was applied for traffic conditions with traffic speed ranges between 3 – 65 mph. This criteria was used because vehicles will not reside inside tunnel for a period longer than 30 minutes in a three-km long tunnel. This is a reasonable assumption unless there is an emergency condition where exceptional standstill congestion condition develops. During an emergency condition, an aggressive tunnel ventilation mode, using all available fans, will be employed.

Following the discussion with the AHJ, CO concentration of 30 ppm has been elected to kick on the ventilation operations. Based on the emission pollution and the air demand calculations, traffic speeds play a significant role on the emissions and the air demand, with lower traffic speeds demanding more outside air supply. Considering greater Seattle area vehicle fleet make up consisting of 5% diesel vehicles, carbon monoxide (CO) has been determined as the driving pollutant for ventilation air demand during non-emergency operating conditions. Furthermore, air demand to control the CO at an acceptable concentration is driven by traffic flow conditions where the traffic speed is 3 mph (5 km/h). This conclusion is in agreement with work developed by Reiss I.R. et. al[4]. According to the MOBILE 6.2 calculation in Table-B3, the air flow required to dilute CO to meet the tunnel air quality criteria ranges from 141 kcfm at 65mph to 549 kcfm at 3 mph. Therefore, the fan sizing for the ventilation design for non-emergency condition is based on carbon monoxide at 3mph traffic speed, and the operation schedule will consider CO only for the air demand calculation.

5 AIR QUALITY ASSESSMENT

Subway Environment Simulation (SES) software was used for computer modelling of airflow that can be developed with and without the mechanical ventilation. Piston effect generated by the moving vehicle at different traffic speeds and mechanical ventilation of exhaust and jet fans were considered in the SES analysis. The analysis was limited to only south bound (SB) tunnel since both roadways resemble each other.

The objective of the analysis is to determine under which traffic and meteorological conditions the mechanical system is required to operate, and under which conditions the exhaust fans must operate to meet portal air quality criteria.

The diluted local emission concentration along the tunnel length has been plotted in Figure 2 to demonstrate where the acceptance criteria has been satisfied. For a traffic speed of 20 mph, jet fans, or both jet fans and exhaust fans will be required to operate in order to maintain emissions concentration below the acceptance level. This can be seen in Figure 2 where the CO concentration line corresponding to 20 mph traffic speed exceeded the horizontal threshold line for 35 ppm at approximately 1500 m into the tunnel. This calculation considers an ambient CO concentration of 15.5 ppm.

Specific tunnel technical parameters related to mechanical ventilation are summarized in Appendix C, Table-C1. To calculate the airflow developed with vehicle traffic piston effect and the operation of mechanical ventilation system, SES network model has been developed for both south bound and north bound roadways, the model also includes air/smoke duct, maintenance air duct, egress passage, damper openings and leakage area considering loss coefficient, tunnel gradient, etc. Each segment of the tunnel network model has a length of 67 m with a total of approximately 47 segments for each of the tunnel roadways, the tunnel wall surface roughness is assumed 0.011 m. The air/smoke duct is simulated with 65 of the 67 m long segments, with a friction loss K factor assumed 0.65[1]. Piston effect generated by traffic movement has been incorporated with SES model based on the following assumptions:

- No jet fan or exhaust fan operating
- Consider no wind condition for worst scenarios
- Vehicle average frontal area of 1.63 square meters
- Average vehicle frontal drag coefficient of 0.35
- Average vehicle skin drag coefficient of 0.01
- Two lanes of traffic
- Vehicles enter tunnel at designated speed

- Vehicle spacing varies per traffic speed based on PIARC 2012[2]
- Northbound and southbound traffic behaviours equivalent

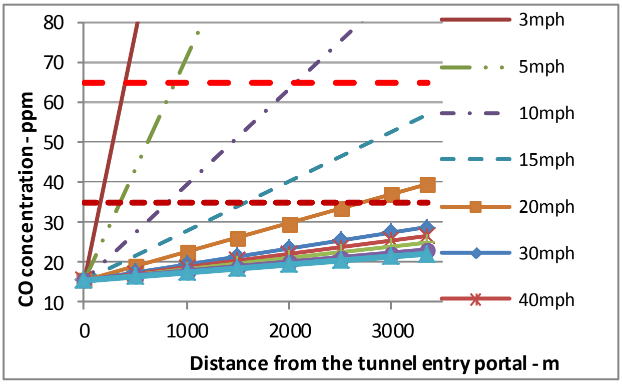

Figure 2: CO emissions concentration along the tunnel when no mechanical ventilation operating

Modelling shows that at traffic speeds higher than 20 mph, no mechanical ventilation is required because traffic generated piston effect can induce sufficient airflow to dilute the emissions to a level which satisfied the acceptance criteria. When traffic speed is reduced to 20 mph but higher than 5 mph, 4 exhaust fans will be required to run to exhaust the polluted air. When traffic speed is reduced to less than 5 mph, all portal jet fans and all exhaust fans will be required to run to push enough outside air into the tunnel and extract the vitiated air from the midway of the tunnel and discharge through the ventilation outlet. Requirements of mechanical ventilation to achieve the airflow at different traffic speed are given in Table-2 and Table-3. Figure 3 shows the air demand and the airflow generated with piston effect with different vehicle traffic speeds. The analysis shows that, if the traffic speed is reduced lower than 20 mph, mechanical ventilation is required.

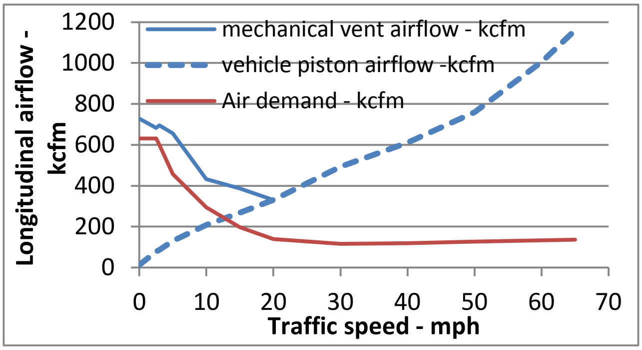

Figure 3: Air demand for emission ventilation vs the airflow generated with piston effect

The SES modelling calculated the tunnel airflow reaction time, for 20 mph travel speed, when jet fans or exhaust fans are activated due to a CO level greater than 30 ppm. The

CO level is based on the 5-minute averaged environmental monitors CO concentration. Figure 4 and Figure 5 illustrate this airflow response time, and indicate that 300 seconds is required to establish an airflow steady state condition at the exit portal after the entry portal jet fans are all switched on. Figure 6 illustrates CO concentration response with different number of fans put in operation.

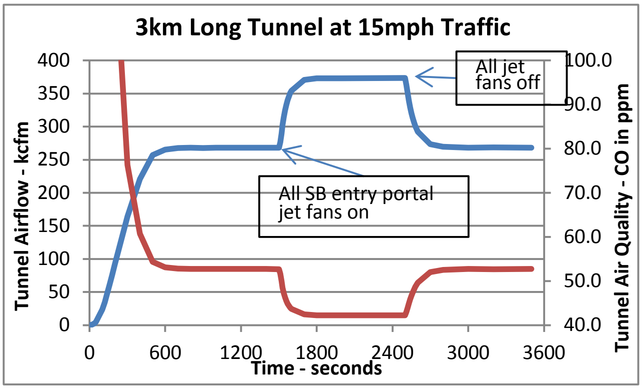

Figure 4: Airflow response curve when four jet fans at entry portal are activated and deactivated at 15 mph traffic speed

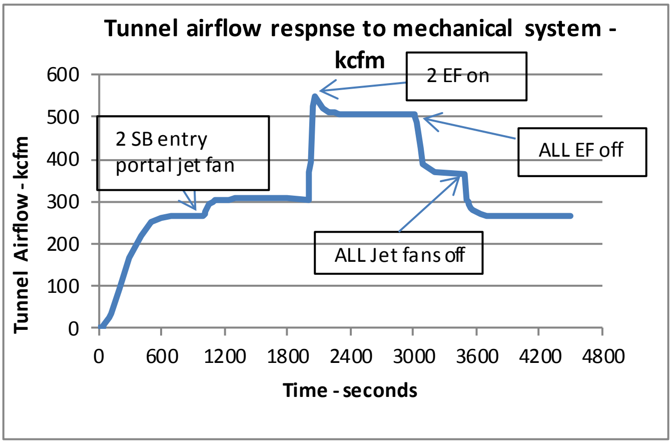

Figure 5: Airflow response curve when two jet fans and two exhaust fans (EF) are activated and deactivated for 15 mph traffic speed

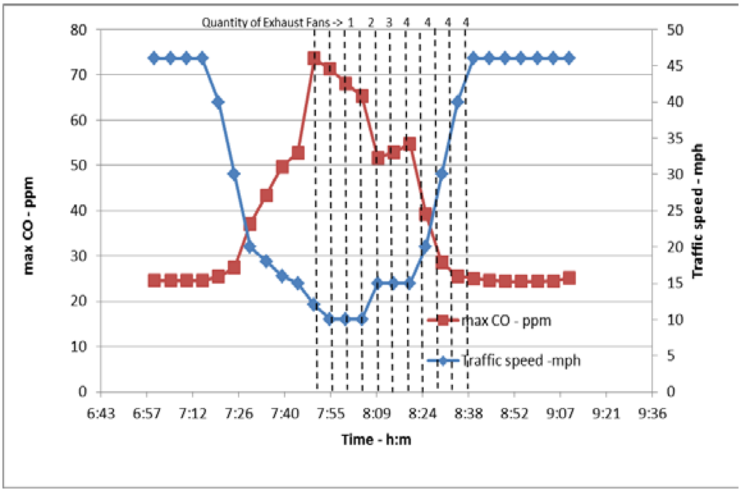

Figure 6: CO concentration response versus traffic speed with airflow generated exhaust fans and piston effect

Based on 65ppm admissible and 15.5ppm ambient criteria, mechanical ventilation operating requirements for acceptable exit portal discharge of pollutants is shown in Table-2. Total CO discharge at the portal can be calculated based on traffic volume and the traffic speeds. It is the sum of CO produced from all vehicles that inside the tunnel plus the ambient CO concentration level.

Table-2: Achieved airflow with natural or mechanical ventilation for SB roadway allowing discharge through exit portal

Traffic Speed - mph	Number of Vehicles in Tunnel	Achieved Volume Flow from Up + Down Stream – kcfm*	Volume Flow Required to Meet PDEC – kcfm	Entry and Exit Portal Airflow** (kcfm)	Mechanical System Operating
0	704	(380+349)/0	549	503/-497	4 Entry JF & 8 EF
2.5	578	(428+255)***/78	721	544/-401	4 Entry JF & 8 EF
3	572	(434+258)***/86	649	554/-405	4 Entry JF & 8 EF
5	548	(464+193)***/139	472	586/-332	8 EF
10	452	(302+131)***/209	304	312/-200	4 EF
15	328	(280+108)/268	202	274/268	None
20	246	(341+50)/330	144	334/330	None
30	212	493	120	497/493	None
40	212	611	124	636/611	None
50	212	760	130	760/750	None
60	212	1005	137	1018/1005	None
65	212	1160	141	1179/1160	None

* Recorded at the extraction location, where the pollutants concentration is at the maximum value, when natural ventilation airflow developed with piston effect only, no mechanical ventilation system operating.

**Airflow speed greater than zero refers to airflow in direction of vehicle travel, speed with negative value refers to airflow direction is opposite to the direction of travel, i.e., a reverse flow from outside into the tunnel.
*** Recorded at upstream and downstream of the extraction location, where the pollutants concentration is at the maximum value.

Table-3 shows the total CO and CO concentration discharge at different traffic speeds for the SB roadway. For a traffic speed lower than 10 mph, the pollutants discharged at portal exceeds the EIS allowable level of 7.29 g/sec, therefore exhaust fans and jet fans must be operated to reduce the emissions discharged at exit the portal. By controlling the outside airflow into the tunnel. EF and JF in Mechanical System column refer to the Exhaust Fans and Jet Fans, respectively. PDEC of 7.29g/s is Portal Discharge Emissions Criteria.

Table-3: Estimated vehicle emission discharge through SR99 SB tunnel exit portal

Traffic Speed - mph	No. of Veh. in Tunnel	CO Emis – g/min per vehicle	CO Discharge at Exit Portal– g/sec	CO Discharge at Exit Portal *** ppm	CO Discharge at Open Damper **** ppm	Vel – fpm (piston effect only)	PDEC satisfied (Y/N)
0	704	1.306	0/(15.32)*	>400	(52.8)	0	Y*
3	572	1.8794	0/(17.18)*	388.8	(64.9)	128	Y*
5	548	1.4416	0/(13.17)*	183.5	(51.0)	207	Y*
10	452	1.1260	0/(8.48)*	87.5	(50.2)	311	Y*
15	328	1.0300	5.63	52.8	(41.2)	399	Y**
20	246	0.9816	4.02	37.1	(33.7)	491	Y**
30	212	0.9449	3.34	27.5	NA	734	Y
40	212	0.9759	3.45	25.5	NA	910	Y
50	212	1.0302	3.64	24.0	NA	1132	Y
60	212	1.0851	3.83	22.3	NA	1449	Y
65	212	1.1129	3.93	21.5	NA	1728	Y

*Airflow direction is in opposite direction of the vehicle traffic, so airflow direction is from outside toward the tunnel, no polluted air exits the portal with the mechanical ventilation system operating to extract the polluted air from the midway of the tunnel as per equipment used in Table-2.
**For traffic between 15 and 20 mph, mechanical system should be operated to extract the polluted air near the exit portal, if the sensors inside tunnel monitored an elevated pollution concentration exceeds the admissible limits.
***Exit portal discharge CO concentration calculated based on the volumetric ppm: Ambient CO + total discharge CO x 1e6/(air supply in kcfm x 0.47 m3/kcfm x CO density g/m3); values in refers to the maximum CO concentration inside tunnel, when natural ventilation airflow developed with piston effect only, no mechanical ventilation system operating.
**** values in the bracket refers to the maximum CO concentration inside tunnel while mechanical system running, the polluted air is not to be discharged through the portal as exhaust fan will operate to generate reverse flow into the tunnel exit portal.

The ventilation analysis determined the mechanical ventilation operation required to avoid portal emissions. The required ventilation equipment operation is summarized in Table-4. In nearly all conditions, all eight exhaust fans and two to four jet must operate. This operation was estimated to pave power cost exceeding $1.2 million per year. Entry JF refers to the jet fans at the entry portals. RJF and EF in Mechanical System column refer to reversed jet fan at the exit portal and exhaust fan, respectively.

Table-4: Achieved airflow with natural or mechanical ventilation for SB roadway avoid exit portal emission discharge

Traffic Speed - mph	Number of Vehicles in tunnel	Achieved Volume Flow from up + down stream - kcfm	Volume Flow Required to Meet PDEC – kcfm	Entry and Exit Portal Airflow* (kcfm)	Mechanical System Operation
2.5	578	(428+255)**/78	631	544/-401	4 Entry JF & 8 EF
3	578	(434+258)**/86	631	554/-405	4 Entry JF & 8 EF
5	548	464+193	457	586/-332	8 EF
10	452	302+131	294	312/-200	4 EF
15	328	279 + 108	197	291/-112	2 EF
20	246	341 + 49	139	351/-52	2 EF
30	212	510 +59	116	522/-63	3 EF
40	212	662 +37	120	680/-42	2 RJF, 4 EF
50	212	721 + 40	127	921/-45	4 RJF, 6 EF
60	212	1017 +	133	1160/-7	4 RJF, 8 EF
65	212	1035 +	137	1164/-2	4 RJF, 8 EF

*Airflow speed greater than zero refers to airflow direction is from tunnel to the outside, speed with negative value refers to a reverse flow from outside into the tunnel.
**Represent (upstream + downstream) flow rate.

6 FAN OPERATION ANALYSIS

In order to optimize ventilation Life-Cycle-Cost, a recommended ventilation system operation based on CO concentrations and an operation schedule based on predicted traffic were developed. These operation schedules are summarized in Table-5 and Table-6.
According to the analysis presented, only extremely slow or “stop and go” traffic may result in excessive pollutants concentrations requiring mechanical ventilation. Ventilation modelling determined that mechanical ventilation is likely required when traffic volumes are greater than 3000 vehicles per hour. Therefore, it is recommended that during the period of times highlighted in Table-6, the exhaust fans and the exit portal jet fans be programmed to operate as shown. Resolution of stop and go traffic over the period of highlighted times is provided in Tables-D1a and D1b in Appendix D. This

operation will reduce portal pollution and reduce fan on/off cycling during the congested peak traffic hours.

Table-5: Equipment Schedule and Control Sequence

SENSOR TYPE	CO	NO_2	NOx	VISIBILITY	VELOCITY
QUANTITY	6-OFF	6-OFF	6-OFF	6-OFF	6-OFF
RANGE	0 to 200 ppm	0 to 2ppm	0 to 30ppm	0.015/m	±20 m/s
ACCURACY (MINIMUM)	±1 ppm	±0.01ppm	±0.1 ppm	0.0002/m	±0.2 m/s
OPERATING TEMPERATURE	-20 TO 45 °C	-20 TO 45 °C	-20 TO 45 °C	-20 TO 45 °C	-20 TO 45 °C
JET FAN ON	>30 ppm for any cell	OR >0.6ppm for any cell	OR >6ppm for any cell	OR >0.003/m for any cell	OR < 1.5m/s for any cell
JET FAN ON SEQUENCE	Start one pair each time, interval 5 minutes, minimum run time 15 minutes				
JET FAN OFF	< 25ppm for all cell	AND <0.4ppm for all cell	AND <4ppm for all cell	AND <0.002/m for all cell	N/A
JET FAN OFF SEQUENCE	ALL Jet Fans off when 3rd Exhaust fan on				
EXHAUST FAN ON	>50 ppm for any cell	OR >0.8ppm for any cell	OR >8ppm for any cell	OR >0.0045/m for any cell	OR Cell #6 >PDEC
EXHAUST FAN ON SEQUENCE	Start one Exhaust Fan each time, interval 5 minutes, minimum run time 15 minutes				
TUNNEL CLOSURE	>150ppm	OR >1.5ppm	OR >20ppm	OR >0.012/m	N/A
EXHAUST FAN OFF	<30 ppm for all cells	AND <0.6ppm for all cells	AND <6ppm for all cells	AND <0.003/m for all cells	AND cell#6 <PDEC
EXHAUST FAN OFF SEQUENCE	Turn off Exhaust Fan one by one when all criteria satisfied				
PDEC criteria	If flow speed >0 (flow direction same as traffic), and the product of airflow rate and Cell #6 concentration of CO, NO_2, NOx or PM not to exceed the acceptance portal discharge limit for each species.				

Table-6: 2015 Recommended mechanical ventilation operation schedule for mainline bored tunnel of SR99 Alaskan Way

Starting time	NB Traffic volume – veh/hr	NB Traffic speed - mph	SB Traffic volume – veh/hr	SB Traffic speed - mph	Mechanical system

0:00	293	50	295	50	None
1:00	156	50	186	50	None
2:00	132	50	146	50	None
3:00	128	50	129	50	None
4:00	265	50	271	50	None
5:00	841	50	758	50	None
6:00	2096	50	2261	50	None
7:00	3394	46	3325	46	1-8 JF
8:00	3750	45	3430	46	2-4EF, 2-4JF, 2-4RJF
9:00	2590	50	2361	50	1 EF
10:00	2107	50	1796	50	None
11:00	2079	50	1772	50	None
12:00	1946	50	2011	50	None
13:00	2015	50	2259	50	None
14:00	2385	50	2655	50	1 EF
15:00	3104	48	3462	47	1-8 JF
16:00	3832	45	3746	46	2-4EF, 2-4JF, 2-4RJF
17:00	4050	44	3890	45	1-8 JF
18:00	2613	50	3235	48	2-4EF, 2-4JF, 2-4RJF
19:00	1504	50	1787	50	None
20:00	1170	50	1193	50	None
21:00	1129	50	1155	50	None
22:00	964	50	940	50	None
23:00	547	50	647	50	None
24:00	293	50	295	50	None

Energy consumption has been calculated based on the fan motor power (500HP for centrifugal exhaust fan, 75HP per jet fan) and operation time on two options as shown in Table-7. Energy consumption is estimated considering 380 kW (500HP) per exhaust fan (EF), and 56 kW (75HP) per jet fan (JF).

Table-7: 2015 Power requirements based on recommended mechanical ventilation operation schedule for mainline bored tunnel of SR99 Alaskan Way

Option ID	Option 1: Portal emissions	Option 2: No portal emissions
Environment criteria	CO 65ppm in tunnel; CO exit portal discharge no more than 35 ppm	Reverse flow to be developed if traffic speed lower than 30 mph
Traffic condition and portal discharge	CO 65ppm in tunnel, zero portal emissions	Reverse flow to be developed for any traffic condition
Fan Operation	Varies : 2 to 8 56 kW Jet Fans 2 to 8 380 kW Exhaust Fans	8 x 56 kW Jet Fans 8 x 380kW Exhaust Fans

Daily Jet fan power consumption	12,144 kWH	84,864 kWH
Daily Exhaust fan power consumption	26,640 kWH	948,480 kWH
Hours of operation	3	24
Energy consumption annually* - kWh	1.25 million kWh	33.0 million kWh
Annual operation cost**	$0.11 million	$2.05 million

*Apart from the fan motor power consumption, this also includes the electrical power consumption of the auxiliary system.
**Operation cost estimated based on electricity price of $0.0668 per kWh.

Considering the energy cost indicated in Table 7 for commercial activities, the saving on energy will be approximately 1.9 million US dollars annually.

7 CONCLUSIONS

Computer modelling was performed to calculate pollutants emissions inside the tunnel, pollution discharged through the exit portal and the demand of mechanical system in different traffic conditions to meet the acceptable environmental criteria inside the tunnel and outside the tunnel portals.

For the normal ambient condition with light pollution, and traffic volumes less than 3000 vehicles per hour, no mechanical fan operation is required.

For traffic speed less than 30 mph or with a traffic volume of more than 3000 vehicles per hour, exhaust fans should operate to extract the polluted air into the air duct to be exhausted through the ventilation outlet (stacks). Exit portal jet fans need to run in reverse direction and all exhaust fans (8 exhaust fans) are required to run one hour in the morning peak hour and two hours in the afternoon peak hour each weekday. However, if zero portal emission is to be imposed, then the fans need to run at 24 hours per day.

Optimization of the system operation shows, if allow minimal exit portal emissions with a CO emission limit of no more than 30ppm, energy saving will be over 31 million kWh annually compared to imposing zero emissions at the exit portal.

ACKLEDGEMENT

We appreciate the partnerships between WSDOT, HNTB and Seattle Tunnel Partners during the development of tunnel ventilation operating modes and the preparation of this paper.

REFERENCES

[1] Subway Environment Simulation Computer program – SES VERSION 4, Part I User’s Manual, December 1997.

[2] PIARC Road tunnels: vehicle emissions and air demand for ventilation, 2012.

[3] Bendelius, Arthur G, Road Tunnel Ventilation and Fire Control- Regulations, Standards, and Guidelines, ASHRAE Transactions; 2008, Vol. 114 Issue 2, p273.

[4] Reiss I.R., Schneider G., Brandt R., On longitudinal ventilation and congested traffic, International conference of Tunnel safety and ventilation, Graz, 2004

[5] Longley, Ian, NIWA Ltd. TP05: Road Tunnel Stack Emissions. Rep. N.p.: New South Wales Government Advisory Committee on Tunnel Air Quality, July 2014. TP05: Road Tunnel Stack Emissions. New South Wales Government Advisory Committee on Tunnel Air Quality. Web

[6] *SR 99: Alaskan Way Viaduct Replacement Project Air Discipline Report Final EIS*. Rep. Seattle: Washington State Department of Transportation, July 2011. Report Print.

[7] *SR 99: Alaskan Way Viaduct Replacement Project Transportation Discipline Report Final EIS*. Rep. Seattle: Washington State Department of Transportation, July 2011. Report Print.

Appendix A: Acronyms and definitions

AASHTO – American Association of State Highway and Transportation Officials
EF – Exhaust Fan, also called an Extraction or Exhaust/Extraction Fan
EPA - Environmental Protection Agency
JF – Jet Fan
RJF – Reversed operation direction of jet fan
NAAQS -- National Ambient Air Quality Standards
OSHA – Occupational Safety & Health Administration
PDEC - Portal Discharge Emissions Criteria
PIARC – World Road Association. AASHTO serves as the National Committee of the United States of America, World Road Association
RJF – Reverse Direction Jet Fan – The fans at the exit portals
WSDOT – Washington State Department of Transportation
SF – Square feet

Appendix B: MOBILE 6.2 emission calculations and air flow requirements

Table- B1: Background Concentration of CO, NO_2 and PM_{10}

Pollutant	Background concentration
CO	15.5 ppm
NO_2	0.05 ppm
PM_{10}	50 µg/m³

For the SR99 Tunnel, WSDOT based the air quality criteria for inside the SR 99 Tunnel on the OASHA air quality standards. The in tunnel air quality acceptance criteria for CO, NO, NO_2 and PM_{10} are summarised in Table 2 below.

Table- B2: Air quality acceptance criteria inside tunnel

Pollutant Species	Time Average	Air quality limit
Carbon Monoxide (CO)	15 minutes (Free-flowing conditions)	120 ppm
	30 minutes	65 ppm
	45 minutes	45 ppm
	1 hour	35 ppm
NO		25 ppm
NO_2		1 ppm
Visibility extinction coefficient, haze (PM)		0.005 m^{-1}

Table- B3: Total Production of CO in SR99 tunnel under different traffic speeds

Traffic speed - mph	Number of vehicles in tunnel	CO Admissible - ppm	CO emissions – g/min per vehicle	Air flow volume requirement to meet tunnel air quality criteria – kcfm*
0	704	65	1.306	549
3	572	65	1.8794	649
5	548	65	1.4416	472
10	452	65	1.1260	303
15	328	65	1.0300	202
20	246	65	0.9816	144
30	212	65	0.9449	120
40	212	65	0.9759	124
50	212	65	1.0302	130
60	212	65	1.0851	137
65	212	65	1.1129	141

* Calculation based on: V_dot [flow (kCFM)] = N [# of veh] x e [vehicle emissions (g/60sec)] x 2.118 [1000 ft3/min * sec/ m3] x (65 [ppm] – 15.5 [ppm]) x (1/1233.8 g/m3) x 1E-6 ppm

Table- B4: Total production of NO_2 in SR99 tunnel under different traffic speeds

Traffic speed - mph	**Number of vehicles in tunnel**	**NO_2 Admissible - ppm**	**NO_2 emissions – g/min per vehicle**	**Air flow volume requirement to meet tunnel air quality criteria – kcfm***
3	**572**	**1**	**0.01036**	**110**
5	**548**	**1**	**0.00935**	**94**
10	**452**	**1**	**0.00779**	**65**
15	**328**	**1**	**0.00679**	**41**
20	**246**	**1**	**0.00624**	**28**
30	**212**	**1**	**0.00569**	**22**
40	**212**	**1**	**0.00572**	**22**
50	**212**	**1**	**0.00613**	**23**
60	**212**	**1**	**0.00692**	**27**
65	**212**	**1**	**0.00754**	**29**

* Calculation based on: V_dot [flow (kCFM)] = N [# of veh] x e [vehicle emissions (g/60sec)] x 2.118 [1000 ft3/min * sec/ m3] x (65 [ppm] – 15.5 [ppm]) x (1/1233.8 g/m3) x 1E-6 ppm

Table-B5: Total production of PM_{10} in SR99 tunnel under different traffic speeds

Traffic speed - mph	**Number of vehicles in tunnel**	**PM_{10} Admissible – mg/m^3***	**PM_{10} emissions – mg/min per vehicle**	**PM_{10} emissions – g/min**	**Air flow volume requirement to meet tunnel air quality criteria – kcfm***
3	**572**	**1.0426**	**5.70**	**3.29**	**116**
5	**548**	**1.0426**	**5.70**	**3.11**	**111**
10	**452**	**1.0426**	**5.70**	**2.56**	**92**
15	**328**	**1.0426**	**5.70**	**1.86**	**67**
20	**246**	**1.0426**	**5.70**	**1.45**	**52**
30	**212**	**1.0426**	**5.70**	**1.20**	**43**
40	**212**	**1.0426**	**5.69**	**1.20**	**43**
50	**212**	**1.0426**	**5.69**	**1.20**	**43**
60	**212**	**1.0426**	**5.69**	**1.20**	**43**
65	**212**	**1.0426**	**5.69**	**1.20**	**43**

*** Based on 1g=4.7m^2 the admissible PM_{10} concentration is 1.0426 mg/m^3 for admissible haze of 0.005 m^{-1}.**

Tunnel airflow rate capable to dilute pollutant concentrations to satisfy the acceptance concentration limit of each of the pollutants inside tunnel as nominated in Table-B2. System would be operated to establish required airflow capacities to satisfy tunnel interior acceptance criteria for each traffic condition. Operating capacity would be modified to also maintain ambient pollutant concentration in air discharge through the exit portal below nominated ambient concentration limits given in Table B3.

APPENDIX C: SR99 Alaskan way tunnel ventilation system parameters

Table- C1: SR99 Alaskan Way Tunnel Ventilation System Parameters

Item	**North bound roadway**	**South bound roadway**
Tunnel length	3343 m	3058 m
Roadway cross section Area	59 m^2 (671 SF)	62 m^2 (594 SF)
Roof height	6.2 m	6.2m
Entry portal jet fan	4 Jet Fan + 2 Jet Fan	4 Jet Fan
Exhaust fans	4 Extraction Fan	4 Extraction Fan
Exhaust duct size	12.5 SF	12.5 SF
Exhaust damper size	10 m^2	10 m^2
Exhaust location	Wall damper spaced at every 33m along the tunnel	Wall damper spaced at every 33m along the tunnel
Exit portal jet fan	4 JF	4 JF
Jet fan parameter		
NB-entry mainline JF	3 x 34.4 m/sec, unidirectional, 56 kW each	
NB-entry on ramp JF	2 x 32.1 m/sec, unidirectional, 45 kW each	
NB-exit JF	4 x 31.5 m/sec, reversible, 45 kW each	
SB-entry JF	4 x 33.3 m/sec, unidirectional, 56 kW	
SB-exit JF	4 x 33.7 m/sec, reversible, 56 kW	
Exhaust fan parameter		
SP fan room (4 x 500 HP)	4 x 99.9 m^3/sec at 2.2 kPa inwg or 75.8 m^3/sec at 4.0 kPa	
NP fan room (4 x 500 HP)	4 x 99.9 m^3/sec at 2.2 kPa or 75.8 m^3/sec at 4.0 kPa	

APPENDIX D: SR99 Alaskan way tunnel – recommended mechanical ventilation operation schedule during peak traffic hours

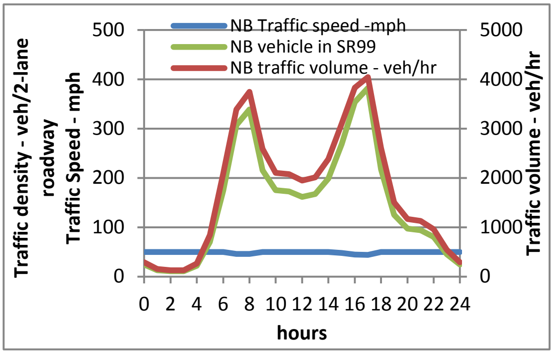

Figure D1: North bound traffic volume, traffic density for 2-lane tunnel and traffic speed during 24 hours for a typical weekday

Table-D1: 2015 Recommended mechanical ventilation operation schedule for mainline bored tunnel of SR99 Alaskan Way – Morning Stop and Go Traffic

Starting time	SB Qty Veh.	SB Traffic speed - mph	CELL 6 CO ppm	CELL 6 Air Velocity fpm	Oper. Mode	Mechanical System*
7:00	212	46	24.6	1020	N20	None
7:05	212	46	24.6	1020	N20	None
7:10	212	46	24.6	1020	N20	None
7:15	212	46	24.6	1020	N20	None
7:20	212	40	25.5	910	N20	None
7:25	212	30	27.5	734	N20	None
7:30	246	20	35.0	484	N24	2 JF
7:35	278	18	36.5	517	N24	4 JF
7:40	311	16	36.9	599	N24	6 JF
7:45	328	15	34.6	675	N24	8 JF
7:50	402	12	41.4	650	N24	8 JF
7:55	452	10	46.4	627	N24	8 JF
8:00	452	5	56.1	N/A	N30	2 EF + 8 JF
8:05	452	10	50.2	N/A	N36	4 EF
8:10	452	10	49.8	N/A	N36	4 EF
8:15	328	15	34.4	N/A	N36	4 EF
8:20	328	15	34.5	N/A	N36	4 EF
8:25	328	15	34.5	N/A	N36	4 EF
8:30	246	20	27.6	N/A	N36	2 EF
8:35	212	30	25.5	734	N20	None
8:40	212	40	24.7	910	N20	None
8:45	212	46	24.7	1020	N20	None
8:50	212	46	24.2	1020	N20	None
8:55	212	46	24.4	1020	N20	None
9:00	212	46	24.4	1020	N20	None
9:05	212	46	24.8	1020	N20	None
9:10	212	46	25.1	1020	N20	None

Table- D2: 2015 Recommended mechanical ventilation operation schedule for mainline bored tunnel of SR99 Alaskan Way – Afternoon Stop and Go Traffic

Starting time	SB Qty Veh.	SB Traffic speed - mph	CELL 6 CO ppm	CELL 6 Air Velocity fpm	Oper. Mode	Mechanical System*
16:10	212	40	25.5	910	N20	None
16:15	212	30	27.5	734	N20	None
16:20	246	20	35.0	484	N24	2 JF

16:25	278	18	36.5	517	N24	4 JF
16:30	311	16	36.9	599	N24	6 JF
16:35	328	15	34.6	675	N24	8 JF
16:40	402	12	41.4	650	N24	8 JF
16:45	452	10	46.4	627	N24	8 JF
16:50	452	5	56.1	N/A	N30	2 EF + 8 JF
16:55	452	10	50.2	N/A	N36	4 EF
16:60	452	10	49.8	N/A	N36	4 EF
17:00	328	15	34.4	N/A	N36	4 EF
17:05	328	15	34.5	N/A	N36	4 EF
17:10	328	15	34.5	N/A	N36	4 EF
17:15	246	20	27.6	N/A	N36	2 EF
17:20	212	40	25.5	910	N20	None
17:25	212	46	24.7	1020	N20	None
17:30	212	46	24.6	1020	N20	None
17:35	212	46	24.6	1020	N20	None
17:40	212	40	25.5	910	N20	None
17:45	212	30	27.5	734	N20	None
17:50	246	20	35.0	484	N24	2 JF
17:55	278	18	36.5	517	N24	4 JF
18:00	311	16	36.9	599	N24	6 JF
18:05	328	15	34.6	675	N24	8 JF
18:10	402	12	41.4	650	N24	8 JF
18:15	452	10	46.4	627	N24	8 JF
18:20	452	5	56.1	N/A	N30	2 EF + 8 JF
18:25	452	10	50.2	N/A	N36	4 EF
18:30	452	10	49.8	N/A	N36	4 EF
18:35	328	15	34.4	N/A	N36	4 EF
18:40	328	15	34.5	N/A	N36	4 EF
18:45	328	15	34.5	N/A	N36	4 EF
18:50	246	20	27.6	N/A	N36	2 EF
18:55	212	40	25.5	910	N20	None