TUNNEL AIR QUALITY MODELING: A CASE STUDY OF THE SOUK SAGHEER TRAFFIC TUNNEL, MAKKAH, SAUDI ARABIA

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by

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Abstract

Traffic tunnels have become increasingly popular in modern cities as a way to ease traffic congestion and overcome natural barriers. However, traffic tunnels present significant environmental and health issues due to the elevated levels of pollutants inside the tunnels, poor visibility, and smoke caused by accidents. In this research, a critical review of the recent literature on air pollution modeling in traffic tunnels and on the ventilation systems used in tunnels is presented. In addition, an air quality modeling concept that has been applied to the Souk Sagheer Traffic Tunnel in Makkah, Saudi Arabia, is also presented. This tunnel is bidirectional and has a forced ventilation system. The level of air pollution inside the tunnel, especially the carbon monoxide (CO) concentration, has been reported to exceed the permissible limits. The tunnel is particularly congested with traffic during the pilgrimage season and has different modes of operation at different times of the year. In the present work, the current status of the tunnel is simulated using a one-dimensional model that takes into consideration the effects of the forced ventilation and the piston action of vehicles. The developed model that validated with measured data, and the Mann-Whitney test shows that the means values of measured and predicted results are equal at a 7% significance level. The measured results show that during peak traffic times, high concentrations of CO, nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and fine particulate matter often exceed the regulatory limits. SO_2 has the highest ratio of measured to recommended concentration of all of the pollutants considered. In this study, several solution scenarios are simulated, such as improving the current longitudinal ventilation, utilizing a transverse ventilation system, or building a wall to separate the tunnel into two smaller tubes. The simulation results show that building a separation wall between the two directions of traffic will significantly reduce the pollution inside the tunnel. For example, the mean value of CO

inside the tunnel is reduced from 43.8 mg/m^3 to 12.1 mg/m^3 when a wall barrier is introduced. A wall barrier will increase the wind speed and enhance the piston action, thus improving the longitudinal ventilation. Finally, a risk assessment chapter calculates the ratio of exposure and maximum allowable limits by World Health Organization. The ratios are calculated for short exposure level.

This study is important because it shows that bidirectional tunnels are inefficient to ventilate. Moreover, it shows that for the case of the Souk Sagheer Tunnel, additional rows of jet fan does not seem to solve the air quality problem inside the tunnel. Finally, this paper highlights the necessity to investigate SO_x emissions because they seem to be the most polluting inside the tunnel.

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List of Abbreviations

AQM	Air Quality Modeling
BEADS	Benzene Exposure and Absorbed Dose Simulation
BEAM	Benzene Exposure Assessment Model
CH_4	Methane
CO	Carbon Monoxide
CTDMPLUS	Complex Terrain Dispersion Model Plus Algorithms for Unstable Situations
EMEP	Co-operative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe
EU	European Union
HAPEM-MS	Hazardous Air Pollutant Exposure Model for Mobile Sources
HVAC	Heat, Ventilation, and Air Conditioning
N_2O	Nitrous oxide
NAAQS	National Ambient Air Quality Standards
NEM	National Exposure Model
NFPA	National Fire Protection Association
NO_2	Nitrogen Dioxide
NO_x	Nitrogen Oxides
PIARC	The World Road Association
PM	Particulate Matters
PME	Presidency of Meteorology and Environment, Saudi Arabia
RAINS	Regional Air Pollution Information and Simulation
RTA	Road Tunnel Authority, Australia

SHAPE	Simulation of Human Activity and Pollutants Exposure
SO_2	Sulfur Dioxide
SO_x	Sulfur Oxides
UNECE	United Nations Economic Commission for Europe
USEPA	United States Environmental Protection Agency
WHO	World Health Organization

List of Symbols

A	Tunnel cross-sectional area
$A_{(V(j))}$	Cross section area of vehicle type j (M2)
A_i	Tunnel area of segment i (m^2)
$C^{(n+1)}$	Concentration at time $t^{(n+1)} = (n+1)\,\Delta t$
C^n	Concentration at time $t^n = (n)\,\Delta t$
$C_{(DBVj)}$	Drag coefficient at back end of vehicles of type j
$C_{(DFVj)}$	Drag coefficient at front end of vehicles of type j
$C_{(DTVj)}$	Drag coefficient weighted total truck area for vehicles of type j (m^2)
C_{BL}	Concentration of pollutant at the left boundary
C_{BR}	Concentration of pollutant at the right boundary
c_i	Concentration
d_i	Hydraulic diameter of tunnel segment i (m)
E_i	Emission flux
H	Stack hight
K_x	Hoizontal dispersion coefficient
L	Tunnel length
$l_{(Vj)}$	Length of vehicles of type j (m)
l_i	Length of tunnel segment i
l_{vij}	Length of vehicle type j in tunnel segment i (m)
$N_{(back\_ij)}$	Number of back ends of vehicles of type j in segment i.
$N_{(front\_ij)}$	Number of front ends of vehicles of type j in segment i
P^*	Sink term

$p_{(Vj)}$	Perimeter of vehicles of type j (m).
q	Source strength
R_i	Chemical generation rate
S^*	Source of pollutant
S_i	Removal flux of sink term
u_x, u_y, u_z	Velocity
w	Wind speed
Δp_{frict}	Pressure change due to friction against walls (Pa)
Δp_{fricv}	Pressure change due to friction against vehicles
Δp_{piston}	Piston pressure rise
Δt	Discrete temporal step
Δx	Grid size
η	Non-dimensional ratio between vehicle and tunnel cross-sectional areas
$\lambda_{(V\_j)}$	Skin friction coefficient for vehicles of type j
$\lambda_{(VS\_j)}$	Skin friction coefficient related to viscous drag for vehicles of type j
λ_T	Friction factor for tunnel wall
ρ_i	Mean density of air in tunnel segment i (kg/m^3)
σ_y, σ_z	Lateral and vertical dispersion coefficients
$\upsilon_{(V\_ij)}$	Velocity of vehicle j in segment i, positive from left to right (m/s)
υ_i	Mean air velocity in segment i, positive from left to right (m/s)
$\Phi_{(i+1)}$	Represent mass flux at position $i\Delta x$
Φ_i	Represent mass flux at position $(i-1)\Delta x$

Chapter 1

INTRODUCTION

Urban air quality is increasingly recognized as a major threat to public health and the environment. Urban air pollution is caused by a mixture of pollutants, including sulfur oxides (SO_x), nitrogen oxides (NO_x), carbon monoxide (CO), particulate matter (PM), and organic compounds such as benzene, toluene, and xylene, several of which are very toxic and/or carcinogenic. These pollutants are mostly emitted by local sources, but some fraction of the pollution is also transported through the atmosphere from sources located outside the city.

The Kingdom of Saudi Arabia has developed ambient air quality standards with averaging time for these pollutants, which are used as regulatory guidelines. These standards are listed in Table 1.1. Comparing air quality at a location with standards gives an indication as to whether the air inhaled by people in that location is safe or not.

In Makkah, where several millions of people gather every year during two seasons, the Hajj pilgrimage and Ramadan (month of fasting), air pollution produced by automobiles may have an impact on the health of the visitors coming for pilgrimage and also on the local population. Furthermore, the Souk Sagheer Traffic tunnel is one of the busiest traffic tunnels in Makkah. It is subjected to congestion, and traffic can become very slow inside the tunnel.

In the research presented here, a detailed investigation is made, and measurements of the air quality in this tunnel are compiled. Various air quality tunnel models are reviewed, and the model that is most suitable for the Souk Sagheer Tunnel is implemented to assess the current performance of the ventilation system. Improvements to minimize risk to pedestrians and passengers using the tunnel are also proposed.

Table 1.1 PME air quality standards (PME, 1989)

Averaging Time	Maximum Concentration	Allowable Exceedances
Sulfur Dioxide (SO_2)		
1 hour	730 μg/m^3 (0.28 ppm)	twice per 30 days
24 hours	365 μg/m^3 (0.14 ppm)	once a year
1 year	80 μg/m^3 (0.03 ppm)	(none)
Inhalable Particulate (IP)		
24 hours	340 μg/m^3	once a year
1 year	80 μg/m^3	(none)
Photochemical Oxidants (Defined as Ozone, O_3)		
1 hour	295 μg/m^3 (0.15 ppm)	twice per 30 days
Nitrogen Oxides (Defined as Nitrogen Dioxide, NO_2)		
1 hour	660 μg/m^3 (0.35 ppm)	twice per 30 days
1 year	100 μg/m^3 (0.05 ppm)	(none)
Carbon Monoxide (CO)		
1 hour	40 mg/m^3 (35 ppm)	twice per 30 days
8 hours	10 mg/m^3 (9 ppm)	twice per 30 days
Hydrogen Sulfide (H_2S)		
1 hour	200 μg/m^3 (0.14 ppm)	twice per 30 days
24 hours	40 μg/m^3 (0.03 ppm)	once a year
Fluorides (F^-)		
30 days	1 μg/m^3 (0.001 ppm)	(none)

1.1 Background

Makkah is a city located in the western region of Saudi Arabia, and it is the capital of Makkah Province, which includes Jeddah, Taif, and other smaller towns. It is located inland, approximately 75 km to the east of Jeddah. The center of Makkah is in a valley, surrounded by hills and mountains. According to the most recent official census, the population of Makkah, based on local residents only, is estimated at 1.3 million (Makkah Development Commission, 2004-2005).

Makkah is also considered the capital of the Muslim world, and it is visited by millions of Muslims who come to perform religious rituals, especially during the month of Ramadan (the month of fasting, which is the 9th month of the Arabic Hijri Calendar) and during Hajj (Hajj is a religious duty that takes place once a year during the month of Dhu al-Hijja, which is the last month of the Arabic Hijri Calendar). Muslims around the world visit Makkah to perform the two rituals, Umrah and Hajj. Umrah is performed year round with the peak season during the month of Ramadan. During Ramadan, the number of visitors to Makkah exceeds one million (Ministry of Hajj, 2006). However, the total number of visitors to Makkah for the year 2010 is expected to be almost 6 million, and of these, 2 million will visit during the Hajj season. The Grand Mosque is the final destination for all visitors coming for Hajj or Umrah (Ministry of Hajj, 2006).

Transporting such a large number of visitors is a challenge, and the hilly terrain of Makkah makes transportation even more difficult. Many hills and mountains have necessitated the establishment of road tunnels. Although some ambitious projects that involve building trains and a metro to ease congestion in Makkah are in the planning stage, the majority of the city is still only accessible by the road network.

There are 54 road tunnels in Makkah city with a total length of 31 km (Saati and Shahine, 2000). However, additional road tunnels are in the planning stage. One important road tunnel in Makkah is the Souk Sagheer Tunnel. This is a bidirectional tunnel that is approximately 1500 m in length with four lanes – two in each direction. The tunnel is constructed with four waiting zones, including a bus station underneath the Grand Mosque, and it is considered to be one of busiest tunnels in the city.

Concerns regarding the safety of the tunnels have been raised by the Hajj Research Institute and the Presidency of Meteorology and Environment (PME). The Hajj Research Institute is a research center that is affiliated with Umm Al-Qura University, based in Makkah, and the PME is the government agency responsible for setting regulatory standards and monitoring the environment in the Kingdom of Saudi Arabia.

A study conducted by Ashor (2000) reported a decrease in the oxygen (O_2) levels in the blood of pedestrians crossing the Souk Sagheer Tunnel from one end to the other. This drop in O_2 levels is attributed to the elevated levels of CO inside the tunnel.

The main concern regarding safety in the road tunnels is the air quality. Although all road tunnels in Makkah have mechanical ventilation systems, recent reports show elevated concentrations of pollutants, mainly CO, in these tunnels. This issue has particularly raised concern in the road tunnels where pedestrians commonly walk, as they are directly exposed to high levels of pollutants. It has also been observed that during traffic congestion, traffic police and the Municipality of Makkah control the entrance of traffic into the tunnels until the congestion has been relieved. The issue of air quality in the

Souk Sagheer Tunnel has received significant attention from the Hajj Research Institute and the PME due to its location and the capacity of the tunnel.

Although air quality of the tunnel has a great impact on the health of the people who travel through it, most studies have focused on the impact of the road tunnels on their surrounding environments.

Tunnels redistribute air pollutants from road emissions, and the tunnel exhausts could have a significant impact on nearby residential areas. Therefore, regulations and guidelines have been established to ensure a minimum impact on the areas surrounding tunnels. Although the focus of this study is to assess air quality inside the Souk Sagheer Tunnel, the impact of the exhaust from the tunnel on the surroundings may also be significant.

1.2 Objectives

The Souk Sagheer Tunnel is the most important road tunnel connection in Makkah city. It not only connects major hubs, but it is also the only tunnel below the Grand Mosque, where more than two million people are gathered during the pilgrimage period. However, monitoring that has been conducted in the tunnel for the last 20 years shows that CO levels have been increasing and exceeding the acceptable limits during the peak traffic periods.

The objective of this study is to assess the level of air pollutants in the Souk Sagheer Tunnel during different seasons and to suggest effective and economical solutions to reduce pollution levels through structural changes and also by modifying the ventilation systems. Such estimates are based on the findings of a dispersion model for the Souk Sagheer Tunnel.

To accomplish the above objective, the following tasks were performed:

- A review of the recent literature on air quality modeling in traffic tunnels
- Assessment of current air quality conditions inside the Souk Sagheer Tunnel during peak and non-peak seasons according to the selected model
- Application of an air quality model in order to perform quantitative assessment of current conditions, and to evaluate different potential solutions.
- Proposal of solutions to reduce air pollution levels inside the Souk Sagheer Tunnel
- Examination of the solutions' effectiveness at improving air quality to acceptable levels
- Assessment of the consequences of ventilation failure on air quality levels inside the tunnel
- Assessment of the current health risks imposed by the current air quality levels during peak seasons based on model calculations
- Development of recommendations for solutions that may be used to improve air quality in the Souk Sagheer Tunnel.

1.3 Scope

The scope of this research includes a review of the recent literature on tunnel air quality management and design criteria. This includes a review of the ventilation options that are used in modern traffic tunnels. Moreover, the literature review presents the results of modeling of air pollution dispersion inside the traffic tunnels in order to implement a mathematical model for the Souk Sagheer Tunnel scenario.

Furthermore, using mathematical modeling, the current status of the tunnel is assessed in terms of air pollutants. The mathematical model is used to predict a selected number of major traffic-induced primary air pollutants.

After analysis of the current situation, possible solutions to mitigate air pollution are listed.

A risk assessment study is provided to quantify risk by calculating the ratios of average pollutant concentrations with recommended limits by the World Health Organization (WHO).

Finally, conclusions and recommendations are made for improvement of the air quality inside the tunnel, and suggestions for future study are given.

1.4 Structure of the thesis

This study is organized into 6 chapters. Chapter 1 is the introduction, which gives background information on the road tunnels, their impact on the environment and their impact on human health. Specific details of the Souk Sagheer Tunnel in Makkah city are given. This chapter also summarizes the objective of the study and its research scope.

Chapter 2 provides a literature review. In this chapter, air quality management in road tunnels is discussed. The sections in Chapter 2 include an introduction that summarizes the history air quality management in road tunnels. Air quality and ventilation requirements as recommended by UNECE and PIARC are also reviewed and presented in this chapter. Additionally, this chapter describes various air quality models with emphasis on road tunnel air quality prediction under different traffic scenarios and tunnel configurations.

Chapter 3 summarizes the current status of the Souk Sagheer Tunnel. This chapter presents an overview of the studies that have been conducted by the Hajj Research Institute, studies that have been performed by the PME, and studies that have been performed by individuals on the Souk Sagheer Tunnel. Information on the current ventilation system and mode of operation inside the tunnel is also presented in this chapter. Finally, background concentrations of pollutants in Makkah and wind statistics are summarized in this chapter.

Chapter 4 discusses air quality modeling, model building, and underlying assumptions of the models. Simulation runs of air quality scenarios are presented to assess the current air quality status of the tunnel and the proposed solutions. After the modeling results are presented, validation of the model by comparing the predicted and measured concentrations is discussed. Finally, the analysis section summarizes the results and compares the various scenarios and their impact on air quality inside the tunnel.

Chapter 5 describes a risk assessment of the current situation with respect to the air quality inside the tunnel. In this chapter, average concentrations of carbon monoxide are compared with the permissible short-term exposure limits set by the World Health Organization (WHO).

The conclusions of the study and recommendations to improve air quality are summarized in Chapter 6 of the thesis.

This study is considered important because the air quality of the Souk Sagheer Tunnel has been studied in the past but there was never an air quality model that has been applied. Most recommendations were based in qualitative judgments. However, this study will look at different solutions and evaluate them using a mathematical model that can produce a reliable conclusion.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

Subways and road tunnels have become an integral part of modern cities. From a design perspective, the release of pollutants must be considered; if allowed to persist, pollutants released from subways and road tunnels could cause acute health and ecological effects inside the tunnels and in their surrounding locations.

The air pollution in road tunnels has not received much attention in the past, despite the fact that ventilation has been studied extensively (Coke et al., 2000). In road tunnels mostly meant for highway driving, passengers inside closed vehicles are not exposed to the pollutants directly, so the health risk may not be as significant as the immediate breathing of polluted air. There is, however, one factor that distinguishes the Souk Sagheer Tunnel from other tunnels: this is not a highway road tunnel, but a road link that resembles a subway environment in which people are directly exposed to air pollution. The effects of pollution on pedestrians, passengers, personnel, and other activities, such as the selling of goods, are described in the following chapter. Activities and people exposed directly to vehicle emissions make the situation inside the Souk Sagheer Tunnel more challenging from a ventilation perspective, and as a result, the high levels of pollutants may impose a health risk to users.

In the following sections, the regulations, policies, and safety requirements of road tunnels are presented, and the ventilation of road tunnels in general is discussed. Then air pollution dispersion modeling in road tunnels is reviewed, with special emphasis on the model applied in this study for the Souk Sagheer Tunnel.

2.2 Transportation Emission: An Overview

According to the USEPA (2006), greenhouse gas emissions (GHG) that are attributed to transportation account for 27% of the total GHG emissions in the US. If this is the situation in a highly developed industrialized economy, it can be expected that transportation accounts for higher percentages of GHG emissions in developing countries, where the share of GHG emissions by industries and factories could be lower. However, transportation emissions also include some compounds other than greenhouse gases, such as ozone and carbon monoxide.

There are many compounds associated with transportation emissions, such as ozone, CO, CO_2, NO_x, SO_x, CH_4, N_2O, and particulate matter (US EPA, 2006). However, the scope of this study is to focus on the air quality of the tunnel with regard to representative pollutants such as CO, NO_x, SO_x and PM. The emission of on-road transportation sources depends on many components, which include the type of engine, the type of fuel, the driving style, the road gradient, the type of exhaust, and the maintenance condition of the vehicle (Colberg et al., 2005).

2.3 Regulations Governing Road Tunnel Safety Requirements

There are a number of standards, guidelines, and regulations for fire and safety in road tunnels that address ventilation issues from a regulatory point of view. These include standards from the NFPA (National Fire Protection Association), regulations by the EU

Directive 2004/54/EC, guidelines by the PIARC (The World Road Association), and the UNECE (United Nations Economic Commission for Europe).

The EU Directive 2004/54/EC was published on April 29, 2004. It addresses the issue of road tunnel safety in European countries. These regulations are applicable to road tunnels that are greater than 500 m in length. The directive defines several parameters to be considered in the safety measures. These factors are the geometry of the tunnels and their design, safety equipment, traffic management, training of emergency services, incident management, provision of information to users on the behaviors of the traffic, and communication with safety personnel. The EU Directive also identifies different tunnel authorities, such as tunnel managers, safety officers, and independent inspection entities. According to the EU Directive, these authorities should perform the following tasks: testing and inspecting safety equipment in the tunnels on a regular basis, implementing risk redemption measures, and defining procedures for immediate closures in case of emergency.

From a design perspective, the EU Directive defines 16 safety measures to be considered. These are as follows:

- Tunnel length
- Number of tubes
- Number of lanes
- Cross sectional geometry
- Vertical and horizontal alignment
- Type of construction

- Unidirectional or bidirectional traffic
- Traffic time per tube (including time distribution)
- Risk of congestion
- Access time for emergency services
- Presence and percentage of heavy goods and vehicles
- Presence, percentage and type of dangerous goods traffic
- Characteristics of the access roads
- Lane width
- Speed consideration
- Geographical and meteorological environment

In the EU Directive, according to annex I, paragraph 2.1.2, it is stated that the tunnel should be unidirectional if traffic exceeds 10,000 vehicles per day per lane. In other words, the EU Directive does not allow a road tunnel to be bidirectional when traffic is above 10,000 vehicles per day, per lane. This paragraph is especially interesting because the Souk Sagheer Tunnel may not meet the above criterion, which could suggest potential dangers in the case of an emergency fire.

The Directive also defines rules related to emergency exits and requirements for the type of emergency exits. Furthermore, there are some special requirements for bidirectional tunnels without emergency lanes; they should include lay-bys with emergency stations that can provide protective shelters for people trying to escape from smoke and fire.

Finally, with respect to ventilation, the Directive clearly states that ventilation should be capable of controlling pollutants under normal, peak, and stranded traffic conditions. It also states that longitudinal ventilation is allowed in bidirectional tunnels only if a risk assessment proves that it is acceptable, and air pollutants should be monitored regularly for long tunnels.

On the other hand, the UNECE recommendations were published in December 2001. These are guidelines that address road tunnel safety. The UNECE distinguishes between the danger of tunnels compared to regular motorways, which is due to the fact that tunnels are enclosed spaces. Therefore, fires, toxic gases, and the spread of smoke can be particularly dangerous if not controlled properly. This may result in poor visibility, development of high and damaging temperatures, and a reduction in oxygen levels. As a result, the UNECE states that the "Ventilation system (in road tunnels) needs to be fast and efficient, particularly in tunnels with bidirectional traffic" (UNECE, 2001). However, bidirectional tunnels are in a greater danger because it is difficult to control the spread of fires, making it difficult for drivers to escape from them. Moreover, the UNECE reports that the frequency of accidents in bidirectional tunnels is significantly higher than in unidirectional tunnels (up to 40% higher). The guidelines also claim that there should be no turning or reversing in the road tunnels. Finally, it is noteworthy to mention that the UNECE recommends the ventilation of tunnels be sufficient to control a fire of 30 MW power, which is equivalent to a heavy truck fire (Buses are rated at 20 MW) (PIARC, 1999).

In addition, the PIARC has published a number of documents addressing issues concerning road tunnels, which are considered as the means to improve air quality in the local environment, by containing and redistributing air pollutants. Thus, tunnel design should be adequate and beneficial to the local environment. Objectives should be established that the local air quality standards should not exceed the WHO recommended exposure limits, which are based on the health effects of pollutants on vulnerable humans. Moreover, the PIARC indicates that a number of primary pollutants are deemed necessary for investigation. These pollutants are: carbon monoxide (CO), oxides of nitrogen (NO_x), mainly nitric oxide (NO) and nitrogen dioxide (NO_2), particle matter with diameters less than 10 μm (PM_{10}), hydrocarbons such benzene, and lead, which is still mixed with petrol in some countries. In addition to the primary pollutants, the PIARC has also defined ozone (O_3) and ammonia nitrate as secondary pollutants to be investigated. Furthermore, it is important to mention that, in the same report, the PIARC has stated that "it has generally been found that Sulfur Dioxide (SO_2) is not a significant pollutant from traffic" (PIARC, 2008).

When it comes to Air Quality Dispersion, the PIARC report emphasizes mainly the modeling of air quality in the external environment near the tunnels. The PIARC also acknowledges the complexity related to accurately differentiating between the impact of road tunnel exhaust and background concentrations from other sources, given the different parameters of the atmospheric turbulences. The PIARC also states that the modeling of road tunnel air quality is subject to "ongoing research and refinement" (2008). Finally, the PIARC claims that researchers should select the proper model for their specific requirements based on location, meteorology, and topography to model air quality in the vicinity of road tunnel portals.

2.4 Ventilation of Road Tunnels

The purpose of ventilation systems in road tunnels is not only to maintain a healthy air quality level, but also to maintain normal temperatures and humidity levels. The ventilation system should also serve as a control solution in case of fire and evacuation, by driving smoke down to the road and not up toward the travelers.

When designing a road tunnel, several design criteria are considered to effectively embrace the power of natural ventilation and the piston action of the vehicles. However, natural ventilation and piston action are not sufficient for longer tunnels (tunnels that exceed 300 m long usually require forced ventilation).

2.4.1 Design Criteria

There are general design criteria for the construction of tunnels. Tunnels are usually built where the land is very valuable, or where it has irregular terrain, such as hills or valleys. It is recommended that the tunnels preferably be unidirectional, with separate tubes for each direction, to provide better control in the event of fires and to make ventilation more effective. Bidirectional tunnels pose risks in the event of fire because fires can spread in both directions and can make escape difficult.

Another consideration for tunnel design is efficacy. CO is mainly monitored to determine ventilation efficiency. However, other parameters, such as NO_x and particulates, also need to be monitored in tunnels. Electrostatic precipitators (ESP) are widely used in road tunnels in Japan and Norway to reduce PM_{10} and to improve visibility. This is becoming an industry standard, especially where heavy trucks are anticipated. Moreover, the ventilation system should be able to control and withstand fire and extreme temperatures, and the surroundings of tunnels should be considered when designing tunnel mouths and exhaust stacks. Pollutants should disperse away from the populated areas around the tunnels, especially when weather conditions are not favorable.

2.5 Technologies and Control Systems

2.5.1 Removal technologies

Despite the rarity of using treatment technologies to remove pollutants from vehicle emissions in road tunnels, technologies have been developed to clean the air inside road tunnels, and these technologies are in use in Norway, Japan, Austria, and Germany (PIARC 2008; RTA Australia, 2001; RTA Australia, 2004). Electrostatic precipitators were used to reduce PM_{10}. In Japan, the ESPs were used inside tunnels to improve visibility, and they were used in stacks to reduce PM_{10} emissions. These ESPs are not in operation 24 hours a day, but according to a schedule (Norway) or when peak traffic is encountered or visibility is reduced (Japan) (RTA Australia, 2004). In Japan, the use of ESPs for external air quality has been implemented in a number of tunnels, including tunnels with a 0.6- to 3.5-km range (PIARC, 2008)

On the other hand, the use of treatment technologies to reduce emissions to the external environment is rare because treatment technologies are limited to a narrow range of pollutants.

Another air pollution control technology used to reduce NO_2 was developed in Japan in a joint investigation between the Ministry of Land, Infrastructure and Transport, Japan Highway Public Corporation, the Metropolitan Expressway Public Corporation and Hanshin Expressway Public Corporation (2004) (PIARC, 2008). Two removal systems using physical and chemical adsorption achieved a removal efficiency of 90% (PIARC, 2008). A number of devices have been installed in Norway and Japan for experimental purposes (RTA Australia, 2004; PIARC, 2008). However, according to PIARC (2008), depending solely on removal technologies will not reduce all kind of pollutants.

2.5.2 Control Systems

The ventilation systems used in tunnels need to be controlled to accommodate various scenarios of traffic, such as low traffic, congestion, and smoke as a result of fire. For example, when traffic is low, the ventilation system can be switched to operate at its minimum capacity. Before the 1980s, control of ventilation was manual (AE Vardy et al., 2000). In the case of manually controlled ventilation, the control decisions were based on the observations of personnel. However, automated control systems were introduced later. They are usually based on levels of CO and smoke detected by sensors. When CO concentrations reach certain pre-programmed limits, extra ventilation power is activated.

The benefits of automated control systems include fire control, pollution control, and the minimizing of energy costs. Many longitudinal ventilation systems are fully reversible. For example, in the case of fire, it is possible to push smoke into one direction. Transverse ducts can also be used at different power levels according to real time monitoring of CO or any other group of representative pollutants. By keeping ventilation at an optimum level of use, the cost of power, operation, and maintenance can be reduced. However, in a bidirectional tunnel with longitudinal ventilation, the direction of flow should be maintained with the highest traffic flow. This could maximize the drag force of vehicles and drive pollutants outside of the tunnel (piston action) in favor of ventilation.

2.6 Incidents and Episodes

There is a high probability of accidents in transportation on roads compared to other means of transportation. According to the UNECE, "of all modes of transport, transport by road is the most dangerous and the most costly in terms of human lives" (UNECE, 2001). In road tunnels, fires are more dangerous than in the open environment. Fire accidents in tunnels will not only cause damaging temperatures, but they will also make it difficult to breathe inside a tunnel, which can result in high numbers of fatalities due to smoke and heat. Moreover, in confined spaces such as tunnels, escaping becomes difficult, especially when fire spreads in both directions. There are a number of episodes that have occurred in road tunnels, some of which are described below.

In October 2001, a fire took place in the Gotthard road tunnel in Switzerland, claiming eleven lives. The cause of the fire was a collision between two trucks in the bidirectional tunnel. According to a news report by the BBC World Service (2001), heat and black smoke hindered rescue operations. Another deadly fire occurred in the Mont Blanc tunnel in March 1999. This tunnel connects France and Italy; a truck loaded with margarine caught fire in the tunnel, killing 29 people, including a fire fighter. There was a fire control system that drove smoke quickly to one portal. Therefore, some people were able to escape, but others died inside the tunnel due to smoke (Bailey, 2010). In the Tauern Tunnel, which connects Austria and Germany though the Alps, a collision followed by a fire killed twelve people and injured fifty others on May 29, 1999. Four out of the twelve people who were died due to smoke in the tunnel (BBC, 1999).

These incidents demonstrate the importance of controlling fire and smoke inside road tunnels.

2.7 Air Quality Modeling

Air quality modeling is an important component to better understand and describe the air pollutant concentrations inside a road tunnel or in the atmosphere. According to Zannetti et al., "Air quality modeling is an attempt to describe the casual relationship between emissions, atmospheric concentrations, and deposition." (2005).

Air pollutant concentration measurements may provide a good indication of air quality at a certain location, during a specific time when the measurement is taken. However, an air quality model would provide more descriptive information that can account for different traffic volumes, locations, and conditions. Moreover, air quality models can provide objective information regarding the relationship between emission and pollutant concentrations, which will help in future planning.

In the case of road tunnels, it is crucial to use an air quality model to optimize the selection of alternative solutions for remediation of air pollution.

The use of air quality models has been widely accepted and recommended by regulatory agencies such as the United States Environmental Protection Agency (USEPA) and the European Union (EU). Table 2.1 lists some air quality models that are accepted by the Co-operative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe (EMEP, 2010) and the United States Environmental Protection Agency (USEPA, 2010)

These models listed in Table 2.1 are used for regional and local atmospheric dispersion. There is perhaps no specific recommended model for air quality assessment inside road tunnels.

Table 2.1 Example of models accepted by EMEP and USEPA

Model	Purpose	Accepted by
RAINS (Regional Air Pollution Information and Simulation)	Explore synergies and trade-offs between the control of local and regional air pollution and the mitigation of global greenhouse gas emissions	EMEP (EMEP, 2010)
EMEP/MSC-E (Chemical Transport Model)	Regional atmospheric dispersion and deposition of heavy metals (Cd, Pb, Hg) and selected persistent organic pollutants (PCB, PAH, HCB, PCDD/Fs, g-HCH)	EMEP (EMEP, 2010)
AERMOD	Steady state plume model	USEPA (USEPA, 2010)
CALPUFF	Non-steady state puff model	USEPA (USEPA, 2010)
BLP	Gaussian plume dispersion model designed to handle unique modeling problems where plume rise and downwash effects from stationary line sources are important	USEPA (USEPA, 2010)
CALINE3	Steady-state Gaussian dispersion model designed to determine air pollution concentrations at receptor locations downwind of highways located in relatively uncomplicated terrain.	USEPA (USEPA, 2010)
CAL3QHC/CAL3QHCR	CAL3QHC is a CALINE3 based CO model with queuing and hot spot calculations and with a traffic model to calculate delays and queues that occur at signalized intersections; CAL3QHCR is a more refined version based on CAL3QHC that requires local meteorological data	USEPA (USEPA, 2010)
CTDMPLUS	Complex Terrain Dispersion Model Plus Algorithms for Unstable Situations (CTDMPLUS) is a refined point source Gaussian air quality model for use in all stability conditions for complex terrain. The model contains, in its entirety, the technology of CTDM for stable and neutral conditions	USEPA (USEPA, 2010)

The selection of a model is usually based on a number of factors. The model to be selected should be an accurate estimator for air quality in that specific situation. Should the model be inaccurate, then adjustments to the model should be made to verify the actual conditions. Another factor is availability of resources and data collection. Some complex models require detailed input data that may not be easily available. After a model is selected, it can be used to verify the regulatory measures for certain facilities, such as licensing or urban planning. The location of a school, in the proximity of highways where high traffic is expected, is another good example where an air quality model can help in assessing the situation and decision-making.

Ambient air pollution has been studied extensively because of the associated higher risk of human exposure, compared to pollution in road tunnels where people are usually protected from direct exposure. However, even passengers inside their vehicles are exposed to elevated levels of pollutants that are several times higher in urban driving (Barrefors, 1996).

Air quality models are also used to design ventilation systems in the tunnels. In the planning phase, the areas surrounding a tunnel should be taken into consideration. Emissions accumulate inside the tunnel, and high pollutant concentrations are emitted to the surrounding environment through tunnel ends. When an air quality model is implemented, it will help in selecting exhaust locations and stack heights to avoid releasing pollutants downwind to residential areas. Another useful application of air quality models is to determine the level of required forced ventilation. The air quality model is an effective tool to determine the necessary utilization of natural and forced ventilation.

There are a number of air quality models developed for road tunnels that are mainly based on the conservation of mass equation. Fadel et al. (2000) compiles several air quality tunnel models by (Pursall, 1976; Chang and Rudy, 1990; Chan et al., 1996; Bellasio 1997; Rogak et al., 1998). El-Fadel and Hashisho (2000) report that all road tunnel air quality models assume full mixing along y and z axis.

In dispersion modeling, an estimation of pollutant concentration is derived from a mathematical model based on diffusion. Usually, it is used to estimate primary pollutants because it does not consider chemical transformation, with the exception of simple transformations such as the decay factor of pollutants. The dispersion models are usually applied to estimate local concentrations of pollutants over short ranges where chemical transformation is less likely to take place. For road tunnels, dispersion models seem to be suitable for estimation of primary pollutants because the main concern is for direct and short term exposure.

There are a number of dispersion models, some of which will be described in the following section. There are different types of dispersion models, including a Gaussian model, approximate solutions for mass conservation of turbulent fluxes, and trajectory models.

2.8 Air Quality Modeling in Road Tunnels

To model and simulate air pollution in tunnels, there are mainly two parts to consider: one is air pollution dispersion modeling, which is governed by atmospheric turbulence and piston action inside the tunnel. The second part is the source modeling, which is related to estimating emissions from each type of vehicle or emission source.

The atmospheric turbulence in tunnels is mainly caused by ventilation, which can be either natural ventilation, in short tunnels less than 300 m long, or forced ventilation, which uses mechanical ventilation systems. Several other factors affect the atmospheric turbulence inside the tunnel in addition to ventilation, including weather conditions, physical boundaries and objects, chemical properties of pollutants, road gradient, and pressure change at the tunnels mouth.

On the other hand, vehicle movement creates a piston action. The piston action is a force that pushes pollutants down in the driving direction. The higher the speed of the vehicles, the higher the piston action, which, at high speed, results in a continuous action. With stranded vehicles, or idling conditions, there is no piston action generated. Therefore, when a road tunnel is congested, very low piston action is expected and greater pressure is imposed on the ventilation system. Furthermore, bidirectional tunnels become less efficient with respect to piston action because there is an interaction between the aerodynamics generated by the two opposite traffic streams. Moreover, bidirectional tunnels do not only hinder the piston action, but they also impose higher risks in case of fire.

To model air quality inside road tunnels, there are many air quality tunnel models that vary from a simple box model to complex simulation models. There are also some hybrid models that integrate more than one model to serve different purposes. For example, the Eulerian-Lagrangian model (Katolický et al., 2005), in which the conservation of volume at one time and the conservation of mass at another are combined; provides information about concentrations of pollutants in space and time domains.

Some air pollution dispersion models are more suitable in tunnel environments than others. For example, the box model, which is used in the street canyons, seems to be suitable in the tunnel environment if forced ventilation is considered in the model. A number of box models have been implemented in tunnels and subway environments, which include but are not limited to box model and semi-empirical box models (Gokhale et al., 2007). Moreover, the Eulerian-Lagrangian model (Katolický et al., 2005), dense gas dispersion models (WS Atkins, 2001), and one-dimensional simulation model (Coke et al., 2000; Per Sahlin et al., 2003) have also been implemented.

A study by Lee et al. (2006) compared three models to estimate air quality parameters inside a traffic tunnel. These are the Grey model (GM), the Crank-Nicholson implicit scheme model, and the forecasting combination model (FCM). According to Lee et al., (2006), the most accurate among these three models, when applied to a case study for a tunnel in Taiwan, was the FCM model because it is comprised of combination of both GM and Crank-Nicholson models, and as a result, more parameters are considered using FCM modeling (2006).

Lee et al. (2007) employed a standard turbulence model for CO and NOx concentrations inside a traffic tunnel. Both forecasting models (FCM) and the turbulence model were used for ventilation, as well as the piston effect of the moving vehicle.

It is noteworthy to mention that there are some other modeling approaches to predict the spread of pollutants at outlets of the tunnels. Katolický et al. (2002) have used a modeling approach based on the Eulerian-Lagrangian method for moving objects. Although it might be difficult to predict air quality concentrations inside passengers' vehicles, there are a number of studies that have integrated ambient air quality and air quality inside vehicles (Ott W et al., 1993 & 1994; Dor F et al., 1995; Weisel 2005). According to Weisel (2005) "The CO concentration (inside passengers' cars) was typically 1 ppm when driving in areas not surrounded by other cars and 5 to 7 ppm when driving within a tunnel or a traffic jam" This statement shows how a tunnel can impose greater risk, not only to pedestrians, but also to the passengers inside vehicles. Factors such as the type of vehicle, the control of the vehicle, the speed, the proximity to other cars, and closed or open car windows will have an impact on the concentration of pollutants inside passenger cars. Studies also show higher PM concentrations inside passengers' vehicles in traffic jams or in road tunnels (Weisel 2005).

2.9 Illustration of major air quality models

2.9.1 Numerical solution of the equation of conservation of mass

The general equation of conservation of mass is integrated numerically to estimate pollutant concentration. Many models developed different numerical simulations for a number of specific situations where certain parameters are constant. For example, the following Gaussian model is a solution to the general equation of mass conservation. The general equation of conservation of mass (Zannetti et al., 2005) is:

$$\frac{\partial c_i}{\partial t} + u_x \frac{\partial c_i}{\partial x} + u_y \frac{\partial c_i}{\partial y} + u_z \frac{\partial c_i}{\partial z} =$$

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial c_i}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial c_i}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial c_i}{\partial z}\right) + R_i(c_1, c_2, \dots, c_n) + E_i(x, y, z, t) - S_i(x, y, z, t),$$

Eq. 1

where: u_x, u_y, u_z = velocity

c_i = concetration of i^{th} species

R_i = chemical generation rate of species i

E_i = emission flux

S_i = removal flux or sink term.

On the other hand, for road tunnels, a simplified form of the conservation of mass equation assumes a one-dimensional equation of conservation of mass as follows (Bellasio, 1997):

$$\frac{\partial c_i}{\partial t} + u_x \frac{\partial c_i}{\partial x} = \frac{\partial}{\partial x}\left(K_x \frac{\partial c_i}{\partial x}\right) + R_i(c_1, c_2, \dots, c_n) + E_i(x,t) - S_i(x,t).$$

Eq. 2

The source term (E_i) is the function of time and location because emissions occur at different locations inside the tunnel depending on the vehicles (Bellasio, 1996). This simplified form of the conservation of mass equation provides the basis for air quality modeling in road tunnels, where the concentration of pollutants along the direction of the tunnel is the main focus of the research. The validity of the assumptions of adequate mixing along z and y directions is due to traffic motion in confined spaces (Staehelin et al., 1995).

2.9.2 Gaussian model

The Gaussian model is a solution to the general equation of mass conservation. It is called Gaussian because it looks similar to the normal distribution density function.

The Gaussian model is used for steady-state conditions and assumes constant wind speed. There are many forms of the Gaussian model. However, the basic Gaussian model equation (Zannetti et al., 2005) is:

$$c(x,y,z) = \frac{q}{2\pi\bar{u}\sigma_y\sigma_z}\exp\left(-\frac{y^2}{2\sigma_y^2}\right).\left[\exp\left(-\frac{(z-h)^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(z+h)^2}{2\sigma_z^2}\right)\right],$$

Eq. 3

where: $q =$ source strength

$h =$ stack hight

$\sigma_y, \sigma_z =$ lateral and vertical dispersion coefficients.

The Gaussian model is used to estimate air quality in the vicinity of tunnels, especially when stack emissions are used (PIARC, 2008).

2.9.3 Box models

The box model is also based on the principle of the conservation of mass. A one-dimensional box model has been proposed by Bellasio (1997) and is as follows:

$$AL\frac{\partial C}{\partial t} = A\left[C(u+\eta u_{veh}) - K_x\frac{\partial C}{\partial x}\right]_{\text{Left}} - A\left[C(u+\eta u_{veh}) - K_x\frac{\partial C}{\partial x}\right]_{\text{Right}} + S^* - P^*,$$

Eq. 4

where: $A =$ Tunnel cross-sectional area

$L =$ Tunnel length

η = non-dimensional ratio between vehicle and tunnel cross-sectional areas

K_x = Hoizontal dispersion coefficient

S^* = source of pollutants

P^* = Sink term.

This box model gives the pollutant concentration in the time domain only. An additional Eulerian term to account for space will be presented in a later section when Eulerian models are discussed.

The numerical solution for the box model is given by (Bellasio, 1997):

$$C^{n+1} = C^n\left(1 - \frac{\Delta t}{L}\left(\text{Max}(-w,0) + \text{Max}(w,0) + \frac{2K_x}{L}\right)\right) + \frac{C_{BL}\Delta t}{L}\left(\text{Max}(w,0) + \frac{K_x}{L}\right) + \frac{C_{BR}\Delta t}{L}\left(\text{Max}(-w,0) + \frac{K_x}{L}\right) + \frac{\Delta t}{AL}\left(S^* - P^*(C^n - C_{\text{out}})\right),$$

Eq. 5

where: C^{n+1} = Concentration at time $t^{n+1} = (n+1)\Delta t$

C^n = Concentration at time $t^n = (n)\Delta t$

Δt = Discrete temporal step

C_{BL} = Concentration of pollutant at the left boundary

C_{BR} = Concentration of pollutant at the right boundary

w = wind speed.

Although this model has not been validated on a real tunnel case study (Bellasio, 1997), both the sensitivity and the analysis of differences between analytical and numerical methods were discussed by Bellasio (1997).

2.9.4 Lagrangian and Eulerian models

The Lagrangian model can be explained as if an imaginary, very small particle of a pollutant carries certain information regarding its properties and is followed and traced on the wave of turbulence in the space and time domain. On the other hand, the Eulerian model divides the study area into three-dimensional grids. In the time and space domain, the properties of these grids change based on the turbulence.

There are a number of numerical solutions for each model. In addition, some hybrid models that combine both models also exist. In the hybrid Lagrangian-Eulerian model, a particle of pollutant is being followed over a grid network. Compared to the Gaussian and Box models, Lagrangian and Eulerian models require much higher computational capabilities to solve them.

The Eulerian model is solved with finite volume method and is presented by Bellasio (1997). In this model, the tunnel is divided into grids along the x direction. Each grid or box is then integrated to solve the equation of conservation of mass as follows (Bellasio 1997):

$$A\Delta x \frac{dC_i}{dt} = A(\Phi_{\mathrm{i}} - \Phi_{\mathrm{i+1}}) + A\Delta x S_i - A\Delta x R_i(C_i - C_i^{\mathrm{out}}),$$

Eq. 6

where: Δx = grid size

Φ_i = represent mass flux at position $(i-1)\Delta x$

Φ_{i+1} = represent mass flux at position $i\Delta x$

Hint: these fluxes describe dispersion and advection

R_i = exchange rate of air.

The above Eulerian model can estimate concentrations in one dimension because grids are divided along the x-axis only while assuming full mixing on the lateral (y-axis) and vertical (z-axis) direction. This assumption had been justified earlier, when it was mentioned that the vehicle movements facilitate full mixing.

Another Eulerian-Lagrangian model for traffic dynamics in road tunnels has been illustrated by Katolický and Jícha (2005). This hybrid model combines Eulerian and Lagrangian models as well as a CFD model. The first Eulerian-Lagrangian model is to simulate traffic and its impact on the ventilation, while the CFD portion serves to simulate air flow inside the tunnel.

A subway environment simulation (SES) model was developed to help in the designing of subway tunnels (Parsons et al., 1976). This model accounted for aerodynamics and thermal phenomena inside the tunnels. It has been used in designing subway tunnels and mechanical HVAC (Heat, Ventilation and Air Conditioning) systems. However, the SES model did not consider air quality until a report in 2000 by Coke et al., who developed a dispersion model of contaminants inside a subway environment. A modified and enhanced model was developed by Per Sahlin et al. (2003) to address air pollution dispersion as well as road tunnels based on the SES model. This advanced model by Per

Sahlin et al. (2003) utilizes the advantage of modern computational capabilities. This model, which is later called "IDA RTV", uses aerodynamics equations from SES with slight modifications in the road tunnels, which are considered smaller trains that emit pollutants. The one-dimensional numerical model solves the equation of mass conservation using differential-algebraic systems in the Modelica simulation environment (Modelica is a modeling language for complex systems). The new model has been validated using fire experiments and experimental measurements of underground systems, and other well-established analytical methods and modeling approaches, such as CFD modeling of flow dynamics (Per Sahlin et al., 2003). This model has been in use by European tunnel design companies, such as HBI Haerter, Gruner, Halcrow, WSP, Norconsult, Ramböll, Pöyry, and Sweco, and has been commercialized since 1995.

There are three aerodynamics equations used in this model to account for vehicle and atmospheric turbulence inside the tunnels:

The first equation calculates pressure change due to friction against walls, and the second equation estimates the pressure difference induced by vehicle movement. Finally, the piston action equation is given as follows (Source: Per Sahlin et al., 2003).

$$\Delta p_{frict} = -\sum_i \frac{\rho_i}{2}\frac{\lambda_T}{d_i}\left[(l_i - \sum_j l_{V_{ij}})v_i\,|v_i| - \sum_j \frac{l_{V_{ij}}}{\left(1 - A_{V_j}/A_i\right)^3}\left(\frac{A_{V\_j}}{A_i}v_{V_{ij}} - v_i\right)\left|\frac{A_{V\_j}}{A_i}v_{V\_ij} - v_i\right|\right],$$

Eq. 7

where

Δp_{frict} = pressure change due to friction against walls (Pa)

λ_T = friction factor for tunnel wall (dimensionless)

ρ_i = mean density of air in tunnel segment i (kg/m^3)

d_i = hydraulic diameter of tunnel segment i (m)

l_i = length of tunnel segment i (m)

$l_{V_{ij}}$ = length of vehicle type j in tunnel segment i (m)

υ_i = mean air velocity in segment i, positive from left to right (m/s)

$\upsilon_{V_{ij}}$ = velocity of vehicle j in segment i, positive from left to right (m/s)

A_{V_j} = cross section area of vehicle type j (m^2)

A_i = tunnel area of segment i (m^2).

$$\Delta p_{fricv} = \sum_i \sum_j \frac{\rho_i}{8} \frac{\lambda_{V\_j} \cdot l_{V\_j} \cdot p_{V\_j}}{A_i \left(1 - A_{V\_j}/A_i\right)^3} \left(\upsilon_{V\_ij} - \upsilon_i\right) \left|\upsilon_{V\_ij} - \upsilon_i\right|,$$

Eq. 8

where $\lambda_{V_j} = \lambda_{VS\_j} + \frac{C_{DTV\_j}}{4 l_{V\_j} p_{V\_j}}$

Δp_{fricv}= pressure change due to friction against vehicles (Pa)

λ_{V_j} = skin friction coefficient for vehicles of type j (dimensionless)

λ_{VS_j} = skin friction coefficient related to viscous drag for vehicles of type j (dimentionless)

C_{DTV_j} = drag coefficient weighted total truck area for vehicles of type j (m^2)

l_{V_j} = length of vehicles of type j (m)

p_{V_j} = perimeter of vehicles of type j (m).

$$\Delta p_{piston} = \sum_i \sum_j \frac{\rho_i}{2} A_{V\_j} \left\{ \left[\frac{C_{DFV\_j}}{A_i} + \frac{(2A_i - A_{V\_j})}{(A_i - A_{V\_j})^2} \right] N_{front\_ij} + \left[C_{DBV\_j} \frac{A_i}{(A_i - A_{V\_j})^2} - \frac{2}{A_i - A_{V\_j}} \right] N_{back\_ij} \right\} (v_{V\_ij} - v_i) |v_{V\_ij} - v_i|,$$

Eq. 9

where $C_{DBV\_j} = \frac{0.029}{\sqrt{0.5 \lambda_{VS\_j} l_{V\_j} p_{V\_j} / (4A_{V\_j})}}$

Δp_{piston} = piston pressure rise (Pa)

C_{DBV_j} = drag coefficient at back end of vehicles of type j (m^2)

C_{DFV_j} = drag coefficient at front end of vehicles of type j (m^2)

N_{front_ij} = number of front ends of vehicles of type j in segment i

N_{back_ij} = number of back ends of vehicles of type j in segment i.

Here, the front end is defined as the end, either the physical front or back, which has a headwind.

2.9.5 Statistical models

Statistical models use various statistical methods to estimate pollutant concentrations. For example, a statistical model could use a regression equation to estimate the relationship between the number of vehicles and pollutant concentrations, including some parameters such as meteorological conditions. Statistical models, however, require extensive monitoring data. In the literature, a number of studies have used statistical models to estimate air pollutant concentrations inside road tunnels. A study by Lee et al. (2006) compared three statistical models used to predict air quality inside a road tunnel. The study used the mean absolute percentage as a measure to compare the performance of the three models. These three models are the Grey Model, the Combination Model, and the Modified Grey Model. Prior to 2006, the Grey Model has perhaps never been used in estimating air quality in a tunnel with longitudinal ventilation (Lee et al., 2006 and 2007). The advantage of the Grey Model is that it requires less input data than regular forecasting models (Lee et al., 2007). The Grey Model has been developed by Deng (1982, 1989) especially to forecast systems that are poorly characterized. To establish a Grey Model, or statistical models in general, a pre-sampling that uses experimental methods is required. These sampling data are then provided to the model to predict multiple scenarios. In the study by Lee et al. (2007), results show that the modified Grey model performed better than the standard Grey model in predicting carbon monoxide levels in a road tunnel.

2.9.6 CFD modeling

CFD models or Computational Fluid Dynamics models use numerical methods to solve fluid dynamics equations. They are usually applied and calibrated with wind tunnel studies to assess the impact of turbulence. For road tunnels, CFD modeling techniques have been extensively used to model fire propagation inside tunnels, but very little attempt has been made at air quality modeling inside the tunnels (Naser and Murad, 2002).

CFD models can give a good representation of flow directions and turbulences (Figure 2.1), considering both the piston action and the ventilation within the specific geometry of a tunnel. Chen et al. (2000) and Naser (2002) have presented flow patterns in road tunnels using CFD modeling. However, neither study has included vehicular emissions until 2001, when Naser (2001) presented an approach to model vehicular emissions in the road tunnels. More parameters were introduced into the CFD model by Naser (2002), which can simulate emissions from vehicles in both running and stagnant modes. The model is also capable of simulating peak situations of traffic congestion inside a tunnel. The CFD model by Naser (2202) was applied to study the flow patterns for one-directional traffic, rather than bidirectional traffic.

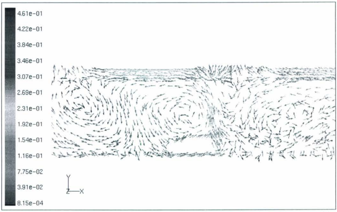

Figure 2.1 A CFD model shows flow patterns inside a road tunnel. (Used with permission from Naser, 2002.)

2.10 Applications and Software

Two popular software programs for air pollution dispersion modeling are the Subway Environment Simulation (SES) (the Urban Mass Transportation Administration, 1998) and the IDA Road Tunnel Ventilation (Equa Simulation, 2008). Computational fluid dynamics software can also be used, such as, CD Adaptco and Fluent.

There are also some other programs available for source emission. It is noteworthy to mention MOVE 2010 by USEPA (USEPA 2010 b). This is user-friendly software, and can be used to predict vehicles' emissions in different topographies and gradients.

2.11 Selection of a model

The selection of a proper model for this study was primarily based on the model's accuracy and its applicability to simulate air quality levels in the tunnels in the longitudinal direction, assuming adequate mixing of pollutants along the vertical and lateral directions. The advanced one-dimensional model by IDA RTV (Per Sahlin et al., 2003) meets these requirements and is suitable for bidirectional traffic patterns such as the Souk Sagheer Tunnel. This model has also been applied for various case studies since 1995 (Equa Simulation). In addition, it has been validated and studied extensively through the years.

There are other accurate models that can be built using CFD tools. However, these models require extensive input data and experimental validation.

Therefore, this research will apply the IDA RTV model in the Souk Sagheer Tunnel to estimate air quality inside the tunnel.

Chapter 3

THE STATUS OF THE SOUK SAGHEER TUNNEL

3.1 Background

Millions of pilgrims visit Makkah every year to perform Hajj and Umrah, and during these short time periods, the transportation of passengers becomes a real challenge. Because Makkah is located between several mountain ranges and three valleys cross the city (Saati and Shahine, 2000), transportation in the city becomes even more difficult. To facilitate the traffic movement and to ease transportation congestion in the city, the Saudi Arabian government has invested heavily in the construction of road tunnels. These tunnels are constructed through mountains, underneath busy intersections, and even underneath the Sacred Mosque, which is the final destination for millions of pilgrims.

There were more than 54 road tunnels in the city as of the year 2000 (Saati and Shahine, 2000), and their combined length is greater than 31 km. Some of these tunnels are particularly short (i.e., <200 m), and some are several kilometers long.

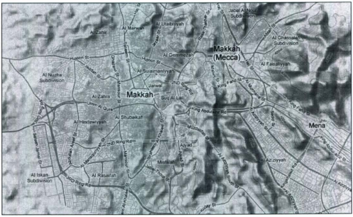

Figure 3.1 A map of Makkah shows the terrain and topography (Google Maps, 2010)

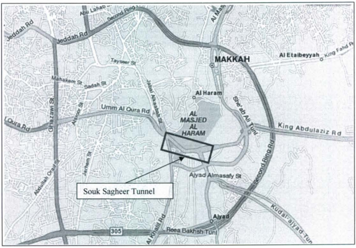

Figure 3.2 Major roadways in Makkah City (MapQuest, 2010)

One of the most important tunnels in the holy city of Makkah is the Souk Sagheer Tunnel (Figure 3.2). This tunnel derives its importance from its location and complexity. The Souk Sagheer Tunnel is located underneath the Grand Mosque, where, during the peak season, more than two million people may be gathered, (i.e., during Hajj and the month of Ramadan). In addition to its high traffic, it has a complex structure in which pedestrians, vehicles, sales activities, waiting areas, personnel, and washrooms are present inside the tunnel structure, which causes concerns for human health because of the heavily polluted environment.

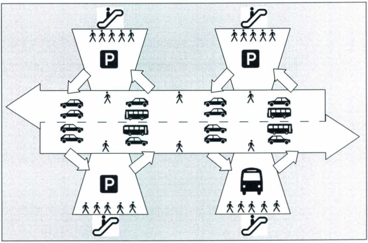

Figure 3.3 Major activities inside the Souk Sagheer tunnel (icons by Wikimedia Commons)

A number of studies have been conducted to identify the pollution risk inside the tunnel, including air pollution, microbiological pollution, and noise pollution (Hajj Research Institute, 2010). However, although many studies have investigated air pollution inside the tunnel, little attention has been paid to air pollution dispersion modeling (Yaqoub et al., 2003). The purpose of this investigation is to study air pollution and dispersion inside the tunnel to improve the ventilation system of the tunnel.

3.2 Location

The Souk Sagheer Tunnel is located beneath the western yard of the Sacred Mosque. It stretches from the southwest to southeast portion of the yard in a semi-crescent shape. Figure 3.4 shows a drawing of the tunnel superimposed over a satellite picture of the area. The center of the tunnel is located at approximately 21° 25' 13 N and 39° 49' 26 E.

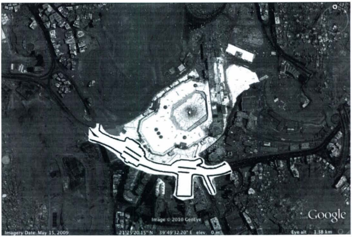

Figure 3.4 Tunnel location in relation to the Grand Mosque. (Source: Google Earth)

3.2.1 Structure and Dimensions

The tunnel has a roadway with two directions of traffic that are separated by a 1-m-high concrete barrier (Shehatah, 2003). Moreover, there are four waiting zones, which are used to load and unload passengers. One waiting zone is used as a bus station by the Saudi Arabian Public Transport Company (SAPTCO) (Yaqoub et al., 2003).

Each waiting zone has stairways leading to the entrance to the Grand Mosque above the ground. Two stairways lead to the King Fahad Door, and the other two lead to the King Abdulaziz Door, which leads to the Mosque, as shown in Figure 3.2.

To simplify the tunnel for the purpose of air quality modeling, the tunnel structure is divided into two sub-tunnels. The first sub-tunnel is called (A), and it encompasses the side with the traffic that drives from west to east from Umm-Alqura Street to King Abdulaziz Road and Ajyad Street. Sub-tunnel (A) is 11 m wide and has two driving lanes and two waiting zones. There is a U-turn 250 m from entrance. The second waiting zone is a bus station.

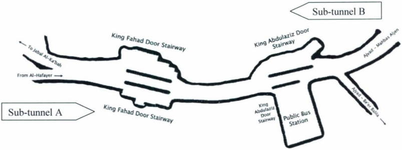

Figure 3.5 Diagram of the Souk Sagheer Tunnel

The second sub-tunnel is denoted as (B). It encompasses the traffic that flows in the east-west direction, from King Abdulaziz Road to Jabal Al-Ka'bah Street. This section also has two waiting zones. Each waiting zone is 90 m long and 8 m wide, with the exception of the bus station. The tunnel will be divided into sub-tunnels in the ventilation system section of this report because there is a slight difference in the number of fans in each sub-tunnel.

There are also four washrooms inside the tunnel structure. However, the entrances to these washrooms are outside the tunnel. This is important because apparently these washrooms are significantly impacted by the air pollution induced by vehicular emissions. (Yaqoub et al., 2003)

The entire tunnel has the following dimensions (Shehatah, 2003):

- Length = 1500 m
- Width = 22 m
- Height = 5.22 m
- No. of lanes (each way) = 2 (11 m wide on each side).

3.3 Ventilation

To find a solution to the high concentrations of air pollutants inside the tunnel, it is essential to understand the forced ventilation system in the tunnel. The ventilation system of the tunnel consists of three different components, including jet fans, supply fans, and exhaust fans (Yaqoub et al., 2003).

A total of 27 jet fans are positioned alongside both walls of the tunnels at a height of around 4 m from the ground and with 50 m between them. The units are 1 m in diameter and 4 m in length (Shehatah, 2003) (Alhazmi, 2008).

The fans are manufactured by Fläkt Woods, and, according to the Fläkt Woods catalog, the fans are model 100JTS jetfoils. See Table 3.1 below for more information.

Table 3.1: Specifications of the jetfoils in the Souk Sagheer Tunnel (source: Fläkt Woods catalog)

Fan Type	Blade Angle (°)	Thrust (lbf)	Volume flow (cfm)	Outlet velocity (ft³/min)	Absorbed Power (hp)	Motor Rating (hp)	Sound power (dBW)	Sound pressure (dBA)
100 JTS 1775 rev/ min	32	215	54200	6420	37.9	39	101	70
	37	250	60000	7090	52.2	53	104	73

In sub-tunnel A (see previous section), 13 jet fans are hung from the roof just next to the side wall, as shown below (Figure 3.3), and 14 jet fans are located in sub-tunnel B.

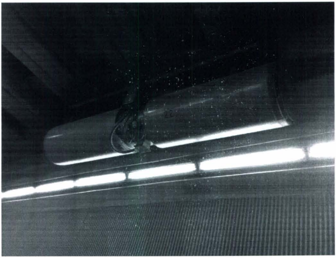

Figure 3.6 Jet fan hung from the roof next to the side wall (Source: PME)

Inside the tunnel are 13 electromechanical rooms, which contain the supply and exhaust fans. There are 18 supply fans and 5 booster fans for a total of 23 fans, which drive air into the tunnel. Likewise, there are 23 exhaust fans, which drive the polluted air out of the tunnel (Yaqoub et al., 2003). The forced ventilation system is controlled by an automated system designed by Landis & Gyr (Yaqoub et al., 2003). This automated system has CO sensors, and the full system is activated when the carbon monoxide levels reach 150 ppm. The study of Yaqoub et al. (2003) recommended that the activation limit should be lowered to 50 ppm.

The supply fans bring fresh air into the tunnel through 245 windows on the side walls. There are 121 windows on the side wall of sub-tunnel A and 124 on sub-tunnel B. Each window is 1.5 m long and 0.9 m wide.

3.4 Modes of Operation

Studies on road tunnels mainly focus on the impact of the exhaust from the tunnels on the surrounding environment. However, in the Souk Sagheer Tunnel, the mode of operation shifts the priority to the inside of the tunnel. This is due to the fact that the Souk Sagheer Tunnel is not meant only for vehicles; there are many other activities that take place inside the busy tunnel. In addition to passenger vehicles and trucks, there are pedestrians walking alongside the tunnel to reach their desired destination. These pedestrians spend up to 50 minutes inside the tunnel according to Shehatah (2003). Security personnel quite often spend more time inside the tunnel.

These activities usually take place inside the waiting zones (see Figure 3.2 above). Waiting zones are mainly for the purpose of loading and unloading passengers. Moreover, they also serve as the entrances to the yard (the mosque courtyard) and are used for short parking during prayer times.

In summary, the mode of operation inside the Souk Sagheer Tunnel can be categorized as follows:

Pedestrians walk on the sides of the tunnel. Moreover, security personnel, workers, and traders spend more time inside the tunnel than typical pedestrians. Vehicles and trucks maneuver in two driving directions with two U-turn conduits and sometimes idle and park in the tunnel.

The increase in traffic during the peak seasons is obvious. This tunnel mainly serves visitors of the Sacred Mosque, so the number of tunnel users can be assumed to be the same as the number of visitors to the mosque.

The month of Ramadan and Hajj are the two busy seasons for the tunnel. During the month of Ramadan, the number of visitors surges from day time to evening because of fasting and an additional prayer in the evening. The number is higher on weekends (Thursday and Friday) and during the last ten days of the month of Ramadan, especially during the nights of odd days (e.g., the nights of the 21st, 23rd, 25th, and 27th). The peak hours in Ramadan usually start one hour before sunset until midnight for the first 20 days and until dawn in the last ten days.

Hajj, however, is a little different. Although the peak happens over a fewer number days, the peak is greater during Hajj season than during Ramadan. More than two million people come each year to perform Hajj.

During other periods of the year, the peaks occur on weekends (especially on Friday) and five smaller peaks occur each day at prayer times.

3.5 Meteorological Data and Air Pollution Data Analysis

Meteorological conditions are important for modeling air pollution dispersion because the dispersion of pollutants mainly depends on atmospheric turbulence. Because the tunnel is not a completely closed building, the outer atmospheric conditions may have an impact on the turbulence inside the tunnel. However, because the tunnel is more than 300 m long, natural ventilation is not enough to circulate the air in the tunnel, and forced ventilation is necessary (Cooley and Turkey, 1965; McCormick, 1994; Rosenhead, 1963; Naser and Murad, 2002). Moreover, Makkah City generally has calm weather conditions.

The box plot in Figure 3.7 shows the monthly average wind speeds from 2005 to 2007. As can be seen in the figure, the typical ambient wind velocity is extremely low. The low wind velocity at the tunnel openings can also be attributed to the location of Makkah and its terrain; the city is surrounded by hills, and the Grand Mosque area is lower than the terrain around the tunnel.

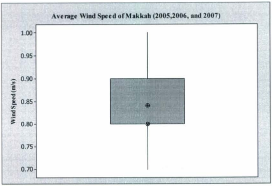

Figure 3.7 Box plot of wind speeds in Makkah (2005-2007).

It is noteworthy to mention that the tunnel is heavily polluted during the peak hours. Monitoring data show that the CO and SO_2 levels have at times exceeded the regulatory limits specified by the Presidency of Meteorology and Environment (PME) by more than ten-fold (Nasrullah, 1982; Jeelani, 1998; Saati and Shahine, 2000). The PME specifies that the levels of CO and SO_2 should not exceed 30 ppm and 0.28 ppm, respectively, for more than one hour.

Despite the above mentioned conclusion that natural ventilation may not provide sufficient air circulation in the tunnel, the ambient concentrations of pollutants are expected to affect the model because the forced ventilation system mainly exchanges the polluted air with ambient air. However, the concentration of pollutants in the ambient air always remains within the regulatory limits. Figures 3.5 and 3.6 indicate that the CO and SO_2 concentrations are within the acceptable limits and are relatively low. For CO, the average concentration ranges from 0.5 to 1.15 ppm, which is considerably lower than the regulatory limits of 9 ppm over a 24-hour period and 35 ppm on an hourly basis. Similarly, the SO_2 concentration is also especially low in the ambient air, with a maximum of 0.0175 ppm, which is lower than the acceptable limit set by the PME (Table 3.2) over any period.

Table 3.2 PME air quality standards (PME, 1989)

Averaging Time	Maximum Concentration	Allowable Exceedances
Sulfur Dioxide (SO_2)		
1 hour	730 $\mu g/m^3$ (0.28 ppm)	twice per 30 days
24 hours	365 $\mu g/m^3$ (0.14 ppm)	once a year
1 year	80 $\mu g/m^3$ (0.03 ppm)	(none)
Inhalable Particulate (IP)		
24 hours	340 $\mu g/m^3$	once a year
1 year	80 $\mu g/m^3$	(none)
Nitrogen Oxides (Defined as Nitrogen Dioxide, NO_2)		
1 hour	660 $\mu g/m^3$ (0.35 ppm)	twice per 30 days
1 year	100 $\mu g/m^3$ (0.05 ppm)	(none)
Carbon Monoxide (CO)		
1 hour	40 mg/m^3 (35 ppm)	twice per 30 days
8 hours	10 mg/m^3 (9 ppm)	twice per 30 days

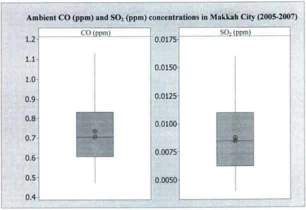

Figure 3.8 Monthly averages of CO and SO_2 concentrations in the ambient air of Makkah City in the vicinity of the Grand Mosque area (from 2005 to 2007).

After illustrating the meteorological data describing the ambient air conditions, it is essential to consider the conditions inside the tunnel for the model. Inside the Souk Sagheer Tunnel, the wind speed generated by forced ventilation varies from 1 m/s to 3 m/s, and the temperature and relative humidity are uniformly distributed at 30 °C and 35%, respectively (Saati and Shahine, 2000). Furthermore, although the scope of this study does not include noise pollution, it is noteworthy to mention that the noise level inside the tunnel is 94 dBA on average (Saati and Shahine, 2000). This noise level is considered to be especially high and is expected to have an impact on human health (WHO, 2009). Moreover, according to NIOSH (1998), exposure to noise at 95 dBA should not exceed 47 minutes.

3.6 Risk to Pedestrians

A health impact study conducted by Ashor (2000) found a significant drop in O_2 level in the blood of pedestrians inside the tunnel compared to those walking outside, which suggest that the pedestrians inside the tunnel have more CO bonded to the hemoglobin in their blood than those outside. The O_2 level in their blood dropped from 96.6% to 85.53%, on average, for a sample of 145 pedestrians (Ashor, 2000).

Chapter 4

SIMULATION MODEL OF AIR QUALITY IN THE SOUK SAGHEER TUNNEL: A CASE STUDY

4.1 Simulation Model

The 1-dimensional model known as IDA RTV has been selected to model the air quality inside the Souk Sagheer Tunnel.

There are two parts to the simulation model: one part is related to the emission factors of vehicles and the other part is related to the aerodynamics of the tunnel. The latter part can further be divided into three major components: (a) the changes in pressure against the walls and vehicles, (b) the piston action of the vehicles, and (c) the buoyancy effect.

The simulation model used below is 1-dimensional (along the x-axis, the length of the tunnel), and assumes that the pollutants are uniformly distributed along the y- and z-axes. The model shown in Equations 7 to 9 is used in both the Subway Environment Simulation (SES) and the IDA Tunnel Simulation Software. Please note that these equations are adopted from (Per Sahlin et al., 2003) and are used in the IDA RTV model.

$$\Delta p_{frict} = -\sum_i \frac{\rho_i}{2}\frac{\lambda_T}{d_i}\,[(l_i - \sum_j l_{V_{ij}})v_i\,|v_i| - \sum_j \frac{l_{V_{ij}}}{\left(1 - A_{V_j}/A_i\right)^3}\left(\frac{A_{V\_j}}{A_i}v_{V_{ij}} - v_i\right)\left|\frac{A_{V\_j}}{A_i}v_{V\_ij} - v_i\right|]$$

Eq. 7

where

Δp_{frict} = pressure change due to friction against walls (Pa)

λ_T = friction factor for the tunnel wall (dimensionless)

ρ_i = mean density of the air in tunnel segment i (kg/m^3)

d_i = hydraulic diameter of tunnel segment i (m)

l_i = length of tunnel segment i (m)

$l_{V_{ij}}$ = length of vehicles of type j in tunnel segment i (m)

v_i = mean air velocity in tunnel segment i, positive from left to right (m/s)

$v_{V_{ij}}$ = velocity of vehicles of type j in tunnel segment i, positive from left to right (m/s)

A_{V_j} = cross-sectional area of vehicles of type j (m^2)

A_i = cross-sectional area of tunnel segment i (m^2)

$$\Delta p_{fricv} = \sum_i \sum_j \frac{\rho_i}{8} \frac{\lambda_{V\_j} . l_{V\_j} . p_{V\_j}}{A_i \left(1 - A_{V\_j}/A_i\right)^3} \left(v_{V\_ij} - v_i\right) \left|v_{V\_ij} - v_i\right|$$

Eq. 8

where $\lambda_{V_j} = \lambda_{VS\_j} + \frac{c_{DTV\_j}}{4 l_{V\_j} p_{V\_j}}$

Δp_{fricv} = pressure change due to friction against vehicles (Pa)

λ_{V_j} = skin friction coefficient for vehicles of type j (dimensionless)

λ_{VS_j} = skin friction coefficient related to viscous drag for vehicles of type j (dimensionless)

C_{DTV_j} = drag coefficient weighted by the total cross-sectional area of vehicle type j (m^2)

l_{V_j} = length of vehicles of type j (m)

p_{V_j} = perimeter of vehicles of type j (m)

$$\Delta p_{piston} = \sum_i \sum_j \frac{\rho_i}{2} A_{V\_j} \left\{ \left[\frac{C_{DFV\_j}}{A_i} + \frac{(2A_i - A_{V\_j})}{(A_i - A_{V\_j})^2} \right] N_{front\_ij} + \left[C_{DBV\_j} \frac{A_i}{(A_i - A_{V\_j})^2} - \frac{2}{A_i - A_{V\_j}} \right] N_{back\_ij} \right\} (v_{V\_ij} - v_i) |v_{V\_ij} - v_i|$$

Eq. 9

where $C_{DBV\_j} = \frac{0.029}{\sqrt{0.5\lambda_{VS\_j} l_{V\_j} p_{V\_j}/(4A_{V\_j})}}$

Δp_{piston}= piston pressure rise (Pa)

C_{DBV_j} = drag coefficient at the back ends of vehicles of type j (m^2)

C_{DFV_j} = drag coefficient at the front ends of vehicles of type j (m^2)

N_{front_ij} = number of front ends of vehicles of type j in tunnel segment i

N_{back_ij} = number of back ends of vehicles of type j in tunnel segment i

The front end is defined as the end that has a headwind and could be either the physical front or back of the vehicle.

4.2 Model Assumptions

The model consists of a number of components, which include:

- Vehicle piston action.
- Vehicle emissions.

- Tunnel geometry, i.e., the space in which the aerodynamics and flow occur. This includes main stream of the tunnel as well as the waiting zones.
- Ventilation, both longitudinal and transverse. Ventilation is important because it is the main driving force for turbulence inside the tunnel.
- Air intake and air exhaust, which includes the tunnel portals which function as both intake and exhaust vents and the ventilation ducts of the transverse ventilation system.
- Traffic conditions: peak and non-peak.
- Pedestrians, which are considered to be part of the system but are assumed to have a negligible effect on the air quality inside the tunnel.

There are a number of model assumptions made to perform the simulation. Some of the assumptions are related to the 1-dimensional model itself and have been discussed in the previous section. Other assumptions are made from actual and estimated parameters. These parameters include the structure and dimensions, ventilation, vehicular distribution and models, and emission factors. However, over short term exposure, this model assumes that there is no chemical reactions or decay taking place inside the tunnel. Moreover, it assumed ambient weather conditions at the boundaries.

4.2.1 Structure and Dimension

The tunnel structure is divided into sub-structures that are connected to form one tunnel. The sub-structures are assumed to accommodate the differences along the tunnel in terms of gradients, branches, and ventilation. In the first scenario, which represents the current structure of the tunnel, there are nine major sub-sections (see Figure (4.1) below).

Sections 1 to 5 include the main driving streams for both driving directions. Sections 6 to 9 are the waiting zones for drop off and pick up only.

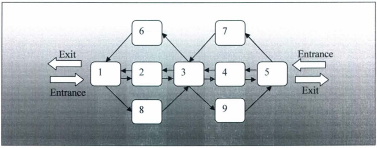

Figure 4.1 Schematic diagram of structure division in current state modeling

One of solutions proposed to mitigate the air pollution in the tunnel involves modifying its structure. This modification leads to uni-directional driving or divided tunnel tubes. With the resulting modification, each tunnel direction will have half of the total cross-section of the current state. Moreover, each section will have two waiting zones instead of four. Figure 4.2 represents one side of the tunnel; the other side is shadowed in Figure 4.2. An isolated side is shown in Figure 4.3, in which half of tunnel structure is considered: half of main tunnel stream, and two waiting zones.

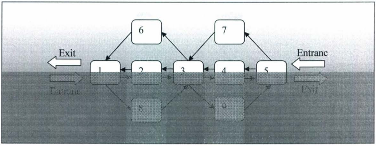

Figure 4.2 Shadow covering half of the structure of the tunnel

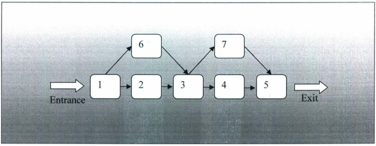

Figure 4.3 Remodeled tunnel with half the structure and one-way driving

4.2.2 Ventilation

The IDA RTV model assumes that only longitudinal ventilation, which is the primary ventilation route in the tunnel, is used. On the other hand, the transverse system will not be absent from the modeling scenarios and will be estimated as part of the solution model.

In addition, the distribution of the longitudinal jet fans is illustrated in Figure 4.4. According to the specifications from the Fläkt Woods Catalog (see Section 3.3), the following input values are assumed:

Cross-sectional area of the fan = 0.785 m^2, pressure rise coefficient = 0.6 (because the fans are located at the sides not the center of the tunnel), jet velocity in still air = 32.6 m/s, and total performance = 30 N/KW.

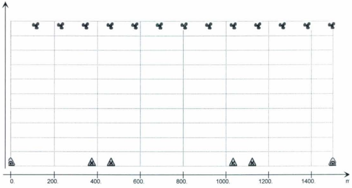

Figure 4.4 Jet fans locations—each fan in the graph represents two jet fans

Other assumptions for solution purposes are made for the ventilation. In three of the solution models the ventilation parameters are varied. These changes include increasing the performance of the current jet fans, introducing additional jet fans, or using transverse duct ventilation.

4.2.3 Vehicle Distribution

The traffic patterns in the tunnel are different for different seasons of the year. For example, during the peak season of Hajj only passenger buses are allowed to go through the tunnel, and this restriction continues for a number of consecutive days (5 to 7 days during the pilgrimage). Additionally, traffic is restricted to buses sometimes during traffic peaks at any time of the year, day or night. Another example is that traffic control uses gates on some busy evenings in Ramadan to control entrance to the tunnel, and, if necessary, traffic is limited only to buses.

Another factor to be considered is the traffic model. There are two different models used to build peak and non-peak situations. In peak operation, it is assumed that the tunnel is congested with the cars, which brings the average speed in the tunnel down to 20 km/h. The density of vehicles during peak operation in the congested model assumes an average of 94 vehicles per lane per kilometer, whereas, in the non-peak traffic model, the average density of vehicles is 12 vehicles per lane per kilometer, and the average speed is 50 km/h. These numbers are estimated based on Level of Service at peak and non-peak conditions (Transportation Research Board, 1994). In addition, it is assumed that the passenger vehicles are 4.5 m long with a frontal area of 2.4 m^2 and a drag factor of 0.4. Passenger buses are assumed to be 12 m long with a frontal area of 6 m^2 and a drag factor of 0.7. Note that vehicles' speed is an initial speed before mixing with traffic which is then reduced at congestion or maintained the same if the tunnel is moving freely.

4.2.4 Emissions Factor

Air emission factors are assumed based on the USEPA (1985) AP-42 report related to the distribution of light, medium, and heavy duty vehicles operated by diesel and gasoline and is also based on their distribution of models. Based on traffic data collected by the municipalities in the major cities in Saudi Arabia and also during Hajj season in Makkah City, it is observed that there are approximately 60% of the traffic is due to passengers vehicles and 40% is due to medium- and heavy-duty diesel trucks and buses. This distribution is assumed in the modeling of the regular state of the tunnel in which vehicle mixing is assumed. The bus only mode is also considered, where 100% of the traffic in the tunnel is due to buses. The weighted emission factors were calculated for (CO, NO_2, and $PM_{2.5}$) using the Ap-42 values published in Appendix H of Volume 2 (USEPA, 1985) for various models of the cars, as shown in Tables 4.1 and 4.2.

Table 4.1 Calculation of (CO) emission factors (Source: USEPA, 1985)

Year	Passengers vehicles (light duty gasoline)			Diesel buses		
	Percentage	Emission factor (AP-42) g/mile	Value	Percentage	Emission factor (AP-42) g/mile	Value
1990	0.05	38.67	1.93	0.05	44.41	2.2205
1995	0.20	29.71	5.94	0.20	33.39	6.678
2000	0.35	27.08	9.48	0.35	29.05	10.1675
2005	0.40	26.55	10.62	0.40	27.17	10.868
Average		27.97 g/mile			29.934 g/mile	

Table 4.2 Calculation of (NO_x) emission factors (Source: USEPA, 1985)

Year	Passengers vehicles (light duty gasoline)			Diesel buses		
	Percentage	Emission factor (AP-42) g/mile	Value	Percentage	Emission factor (AP-42) g/mile	Value
1990	0.05	2.05	0.10	0.05	3.29	0.1645
1995	0.20	1.95	0.39	0.20	2.87	0.574
2000	0.35	1.71	0.60	0.35	2.5	0.875
2005	0.40	1.59	0.64	0.40	2.25	0.9
Average		1.73 g/mile			2.5135 g/mile	

On the other hand, the SO_2 emission factor was estimated from the sulfur content in the gasoline and diesel fuel in Saudi Arabia. Sulfur oxides emissions depend entirely on the sulfur content of the fuel (EPA, 1985), and 95% of the sulfur in the fuel is assumed to be converted into SO_2.

The sulfur content of fuel in Saudi Arabia is high compared to European and North American standards. According to Hart Energy Consulting (2008), while the acceptable limit of sulfur content in gasoline fuel ranges between 30 and 50 ppm in North America and Western Europe, the acceptable range is between 1000 and 2500 ppm in the Middle East (Hart Energy Consulting, 2008).The sulfur content of the gasoline in Saudi Arabia is estimated to be 600 ppm. However, for the sulfur content for diesel fuel is estimated to be 0.9% of the weight.

For gasoline containing 600 ppm of sulfur, 0.6 g of sulfur is in each liter of gasoline. Then, assuming that the average fuel consumption is 5 miles per liter, 0.2 liters are consumed in each mile. Therefore, multiplying 0.6 $\frac{g}{l}$ sulfur by 0.2 $\frac{l}{mile}$ results in SO_x emissions totaling 0.12 g/mile for gasoline vehicles.

The emission factor of SO_x for diesel buses is calculated in a similar way. Assuming a 0.9% sulfur content by weight, 9 g of sulfur are contained in each liter of diesel. Assuming an average consumption of 0.2 liters of diesel per mile, 3.6 g of SO_x are emitted per mile.

Please refer to Table 4.3 for a summary of emission factors for each vehicle category. Finally, for Fine particulate estimation, a report by (Norbeck et al., 1998) have calculated PM emissions from a road tunnel, and then characterized them based on vehicle distribution and counting. Therefore, the emission factors calculated based on PM emissions and vehicle distribution (Norbeck et al., 1998).

Table 4.3 Emission factors for each vehicle category

Emission factor	Light gasoline vehicles (g/v/mile)	Diesel vehicles (g/v/mile)
CO	27.97	29.934
NO_x	1.73	2.5135
SO_x	0.12	3.6
Fine particulate	0.03	0.6

The emission rates are calculated in the model in terms of g/h for different vehicle speeds. Using the emission factors listed in the table above, the emission rates of various pollutants were calculated and are listed in Table 4.4. The NO_2 fraction of NO_x is estimated to be 0.2 (Yao et al., 2005), and the SO_2 fraction of SO_x is estimated to be 0.95 (USEPA, 1985).

Table 4.4 Emission rates of vehicles entering the Souk Sagheer Tunnel

Speed (km/h)	CO (g/h)		NO_x (g/h)		SO_x (g/h)		$PM_{2.5}$ (g/h)	
	Gasoline	Diesel	Gasoline	Diesel	Gasoline	Diesel	Gasoline	Diesel
0	17.38	18.60	1.07	1.56	0.07	11.18	0.02	0.37
5	86.90	93.00	5.37	7.81	0.37	55.92	0.09	1.86
10	173.80	186.00	10.75	15.62	0.75	111.85	0.19	3.73
15	260.70	279.00	16.12	23.43	1.12	167.77	0.28	5.59
20	347.60	372.00	21.50	31.24	1.49	223.69	0.37	7.46
30	521.39	558.00	32.25	46.85	2.24	335.54	0.56	11.18
40	695.19	744.01	43.00	62.47	2.98	447.39	0.75	14.91
50	868.99	930.01	53.75	78.09	3.73	559.23	0.93	18.64
60	1042.79	1116.01	64.50	93.71	4.47	671.08	1.12	22.37
70	1216.58	1302.01	75.25	109.33	5.22	782.93	1.30	26.10
80	1390.38	1488.01	86.00	124.95	5.97	894.77	1.49	29.83

4.3 Model Verification

Although the one-dimensional air quality tunnel simulation model used in this research has been widely applied and validated (Per Sahlin et al., 2003), a number of assumptions are made in the model, so verification or an evaluation of the model with actual values is important.

In the model calculations, there are a number of modeling scenarios that have been proposed. These scenarios are determined based on traffic conditions, and status of the tunnel that is been modeled. Further explanation of scenarios is given in section 4.4.

Data collected by the Hajj Research Institute during peak traffic periods (Table 4.2) was compared with the simulated values for the peak periods. Calculated values are used from scenario one where CO concentrations are calculated for the current tunnel configuration under both mixed and peak traffic assumptions. There are 161 calculated data points calculated versus 56 actual data points, which were collected over two days of peak traffic. Because the data collected by the Hajj Research Institute does not show the exact location or number of vehicles, the simulated data is congregated and rearranged in ascending order for comparison with the calculated data points. Some zero points appear in the actual data, which may not reflect actual concentrations. These zero points could be values below the detection limit of the device used in measuring the CO concentrations, or they could be related to human error.

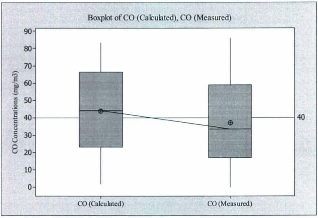

Figure 4.5 Comparison of CO concentrations during peak traffic between actual and calculated values

Figure 4.5 shows two boxplots of CO concentrations, which plot both the calculated and measured data points. The data of Figure 4.5 can be found in Tables 4.5 and 4.6. In the boxplots, the difference in the mean and median seems to be negligibly small. However, both values vary around the PME limit of 40 mg/m^3

Because the two data sets have different sizes, they cannot be paired. Moreover, both data sets are neither normally nor log-normally distributed. Therefore, a non-parametric test called the Mann-Whitney Test (also known as the Wilcoxon Rank-Sum Test), is used to determine if the two data sets are statistically equivalent. A significance level of $\alpha = 0.05$ is selected (α represents the probability of making a type I error, which means that the null hypothesis is rejected when it is actually true). The Mann-Whitney Test is performed on medians.

The following hypotheses were tested:

H_0: $\mu_c = \mu_m$ (medians are statistically equal at the significance level)

H_1: $\mu_c \neq \mu_m$ (medians are not statistically equal at the significance level)

where

μ_c = median of the calculated CO concentrations as calculated from the model results

μ_m = median of the measured CO concentrations

```
Mann-Whitney Test and CI: CO (Calc), CO (Measured)


N  Median
CO (Calc)      161   43.93
CO (Measured)  56   33.50


Point estimate for ETA1-ETA2 is 7.26
95.0 Percent CI for ETA1-ETA2 is (-0.58,15.44)
W = 18281.0
Test of ETA1 = ETA2 vs. ETA1 not = ETA2 is significant at 0.0707
The test is significant at 0.0707 (adjusted for ties)
```

Figure 4.6 Minitab output of the hypothesis test

The p-value, which represents the probability that $\mu_c = \mu_m$ and is used to test against significance level, is larger than α. Therefore, the *null-hypothesis* cannot be rejected at a 0.05 significance level. Thus, no significant difference exists between the calculated and measured values, so the model is considered valid at the chosen significance level.

Although the p-value from the test (0.0707) is not particularly high, a 5% significance is considered sufficient for the study. The measured values typically lower than the calculated values, which mean that the model gives a slightly conservative estimation compared to the actual results.

Table 4.5 Actual CO concentration measured from the Souk Sagheer Tunnel (by Hajj Research Institute)

Date	Time	AM/PM	CO mg/m^3	Date	Time	AM/PM	CO mg/m^3
9/23/2008	5:45:32	pm	67	9/26/2008	5:44:19	pm	24
9/23/2008	6:00:32	pm	60	9/26/2008	5:59:19	pm	20
9/23/2008	6:15:32	pm	2	9/26/2008	6:14:19	pm	0
9/23/2008	6:30:32	pm	13	9/26/2008	6:29:19	pm	6
9/23/2008	6:45:32	pm	37	9/26/2008	6:44:19	pm	21
9/23/2008	7:00:32	pm	46	9/26/2008	6:59:19	pm	25
9/23/2008	7:15:32	pm	65	9/26/2008	7:14:19	pm	46
9/23/2008	7:30:32	pm	65	9/26/2008	7:29:19	pm	80
9/23/2008	7:45:32	pm	17	9/26/2008	7:44:19	pm	82
9/23/2008	8:00:32	pm	0	9/26/2008	7:59:19	pm	80

9/23/2008	8:15:32	pm	0	9/26/2008	8:14:19	pm	79
9/23/2008	8:30:32	pm	0	9/26/2008	8:29:19	pm	36
9/23/2008	8:45:32	pm	1	9/26/2008	8:44:19	pm	28
9/23/2008	9:00:32	pm	21	9/26/2008	8:59:19	pm	1
9/23/2008	9:15:32	pm	18	9/26/2008	9:14:19	pm	59
9/23/2008	9:30:32	pm	23	9/26/2008	9:29:19	pm	31
9/23/2008	9:45:32	pm	21	9/26/2008	9:44:19	pm	21
9/23/2008	10:00:32	pm	9	9/26/2008	9:59:19	pm	37
9/23/2008	10:15:32	pm	15	9/26/2008	10:14:19	pm	72
9/23/2008	10:30:32	pm	42	9/26/2008	10:29:19	pm	59
9/23/2008	10:45:32	pm	54	9/26/2008	10:44:19	pm	57
9/23/2008	11:00:32	pm	23	9/26/2008	10:59:19	pm	59
9/23/2008	11:15:32	pm	14	9/26/2008	11:14:19	pm	4
9/23/2008	11:30:32	pm	56	9/26/2008	11:29:19	pm	17
9/23/2008	11:45:32	pm	37	9/26/2008	11:44:19	pm	72
9/24/2008	12:00:32	am	38	9/26/2008	11:59:19	pm	75

9/24/2008	12:15:32	am	52	9/27/2008	12:14:19	am	86
				9/27/2008	12:29:19	am	78
				9/27/2008	12:44:19	am	17

Table 4.6 Calculated CO concentrations in peak traffic

Calculated CO concentrations (mg/m^3)						
1.9	14.71	26.37	38.05	50.3	65.34	72.85
2.52	15.25	26.89	38.58	50.83	66.76	73.36
3.13	15.8	27.41	39.12	51.36	68.19	73.88
3.73	16.35	27.68	39.65	51.89	69.63	74.39
4.3	16.89	27.8	40.19	52.41	71.08	74.9
4.86	17.44	28.09	40.73	52.94	66.75	75.41
5.42	17.98	28.66	41.26	53.47	63.97	75.93
5.97	18.52	29.23	41.8	54	64.46	76.44
6.52	19.06	29.8	42.33	54.52	64.93	76.95
7.07	19.6	30.37	42.87	55.05	65.49	77.46
7.62	20.14	30.93	43.4	55.57	66.03	78

8.16	20.68	31.5	43.93	56.1	66.56	78.54
8.71	21.21	32.06	44.46	56.62	67.09	79.07
9.26	21.74	32.62	45	57.15	67.62	79.6
9.81	22.25	33.18	45.53	57.67	68.15	80.13
10.35	22.71	33.74	46.06	58.19	68.67	80.67
10.9	22.85	34.29	46.59	58.72	69.2	81.2
11.44	23.16	34.83	47.13	59.23	69.72	81.73
11.98	23.72	35.36	47.66	59.33	70.24	82.26
12.52	24.26	35.9	48.19	59.79	70.76	82.7
13.06	24.79	36.44	48.72	61.15	71.28	83.08
13.61	25.32	36.98	49.25	62.53	71.81	83.43
14.16	25.85	37.51	49.77	63.93	72.33	82.55

4.4 Model Scenarios

Several scenarios for air quality modeling were considered in this study. Each scenario considers the current state of air quality inside the tunnel during peak and non-peak traffic hours. Each scenario also considers both the regular mixed traffic and bus only modes for certain days in the peak seasons. These scenarios are then extended to include a number of proposed solutions for air quality issues inside the tunnel by considering a wide range of management techniques to reduce pollutants.

In the first solution scenario, the tunnel is assumed to be separated into two different tubes. This scenario has been suggested in the literature from a safety perspective considering smoke propagation in the event of a fire. Fire and smoke should spread and disperse in the downwind direction only to allow passengers to escape in the opposite direction. However, having two separate tubes in the tunnel will also impact the air quality inside the tunnel as presented in a later section.

Another solution scenario assumes improvements to the longitudinal ventilation capacity of the tunnel. This particular solution has been suggested in the research reports published by the Hajj Institute (Yaqoub et al., 2003). The last solution scenario utilizes a transverse duct system. Transverse ventilation is capable of controlling the air quality. However, transverse ventilation systems are costly to operate in terms of energy. Even though a transverse system is not feasible for the given capacity, one is presented so that it can be compared with other solutions, and it remains a choice for decision makers.

Finally, a set of air quality episodes are modeled in the case of ventilation failures during both peak and non-peak traffic periods. These scenarios also include ventilation failure episodes in which the tunnel is divided into two unidirectional tubes, as proposed in the first solution scenario.

4.4.1 Scenario 1: Mixed traffic – peak conditions

This is the basic scenario, which represents the most common traffic mode during peak seasons of Ramadan and Hajj. In this model, traffic is assumed to be congested, so the average speed of the vehicles decreases to 20 km/h. Moreover, the traffic is assumed to be a mixture of light gasoline passenger vehicles and diesel trucks with a ratio of 3:2. The ratio is estimated based on typical vehicle distributions on urban roads in Saudi Arabia.

The results of the model are calculated for hourly averages. It is noteworthy to mention that during the peak seasons of Hajj and Ramadan, the traffic is congested for extended periods during, which could last more than 12 hours.

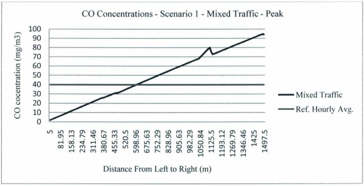

Figure 4.7 Mean CO concentrations calculated in the Scenario 1 simulation, mixed traffic- peak conditions

Figure 4.7 shows that more than half of the calculated CO concentrations are above the hourly average limit set by PME (40 mg/m^3). At a distance of one third of the tunnel length, the hourly average exceeds the regulatory limits. Moreover, at two-thirds of the distance from left entrance, the hourly average is double the regulatory limits.

It is important to mention that the main reason for the CO increase from left to right is that the longitudinal ventilation pushes the air to the right, and with air speed increase, the relationship between concentrations and distance approximate to linear.

The NO_2 concentrations simulated in the model exceed the regulatory limits inside the tunnel. In the first 500 m of the tunnel, the NO_X level is within the PME hourly limits of 660 $\mu g/m^3$. However, further down the tunnel, the level exceeds the PME limits, as shown in Figure 4.8.

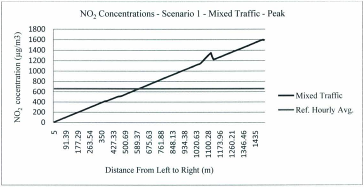

Figure 4.8 NO_2 concentrations calculated in the Scenario 1 simulation, mixed traffic-peak conditions

Therefore, the current status of the tunnel during the peak seasons clearly violates the regulatory standards of the PME.

The following two figures (4.9 and 4.10) represent the air speed and volume of air flow, respectively. These figures will be represented again in the solution scenarios. Only small differences exist between the different modes operation before any structural changes to the tunnel tor changes to the ventilation system are made.

Both the air speed and air flow drop significantly at x = 1050 m from the entrance. This drop is mainly due to openings of two waiting zones that divert a substantial amount of air. This opening occurs near the end of the tunnel where there is a sudden change in the cross-sectional area of the tunnel. On the other hand, the first two waiting zones are near the left entrance, so the air supply compensates the volume increase, which is why the effect of earlier waiting zones is barely noticed in the graphs.

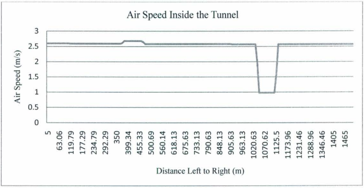

Figure 4.9 Air speed inside the tunnel

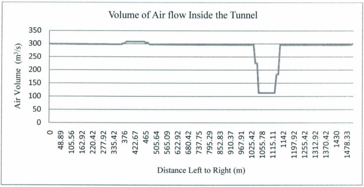

Figure 4.10 Volume of air flow inside the tunnel

4.4.2 Scenario 2: Buses only – peak conditions

During the peak Hajj season, only buses are allowed to enter the tunnel. The model here assumes that only buses are allowed, which take form of medium-duty trucks. Buses are mainly diesel-operated vehicles, and their emission factors are based on the emission factors for medium-duty diesel-operated vehicles in Saudi Arabia. Figure 4.11 compares the CO concentrations calculated for Scenarios 1 and 2. Figure 4.11 shows allowing only buses into the tunnel results in lower CO concentrations. This could be due to the fact that the drag factor of buses is greater than that for passenger vehicles, which results in a stronger piston action. Moreover, the lower CO concentration could also result from the fact that the density of buses is smaller than that of cars. However, the CO concentrations simulated for these conditions also exceed the regulatory limit about halfway through the tunnel, as shown in Figure 4.11.

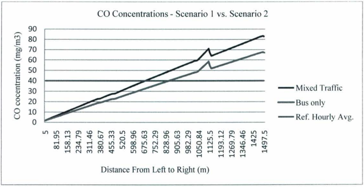

Figure 4.11 Comparison between CO concentrations in Scenarios 1 and 2.

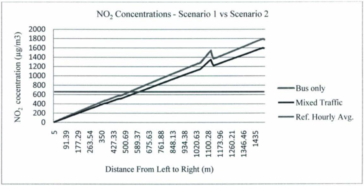

Figure 4.12 Comparison between the NO_2 concentrations calculated for Scenarios 1 and 2

On the other hand, the NO_2 concentration in the bus only scenario is higher than that calculated when gasoline-powered vehicles are included. Figure 4.12 shows that the NO_2

concentrations are slightly higher because buses emit more NO_x than light gasoline vehicles.

4.4.3 Scenario 3: Mixed traffic – non-peak conditions

This scenario is similar to Scenario 1, which represents the current state of the tunnel but differs in the amount of traffic considered. The off-peak season describes times when traffic intensity is about 500 vehicles per lane per hour in both directions or less, which is the situation for most of the year. This number is an estimation given for stable driving conditions according to Level of Service C (Transportation Research Board, 1994). Figure 4.13 shows that the off-peak hourly average CO concentrations are below the 40 mg/m^3 limits defined by the PME. This suggests that the tunnel does not appear to have a ventilation problem during normal/non-peak conditions. Likewise, the hourly average NO_2 concentrations do not exceed the level recommended by the PME, as shown in Figure 4.14.

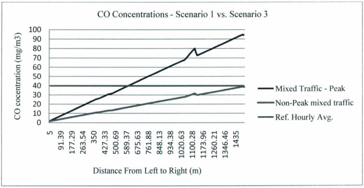

Figure 4.13 CO Concentrations comparison between the peak and non-peak traffic conditions

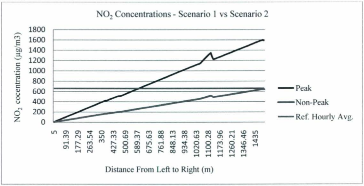

Figure 4.14 NO_2 Concentrations comparison between the peak and non-peak traffic conditions

4.4.4 Scenario 4: Wall barrier as a solution

Scenario 4 is the first solution scenario considered here. In this scenario, the tunnel is separated into two separate tubes. This actually has been suggested not only to remediate air pollution, but it is also recommended from a fire safety point of view. The separation reduces the risk of fire and facilitates fire control. When a fire occurs inside the tunnel it will disperse downwind to the exit and not in both directions.

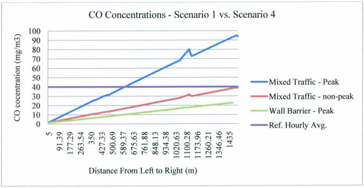

Figure 4.15 Comparison of CO concentrations between the current state and separate tubes

The result in Figure 4.15 shows a significant drop in CO concentrations inside one tube. With the wall separation, the level of CO even during peak traffic periods will be lower than that in the non-peak traffic conditions of the regular bidirectional tunnel, apparently because the air speed inside the tunnel is significantly increased due to the smaller cross-section. Moreover, the piston action of the vehicles is increased because the traffic is parallel to wind direction generated by the longitudinal ventilation. When the tunnel is separated, the longitudinal ventilation should be redirected with the traffic direction because the direction is fully reversible, as mentioned in section 3.3 of this study.

4.4.5 Scenario 5: Longitudinal ventilation as a solution

Another scenario considered in this study uses only longitudinal ventilation to bring air pollution levels down to acceptable standards. This has been suggested in some papers published by the Hajj Research Institute, which suggest that a feasible solution to the air pollution problem could be to add a third row of jet fans to increase the ventilation capacity. In this scenario (Scenario 5), three levels of intervention will be tested to investigate the improvement of the air quality improvement. In Level 1, only the speed of the air leaving the jet fans is increased. The current jet fans eject air at 32.6 m/s. The proposed increase is to improve the speed by 25% to 40.75 m/s. In Level 2, a complete additional row of jet fans is added. The tunnel currently has 26 jet fans, and in this scenario, 13 fans will be added to the simulation for a total of 39 fans. In Level 3, the number of jet fans is doubled compared to the number of fans currently in the tunnel. Currently, 26 fans are in the tunnel, which is increased to 52 jet fans in this scenario by adding two additional rows of fans.

The simulation results in Figures 4.16 and 4.17 show that adding an additional row of jet fans, or even two additional rows, effectively doubling the amount of longitudinal ventilation, does not solve the air pollution problem inside the tunnel. It does, however, shift the point where reference level is exceeded by 500 m further downwind. As shown in Figures 4.18 and 4.19, the air speed and flow improve with the increased levels of ventilation.

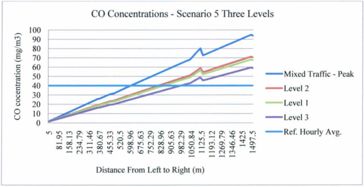

Figure 4.16 Solutions for the CO concentrations in the longitudinal ventilation

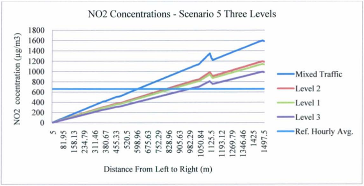

Figure 4.17 Solutions for the NO_2 concentrations in the longitudinal ventilation

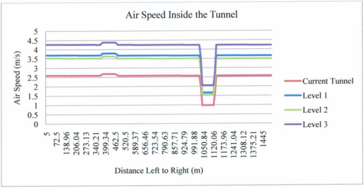

Figure 4.18 Air speed at different longitudinal ventilation levels

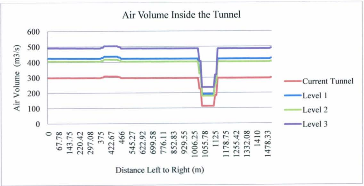

Figure 4.19 Air flow at different longitudinal ventilation levels

4.4.6 Scenario 6: Transverse ventilation as a solution

Using the transverse ducts that already exist in the tunnel is another possible solution for pollution problem. This is not an attempt to alter the current design; rather, this scenario shows how a certain system could improve the air quality in the tunnel. The following transverse system is hypothetical and is designed to reduce air pollution during peak traffic. Four air supply ducts each with 75 m long windows that supply 100 m^3/s of fresh air are proposed to be added to the tunnel. In addition, there are two exhaust ducts measuring 75 m that withdraw 100 m^3/s of polluted air and send it outside the tunnel. The results in Figure 4.20 show that the transverse ventilation system nearly brings the pollution levels within acceptable. The effect could be improved by the optimizing design of the transversal ducts or including additional air exchange ducts either on the supply or exhaust side. It is important to highlight that the transverse duct system is recommended for bidirectional tunnels in which longitudinal ventilation is not effective, despite the fact that transverse duct systems cost more than longitudinal ventilation systems.

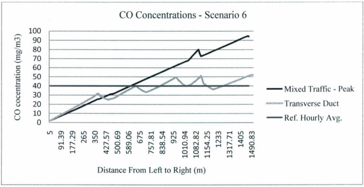

Figure 4.20 CO Concentrations when using transversal ventilation as a solution

4.4.7 Scenario 7: The case of ventilation failure

Ventilation failure could occur for many different reasons. It could result from a total failure of the full system or just part of the system. Loss of power is one common example of ventilation failure. Another point to consider is the failure of ventilation units due to high temperatures in the event of a fire. Regardless of the cause, any ventilation failure could result in extremely high concentrations of air pollutants in the tunnel that would pose a high risk to commuters and pedestrians. For this situation, a number of scenarios are modeled in to predict the possible levels of CO and NO_2 that could accumulate in the tunnel. These scenarios consider both the peak and non-peak traffic for the existing structure and peak and non-peak traffic scenarios in the case that a wall barrier is used to separate both tubes.

4.4.7.1 Ventilation failure at peak and mixed traffic conditions

In this scenario, a hypothetical case of ventilation failure at peak traffic for the current structure of the tunnel is considered. Figures 4.21 and 4.22 show particularly high concentrations of CO and NO_2 that exceed the limits by more than ten-fold. With such high concentrations of pollutants, the tunnel may have to be closed to traffic when the ventilation fails during peak traffic.

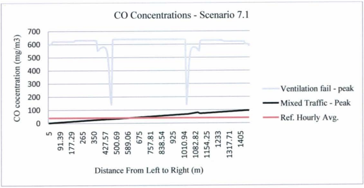

Figure 4.21 CO Concentrations when ventilation fails during peak traffic conditions

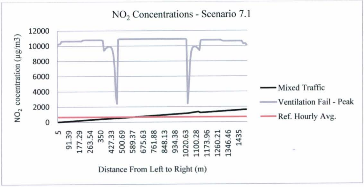

Figure 4.22 NO_2 Concentrations when the ventilation fails during peak traffic conditions

4.4.7.2 Ventilation failure at non-peak and mixed traffic conditions

When ventilation fails during the non-peak traffic period, the CO concentrations also become extremely high (as shown in Figure 4.23). However, the values of CO concentrations are about 50% less than those calculated for the peak traffic scenario. Such high levels of CO pose a significant risk to humans. Therefore, the tunnel must be closed in event of ventilation failure even during non-peak conditions.

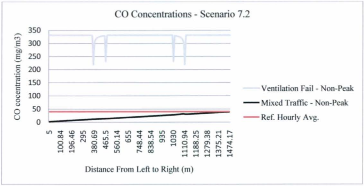

Figure 4.23 CO Concentrations when ventilation fails at during a non-peak traffic mode

4.4.7.3 Ventilation failure when a wall barrier is used during peak conditions

Building a separation wall between two traffic directions was suggested earlier as one solution to the air pollution problem. Figure 4.24 shows that such a wall is not only useful for reducing air pollution, but it also seems to be helpful in the case of ventilation failure. Figure 4.24 shows that although the CO concentrations exceeded the regulatory limit, they are still six times lower than those experienced in the regular condition when ventilation fails. The concentrations are even slightly higher than those in the current regular state during peak conditions.

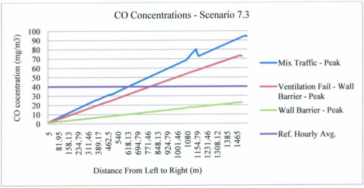

Figure 4.24 CO concentrations when ventilation fails with a wall barrier during peak traffic conditions

4.4.7.4 Ventilation failure when a wall barrier is used during non-peak conditions

In this scenario, when a wall barrier is used and ventilation fails during non-peak hours, the CO level will be within the permissible limit as specified by the PME.

4.4.8 Scenario 8: SO_2 and fine particulates

In this scenario, two other pollutants are modeled in the tunnel to have a broader view of the air quality inside the tunnel. Sulfur dioxide and fine particulates ($PM_{2.5}$) are modeled.

Sulfur dioxide (SO_2) shows incredibly high concentration levels (Figure 4.25). It exceeds the regulatory limits in both the peak and non-peak conditions. Even at the beginning of the tunnel at off-peak condition, the SO_2 concentration reaches 2 mg/m^3, where the limit is 730 μg/m^3 (hourly average, PME standards). The particularly high SO_2 levels in the tunnel could be the result of the high sulfur content in the fuel.

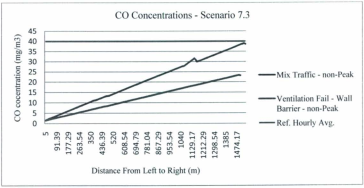

Figure 4.25 CO concentrations when ventilation fails with a wall barrier during non-peak conditions

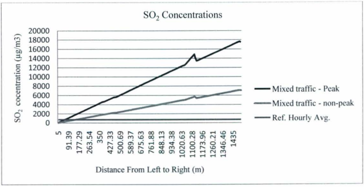

Figure 4.26 SO_2 concentrations during peak and non-peak traffic conditions

The concentration of fine particulate matter also exceeds regulatory limit during peak traffic. However, in the non-peak scenario, the PM_{10} levels were found to be below the PME limit of 340 μg/m³ (Figure 4.27).

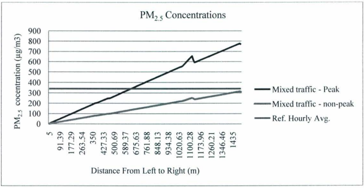

Figure 4.27 Fine particulates in the tunnel during peak and non-peak traffic conditions

4.5 Results and Analysis

4.5.1 Current status of the tunnel

In the previous section, a number of scenarios were modeled to assess current state of the Souk Sagheer Tunnel and to examine possible solutions. A number of factors affect the air quality inside the tunnel. One such factor is the traffic condition. The air quality is significantly affected by whether the traffic is at peak or non-peak conditions. The hourly average longitudinal concentration in the tunnel exceeds the regulatory limits during peak traffic conditions. On the other hand, the hourly average concentrations of CO and NO_2, as shown in Figures 4.28 and 4.29, drops significantly when the traffic switches from peak to normal/non-peak conditions. This may suggest that the current ventilation system is capable of handling off-peak conditions only. However, during the peak seasons, peak conditions could occur for extended time periods. Therefore, the tunnel ventilation requires improvements to reduce health risks and improve the air quality in the tunnel during peak traffic conditions.

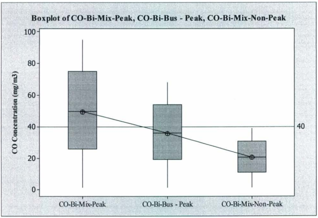

Figure 4.28 Boxplots of CO concentrations during peak and non-peak traffic conditions

4.5.2 Solution scenarios

Three main solutions were proposed to mitigate the current air pollution problems inside the Souk Sagheer Tunnel. The first option is to maintain the current ventilation system and partition the tunnel into two tubes by constructing a wall barrier. The second option is to improve longitudinal ventilation with different levels by adding more fans. These levels were discussed in sections 4.4.4 and 4.4.5. The third option is to utilize a transverse ventilation system in the tunnel.

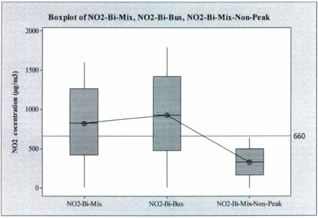

Figure 4.29 Boxplots of NO_2 concentrations during peak and non-peak traffic conditions

Comparing the average CO and NO_2 concentrations for different solution scenarios shows that separating the tunnel into two tubes and improving the transverse ventilation could reduce the high concentrations of air pollutants inside the tunnel to acceptable levels. However, longitudinal ventilation with three different levels does not necessary show significant improvement to reduce pollutants. Moreover, it seems that building a wall barrier is more beneficial than improving the transverse ventilation because it not only significantly reduces the concentrations of pollutants, but also enhances the safety of the tunnel in the event of a fire.

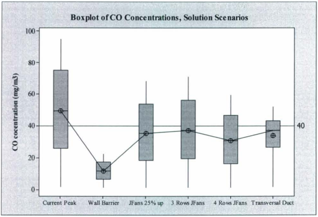

Figure 4.30 Average CO concentrations for different solution scenarios

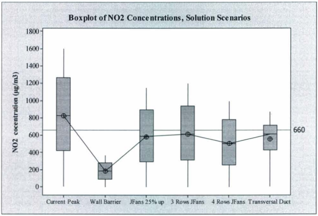

Figure 4.31 Average NO_2 concentrations for different solution scenarios

The final decision on whether to use a wall barrier or a transverse system should be based on the technical and financial feasibility of the project.

The improvement in air quality associated with different solutions can be related to the air speed factor in the tunnel. The air speed inside the tunnel improves when the longitudinal ventilation is improved and when the wall barrier is built. However, the transverse ventilation system works differently, so the air speed factor is not necessarily improved when the transverse ventilation is improved.

Figure 4.32 shows a comparative evaluation between air speeds for different solution scenarios. The highest recorded air speed occurs when the tunnel is separated into two tubes. The two-tube tunnel has an average air speed that is double the air speed for the current state of the tunnel. There are also differences in the air speed when longitudinal ventilation is used. The difference between using three rows of jet fans and two rows of jet fans with increased speed is especially small.

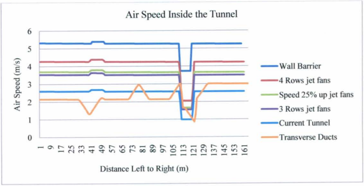

Figure 4.32 Air speed inside the tunnel with different solutions

4.5.3 In the case of ventilation failure

When the ventilation system completely fails, carbon monoxide concentrations reach exceedingly high levels in both the peak and non-peak traffic conditions. However, when the tunnel is separated into two tubes, the CO concentrations remain below 100 mg/m^3, whereas it is higher than 600 mg/m^3 during peak conditions and more than 300 mg/m^3 during non-peak traffic in the tunnel in its current state. That large difference gives the separation solution an advantage that holds even when the ventilation system completely fails. When the tunnel is divided into two tubes, the vehicle piston action is utilized properly. See Figure 4.33. It should be noted that the line in Figure 4.33 is not straight and fluctuates at two points. This fluctuation is due to the opening of the waiting zones, where the volume of air increases at their mouths, which therefore reduces the CO concentrations.

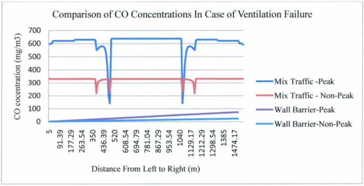

Figure 4.33 CO concentrations in the case of ventilation failure

4.5.4 Impact on waiting zones

Waiting zones are important because all of the activities that were mentioned earlier take place in the waiting zone. These include loading and offloading passengers, sales activities, and the presence of personnel transportation staff and security personnel.

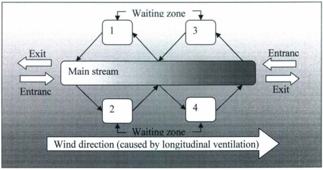

Figure 4.34 Schematic diagram representing waiting zones and wind direction

Waiting Zones are considered in the model as part of the structure of tunnel. However, the model assumes that no vehicles are entering to the waiting zones, and only consider the impact from the main stream air quality on these waiting zones.

The air quality inside waiting zone is largely impacted by the air pollution of the tunnel in main stream (see Figure 4.32). Waiting Zones 1 and 2 as referred from Figure 4.33 are least impacted by the air pollution in the main stream. This is because the main stream at the beginning of the tunnel has lower pollutant concentrations due to the wind direction. As concentration of pollutants increases towards the end of the tunnel, the impact of the main stream on Waiting Zones 3 and 4 increases (see Figure 4.34). In both Figures 4.33

and 4.34, it should be noted that there is a slight difference in the impact on each waiting zone (less than 0.5 mg/m^3 of CO). This difference can be explained by the traffic direction, which exerts a piston action on one side and a dragging effect on the other side.

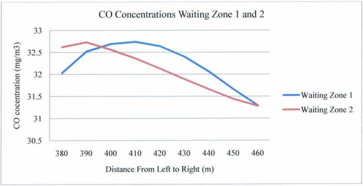

Figure 4.35 Impact of CO concentration in the main stream on Waiting Zones 1 and 2

The impact of the CO concentration in the main stream on Waiting Zones 3 and 4 reaches an average of 67.2 mg/m^3, which is high. This could be a reason to shift to longitudinal ventilation to minimize the impact on the busiest waiting zone, which will certainly be true of the tunnel is divided by a wall.

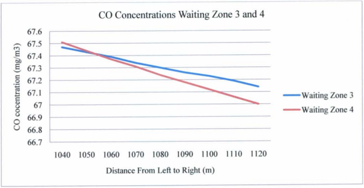

Figure 4.36 Impact of the CO concentration in the main stream on Waiting Zones 3 and 4

Chapter 5

RISK ASSESSMENT

5.1 Risk of transportation emissions in traffic tunnels

Toxic emissions can be inhaled by the pedestrians walking inside the tunnels or by passengers through the intake of vehicle ventilating systems. Each form of emission has a different risk effect. However, this effect can be acute when high concentrations of pollutants accumulate inside the traffic tunnel. This could be the case not only in traffic tunnels, but also closed garages, or multistory parking lots where ventilation is insufficient. Because this study focuses on three main pollutants from car emissions, in this section, we will discuss different risks associated with the emission of carbon monoxide (CO), nitrogen oxides (NO_x), and particulate matter (PM).

5.1.1 Threshold exposure limit

To evaluate the risk associated with emissions in a traffic tunnel, it is logical to see how different agencies have identified the maximum acceptable exposure levels given different exposure durations. For each of the three pollutants, i.e., CO, NO_x, and PM, Table 5.1 shows the threshold limits determined by the Occupational Safety and Health Administration (OSHA), the National Institute for Occupational Safety and Health (NIOSH), and the World Health Organization (WHO).

Table 5.1 Some air pollution standards

Emission	PME Standard (1989)	WHO REL (2005)	EPA Standard (2010)	OSHA PEL (2010)	NIOSH REL (1998)
CO (8 hours)	9 ppm	10 ppm	9 ppm	50 ppm	35 ppm
CO (1 hour)	35 ppm	25 ppm	35 ppm	N/A	N/A
NO_2 (1 hour)	0.35 ppm	200 $\mu g/m^3$ (1 h)	0.053 ppm	5 ppm (C)	1 ppm (STEL)
SO_2	0.28 ppm (1 h)	500 $\mu g/m^3$ (10 minutes)	75 ppb (1 h)	5 ppm (8 h)	100 ppm (immediately dangerous)
$PM_{2.5}$	340 $\mu g/m^3$ (24 h)	25 $\mu g/m^3$ (24 h)	35 $\mu g/m^3$ (24 h)	N/A	N/A

Legend:

- PEL: Permissible exposure limit
- REL: Recommended exposure limit
- C: Ceiling limit (Samples from breathing zones)
- STEL: Short-term exposure limit

From the Table 5.1, we can see that the WHO is the most conservative among the other agencies. The maximum exposure recommended by the WHO for 8 hours exposure of CO is equal to one-fifth of that recommended by OSHA. It seems that the WHO standards can be more adaptable to evaluate the risk of CO in the air of a traffic tunnel. First, because when the WHO estimates the risk limit, it accounts for children and vulnerable people like those with asthma, which make it more adaptable to the traffic tunnel study where different people of different age groups may walk in or be seated in a vehicle. On the other hand, OSHA mainly focuses on occupational risks, where ones would not expect children or even vulnerable people to be in the area. The second reason for preferring the WHO recommended limits of exposure are that they provide the safest and most conservative dose.

5.1.1.1 Carbon Monoxide

According to the WHO, the CO concentration in multistory car parks and road tunnels can rise over 100 ppm for a few hours due to insufficient ventilation. However, this concentration is extremely high. The highest recommended limit is 50 ppm by OSHA. This information should be alarming of how dangerous and risky traffic tunnels can be for pedestrians or even passengers inside vehicles.

In addition, the risk associated with the exposure to CO is high. Carbon monoxide reacts with hemoglobin and decreases the ability of the blood to transport oxygen. A small percentage of carboxyhemoglobin (COHb) can cause short term neurological deficits and/or delayed damage. Moreover, a study by Stern (1988) shows a 35% higher cardiovascular mortality rate to bridge and tunnel officers due to their exposure to carbon monoxide. The result of this study is important because it shows how crucial and sensitive is the air quality situation inside closed areas especially the traffic tunnels.

5.1.1.2 Nitrogen oxides

There are many forms of nitrogen oxides, among which NO and NO_2 are the major components. A great deal of uncertainty exists on the impact of NO_2 on human beings, because most of the studies have been conducted on animals (WHO 2000). The WHO (2000) does not establish a clear recommended exposure limit due to uncertainty. However, it is indicated that 5% of people with asthmatics will respond to a dose between 0.3 to 0.5 ppm for 30 minutes exposure, which is much lower than the OSHA and NIOSH limits of 5 ppm and 1 ppm, respectively. Therefore, it is recommended to monitor and report the levels of NO_x to make sure that the NO_x levels do not exceed the WHO guidelines.

5.1.1.3 Particulate matter

It seems that there is no short term exposure limit for PM as there are for other pollutants in Table 5.1. However, the EPA has developed a standard for ambient air quality in which it divides the PM into inhalable particulate matter (PM_{10}) (which are particles that are less than 10 micrometers in diameter) and fine particulate matter $PM_{2.5}$ (which are less than 2.5 microns in diameter) On a 24-hourly basis averaging period, the PM_{10} and $PM_{2.5}$ concentrations in the air should not exceed 150, and 35 $\mu g/m^3$, respectively (EPA 2006). However, according to the WHO (2000), "(health) effects have been observed at annual average concentration levels below 20 $\mu g/m^3$ (of $PM_{2.5}$) or 30 $\mu g/m^3$ (for PM_{10})." Moreover, the WHO provides tables for estimating the risk associated with long term exposure instead of providing certain guidelines on permissible PM limits (WHO, 2000). Furthermore, a study by Lippman (1996) shows that there is an increase in mortality rate, including several health effects that are associated with a 10 $\mu g/m^3$ increase in PM_{10} and $PM_{2.5}$ concentrations. However, it seems that there is still a need to investigate the short term impact of PM exposure.

5.2 Risk characterization

Pedestrians, passengers, and other personnel inside the tunnel are exposed to pollutants for a short-term period. However, there are some people who might be exposed to the pollutants inside the Souk Sagheer Tunnel more frequently than others.

The exposure time is in this case can happen once in life time. The interest here is in the short term exposure by humans. Based on the model calculation of concentrations at steady state conditions, risk will be characterized when short term exposure limits are found in literature.

Table 5.2 Short term exposure limits given by WHO (1999)

CO	NO_2	SO_2	$PM_{2.5}$
100 mg/m^3 (15 min) 60 mg/m^3 (30 min) 30 mg/m^3 (1 h) 10 mg/m^3 (8 h)	200 $\mu g/m^3$ (1 h)	20 $\mu g/m^3$ (24 h) 500 $\mu g/m^3$ (10 min)	25 $\mu g/m^3$ (24 h)

For CO, the limit specifies that a carboxyhemoglobin level of 2.5% is not exceeded. (WHO, 2004)

To determine the non-carcinogenic risk, the hazard quotient and hazard index are calculated as:

- Hazard Quotient (HQ) = $\frac{Dose}{Reference\ Dose} = \frac{D}{RfD}$
- Hazard Index = $\sum HQ = \sum_i \sum_j (\frac{Dij}{RfDij})$

However, because of the lack of input data and reference doses, the calculation of the hazard quotient and therefore the hazard index is not feasible. Thus, the average concentrations of pollutants will be compared with the short-term exposure limits given by the WHO.

5.2.1 CO concentrations compared to the exposure limit

For short term exposure, the risk will be characterized for three scenarios. Each one differs in exposure duration. First, the risk is characterized for 15 minutes of exposure, the second scenario is for 30 minutes of exposure, and the third scenario is for 1 hour of exposure. Table 5.3 shows ratio of the CO concentrations at different segments in the tunnel and for different exposure durations. The results are also presented in Figures 5.1 and 5.2. The hazard is characterized for peak traffic conditions and shows values for long exposure durations. For example, a 15-minute exposure inside the tunnel results in less than half of the exposure limit, while it exceeded 1.46 times the exposure limit for a 1-hour duration. One the other hand, Waiting Zones 3 and 4 resulted in even higher ratios. This is because of the higher concentrations of CO in these zones.

Table 5.3 Ratios of average CO concentrations/exposure limits

Segment	Tunnel	Waiting Zone 1	Waiting Zone 2	Waiting Zone 3	Waiting Zone 4
(15 min exposure)	0.438418	0.298867	0.297556	0.623311	0.622756
(30 min exposure)	0.730697	0.498111	0.495926	1.038852	1.037926
(1h exposure)	1.461393	0.996222	0.991852	2.077704	2.075852

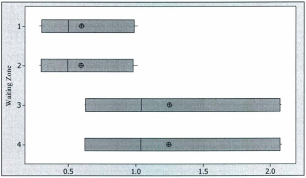

Figure 5.1 Average CO/exposure limit ratios in different waiting zones

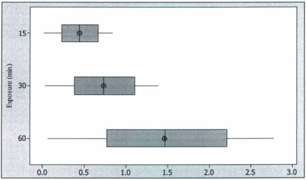

Figure 5.2 Average CO/exposure limit ratios inside main stream

5.2.2 NO_2 concentrations compared to the exposure limit

The NO_2/exposure ratios are calculated for 1 hour exposures only for peak traffic conditions. The risk is characterized for pedestrians in the main stream of the tunnel and in the waiting zones.

Table 5.4 Ratios of average NO_2 concentrations/exposure limits

Segment	Tunnel	Waiting Zone 1	Waiting Zone 2	Waiting Zone 3	Waiting Zone 4
(1h exposure)	3.168634	2.037911	2.023428	4.337756	4.333756

The results in Table 5.4 show that the NO_2/exposure limit ratio is always larger than 1. This could indicate a high risk of exposure. However, these ratios assume 1-hour exposures, and they could be lower for shorter durations.

5.2.3 SO_2 concentration compared to the exposure limit

The risk is characterized for 10 minutes of exposure for pedestrians in the main stream of the tunnel and in the waiting zones.

Table 5.5 Ratios of average SO_2 concentrations/exposure limits

Segment	Tunnel	Waiting Zone 1	Waiting Zone 2	Waiting Zone 3	Waiting Zone 4
(10 min exposure)	18.17658	2.337836	2.321353	4.97668	4.972091

Although the risk is characterized for only 10 minutes of exposure, the resulting ratio of the SO_2/exposure limit exceeds 18.17 in the mean stream. This means that average concentrations of SO_2 inside the tunnel is more than eighteen times the recommended exposure limit for 10 minutes of duration set by the WHO. This may indicate a high risk of due to SO_2, and it is alarming that immediate action is required to bring SO_2 levels to acceptable limits. Further investigations and field measurements are necessary to verify the finding.

For $PM_{2.5}$ allowable short term exposure limits are not found in literature. Further studies are required in this area.

5.3 Discussion

The risk results show their maximum values during peak traffic scenarios. All pollutants that are modeled show high risk in Waiting Zones 3, 4 and the main tunnel stream. Nevertheless, the combined effect of the pollutants could be particularly high. Efforts should therefore be employed to reduce the risks during peak hours. Pedestrians should not be allowed to walk inside tunnel in the main driving stream. Moreover, the waiting times inside the waiting zones should be kept to a minimum, and other activities should be minimized inside the tunnel.

Chapter 6

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

The current status of air quality in the tunnel depends on the traffic intensity. During peak traffic periods, the CO, NO_x, SO_2, and fine particulate concentrations are all above the regulatory limits set by the PME. However, during non-peak traffic hours, the levels of air pollutants inside the Souk Sagheer Tunnel are within the acceptable limits set by the PME.

A number of solutions to the air pollution problem during peak traffic hours have been modeled and tested. These solutions include improved longitudinal and transverse ventilation and introducing a separation wall to make the tunnels unidirectional. Results show that deploying additional jet fans in the longitudinal ventilation system may not be effective. A lot of energy will be required to make a transverse ventilation system sufficient and effective. Therefore, building a separation wall could reduce the air pollutants levels significantly. This study has found that building a wall barrier could reduce air pollutant concentrations significantly up to 70%. Moreover, it has been found that the SO_2 levels car reach warning levels that are up to 18 times more than the maximum permissible limit.

However, in the event of a ventilation system failure, the separation wall has been shown to reduce the impact of the lack of ventilation on the air quality inside the tunnel.

A risk assessment based on calculations from the model of the current peak traffic shows high ratios between mean the pollutant concentrations over the exposure limits for longer exposure duration (more than 15 minutes exposure) in Waiting Zones 3 and 4 and the main tunnel stream. The tunnel is considered a health risk during peak traffic.

6.2 Recommendations

The following recommendations are made:

1. Attention should be paid to the Souk Sagheer Tunnel air quality.
2. Continuous monitoring should be implemented, and the control system should be adjusted to respond promptly.
3. Building a wall to separate the tunnel into two different tubes is environmentally effective, but the engineering feasibility is important to consider before the decision is made. This should take into consideration the benefits of reducing air pollutants and better fire and smoke control, which will enhance the safety of the tunnel.
4. Any activities that are not necessary inside the tunnel should be banned. For example, selling goods should not be allowed inside the tunnel, especially during peak traffic periods.
5. The waiting time of pedestrians inside the waiting zones should be minimized. Moreover, people moving inside the tunnel should avoid the main stream of the tunnel and use the waiting zones only.
6. Tunnel in current conditions during peak traffic shows high levels of CO, NO_2, and $PM_{2.5}$ that exceeds recommended exposure limits by all standards.

7. The simulation shows high level of SO_2 in both peak and non-peak traffic inside the tunnel, which should be given close attention. Further study is required.
8. Results of this study should be communicated to interested parties.

6.3 Future Studies

The tunnel sends massive amount of pollutants into the surrounding area. This impact should be analyzed and estimated.

Electrostatic precipitators (ESPs) have been in use in many tunnels worldwide, especially in Japan, to reduce particulate matter for better feasibility and healthier atmosphere. The use of ESP in the Souk Sagheer Tunnel should be studied.

Other pollutants inside the tunnel during peak traffic, especially SO_2, require further investigation.

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