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RESEARCH ARTICLE

Estimation of real-world traffic emissions for CO, SO_2, and NO_2 through measurements in urban tunnels in Tehran, Iran

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Abstract

Mobile sources are considered to be one of the most important sources of air pollution among which are motor vehicles, recognized as the major contributor of air pollutants in urban areas. To determine the emissions for CO, SO_2, and NO_2 from motor vehicles as part of the attempt to realize the extent of traffic air pollution, measurements were carried out in two heavily traversed traffic tunnels in Tehran metropolitan area. The concentrations of pollutants and metrological and traffic data were collected through intensive measurements from September 27 to October 17, 2016. Resalat Tunnel fleet was composed of about 10% diesel-fueled vehicles and 90% non-diesel-fueled vehicles while throughout the entire duration of our campaign, only non-diesel-fueled vehicles traversed Niayesh Tunnel. Under an average traffic speed of 43 km h^{-1}, emission factors from Resalat Tunnel campaign were measured to be (6.59 ± 2.69)E+3, (1.42 ± 0.84)E+2, and 6.80 ± 4.99 mg km^{-1} for CO, SO_2, and NO_2, respectively. These values were respectively 11% higher, 22% lower, and 40% higher than those from Niayesh Tunnel measurements which were recorded at a traffic speed of 30 km h^{-1}. Current results indicate that the vehicular emissions in certain countries, especially the developing ones and in this case, Iran, are quite different from those measured in developed countries and that the high emission levels of SO_2 in Iran are associated with the high sulfur content of the gasoline.

Keywords Tunnel measurement campaign · Pollutant concentration · Emission factor (EF) · Traffic speed · Tehran

Introduction

To achieve proper air quality control in large urban areas, reliable information on emissions from different sources is required. For this purpose, EFs (emission factors) representing average emissions per source are estimated. Motor vehicle emissions heavily contribute to air pollution in cities. Therefore, a dedicated study of emissions under different conditions for key urban areas is needed.

There is a variety of methods to obtain vehicular emissions which are usually based on collecting experimental data during measurement periods. Measurements are normally carried out under controlled conditions in laboratories (Alves et al. 2015; Durbin et al. 2002) or under real-world conditions with the latter including remote-sensing (Guo et al. 2007; Kuhns et al. 2004), on-road measurement (Canagaratna et al. 2004; Lau et al. 2015), and tunnel studies (Chang and Rudy 1990; Staehelin et al. 1995) as the three widely used approaches to data gathering. Tunnel studies have the advantage of presenting a limited but real-world space that represents a traffic condition similar to that of an urban area (Franco et al. 2013). While there are certain advantages to this method, tunnel studies have their share of shortcomings that should be acknowledged, a more common of which is the difficulty in apportioning the emissions to each vehicle type (Franco et al. 2013). This approach includes monitoring pollutant concentrations at the entrance and exit of the tunnel (Weingartner et al. 1997). Several studies worldwide including Colberg et al. (2005), Gertler and Pierson (1996), and Li et al. (2015) previously took the tunnel

Highlights

- The measurements in two urban tunnels provided similar results.
- The influence of the tunnel ventilation system on the estimation of EFs is of high importance.
- The NO_2 emissions revealed to be different than those of CO and SO_2.
- Estimation of SO_2 emissions with the deposition effect included resulted in higher emissions.
- The traffic speed has a noticeable effect on the average vehicle EF.

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study approach to determine traffic EFs for various pollutants in the USA, several European cities, and China, respectively. However, the results of these studies should not necessarily be applied to other countries, especially in the case of the developing countries where vehicle technology or fuel standard is different. Adding to the aforementioned subject, in Iran, there is clearly a lack of information in terms of available data on emissions from different sources, namely motor vehicles. Yazdi et al. (2015) conducted an experimental campaign to determine CO EFs under light and heavy traffic conditions in Resalat Tunnel in Tehran.

In the present study, we aimed to obtain real-world traffic EFs for CO, SO_2, and NO_2 through measurements performed between late September and early October 2016 in Resalat Tunnel in Tehran, Iran. However, in order to determine the current emissions of Tehran vehicle fleet, we conducted another intense tunnel campaign in Tehran Niayesh Tunnel with its results being compared with the results of the present study.

Methodology

Resalat Tunnel description

The Resalat Tunnel is the first urban tunnel constructed in Tehran and is heavily used by vehicles as an accessible passage between the eastern and western parts of the capital. The tunnel has an approximate length of 0.85 km. It has two unidirectional bores with three main lanes of traffic per bore and an extra lane for emergencies. Figure 1 illustrates the front view from the 3D model of the north bore entrance. The tunnel has a longitudinal ventilation system that consists of 24 jet fans per bore, divided into eight sections along the ceiling with 110 m of distance between every two sections. The total number of activated jet fans is decided automatically in accordance with in-tunnel CO concentration measured by dedicated sensors. However, at the time of our study, these sensors were not in operation due to maintenance services. Thus, the ventilation system was only activated during one evening and occasionally morning periods, resulting in a possible underestimation of emissions during those periods. It should be clarified that the possible underestimation is only a presumption and as will be explained in the following sections this is not necessarily the case and in fact, it resulted in an overestimation of the emissions. It should also be further clarified that the deactivation of the ventilation system should remove the aforementioned error that is introduced through the effects of the ventilation system and the emission results from the periods with the ventilation system deactivated are not under- or overestimated.

Field measurements

Measurements were conducted in the north bore of the Resalat Tunnel over a 1-week period from September 27 to October 3, 2016. The reason that the measurements were conducted in one tunnel bore is that the fleet composition and the traffic volume in the two bores of Resalat Tunnel are very much identical. As a result, we decided to put in the time and effort to conduct an experimental campaign in another urban tunnel that represents a dissimilar traffic condition (i.e., traffic volume and traffic speed), together resulting in two different cases which helps reaching a more definitive understanding of traffic emissions in Tehran as well as figuring out if the tunnel studies can be a reliable means of determining the real-world traffic emissions since the only common aspect between the two campaigns is the traffic fleet composition for the most part, while the tunnel layout and operating and traffic conditions are different. By saying a dissimilar traffic condition, we mean to highlight the difference in the average in-tunnel traffic speed and the traffic volume which is in a range of 4000–5000 veh h^{-1} in Resalat Tunnel as opposed to 2500–3000 veh h^{-1} in Niayesh Tunnel. Even though in

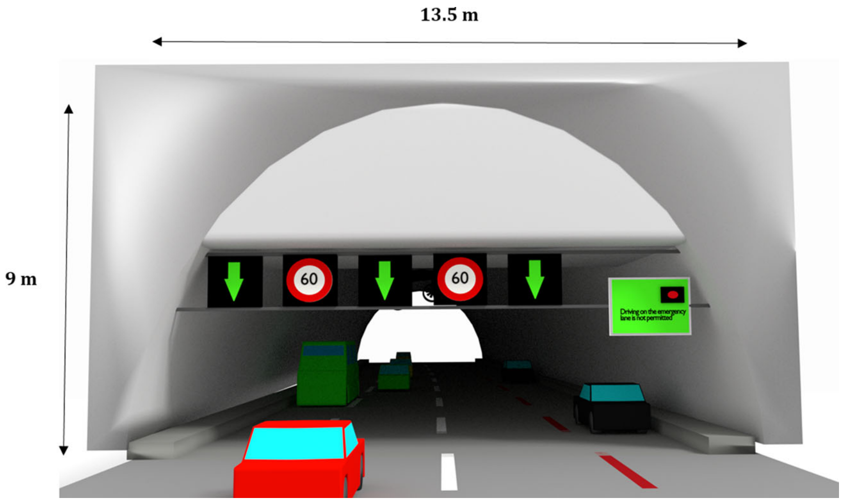

Fig. 1 Front view of the entrance to the north bore of Resalat Tunnel—captured from the 3D model

terms of the proportion of the light-duty vehicles, the traffic fleet composition is for the most part similar in both tunnels, the slight but constant presence of heavy-duty diesel-fueled vehicles in Resalat Tunnel should prove differentiating enough as another aspect that warrants the second part of the campaign to be taken place in another tunnel. As a further consideration during the tunnel campaign, the roadway grade was also taken into account which is 2.7% (1.5°). This further solidified the emphasis on conducting the second part of this campaign in a different tunnel since presumably a different traffic condition and fleet composition affect the results more than the aforementioned roadway grade. Two monitoring sites were used at 150 m from each of the entrance and exit portals, for the measurement of parameters used in the calculation of emission factors. In order to obtain the concentration profile of each pollutant along the tunnel, five more monitoring points were chosen, with two of them being located outside of the tunnel. Figure 2 illustrates the 3D model of Resalat Tunnel north bore while Fig. 3 aids in displaying a better view from each monitoring location along the tunnel. CO, SO_2, and NO_2 concentrations were measured during five time segments of 8:00–10:00, 10:00–12:00, 12:00–14:00, 14:00–16:00, and 16:00–18:00 with a time resolution of 15 min. The reason that CO, SO_2, and NO_2 are chosen to be measured is that these are the three most commonly studied and referenced gaseous air pollutants, otherwise known as criterion air pollutants and since this study marks the first campaign of in-tunnel stationed measurements in the capital Tehran, it was decided that it would be well-justified to carry out the measurements for the aforementioned pollutants. Concentrations of pollutants were measured using a portable air quality monitor, Learian Streetbox, equipped with freshly embedded electrochemical sensors. Through this method, after a chemical reaction involving the sample gas inside of the cell that results in an electric current which is equivalent to the gas concentration, the concentration value is measured. Electrical noises are eliminated through an already-attached anode that comes with the sensor while the effects of temperature and the moisture of the gas sensor are made up for by the introduction of certain calibration characteristics. Calibration was carried out by automation experts according to the manufactures' guideline a few days prior to the start of the campaign. The instrument is quoted to have an accuracy of ± 5%, and the detection limits are 100, 25, and 20 ppb for CO, SO_2, and NO_2, respectively. A similar monitor was previously used in a study by Tomlin et al. (2009). Tomlin et al. (2009) reported that the results obtained from Streetbox revealed to be highly accurate when compared with those of a US EPA–certified CO analyzer that

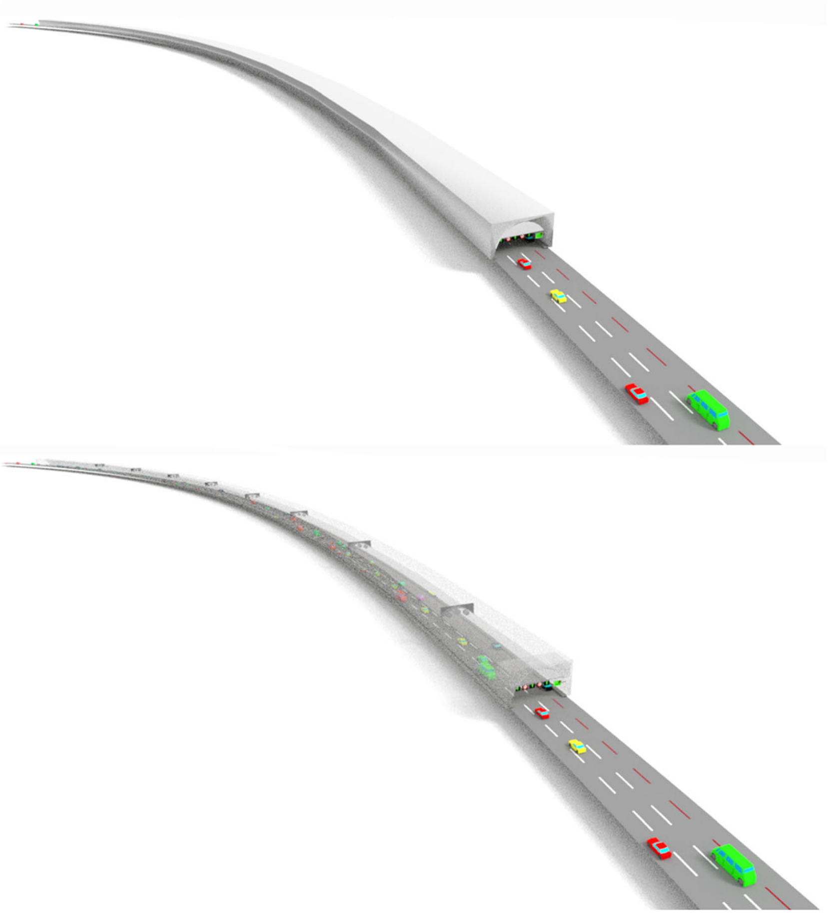

Fig. 2 North bore of Resalat Tunnel as a 3D model—the upper body of the tunnel is transparent in the bottom image, helping to display the jet fans that are embedded along the ceiling between 8 sections (graphic work created using the Blender software)

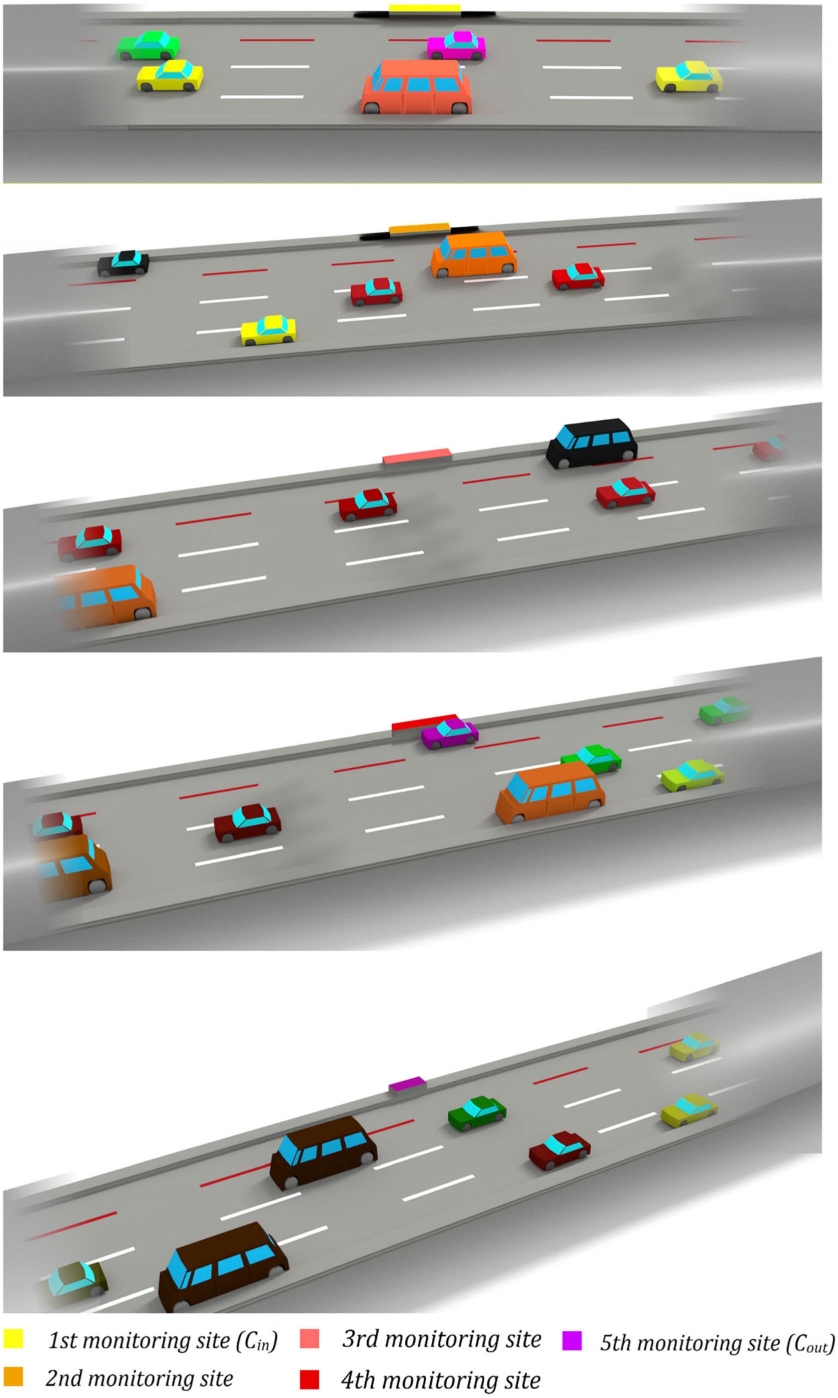

Fig. 3 The side view of each monitoring location along the tunnel length (the virtual camera angle for the side view images is fixed)—from top to bottom comes first to fifth sites with respectively 100 m, 300 m, 500 m, 600 m, and 750 m being the distance of each site from the entrance portal; colored section on the side of each monitoring site is the location in which the measurements were conducted

was used alongside the Streetbox. More information on the performance of Learian Streetbox is provided in Croxford et al. (1996). A TENMARS TM-740 air velocity meter was used for spot measurement of wind speed and temperature. The average in-tunnel wind speed and traffic data were obtained from the tunnel control center for each day. Concentrations and wind speed were measured at 4 m above the ground level using the aforementioned air quality monitor and air velocity meter, respectively, while the average in-tunnel wind speed was measured at the height of 8 m using the in-tunnel equipment embedded just below the tunnel ceiling. Spot measurements of wind speed using the handheld air velocity meter at the height of 4 m were carried out three times during each of the 15-min periods, and the mean value of those three wind speeds which was calculated for each period would then be compared with that which was measured at 8 m from the ground level using the in-tunnel equipment.

Obtaining the traffic data

Traffic data including traffic counts, type of vehicles, and traffic speed were captured from the traffic control system of the tunnel. This system consists of several video recorders and two loop detectors, the latter of which are installed outside of the two adjacent bores. The average traffic volume in the north bore of the tunnel was 84,155 vehicles per day during our 1-week tunnel measurements. Vehicles were initially divided into three types, namely light-duty vehicles (LDVs), medium-duty vehicles (MDVs), and heavy-duty vehicles (HDVs) according to their respective lengths with 93%, 6%, and 1% of the fleet being the proportion of each type, respectively. However, based on our field observations, almost all of the medium-duty vehicles passing through the tunnel were diesel-fueled mini trucks and minibuses. Therefore, it was decided to classify the fleet into two types, namely non-diesel-fueled vehicles (NDVs) and diesel-fueled vehicles (DVs). It is of importance to clarify that the motorcycles were constantly present during our campaign and thus, they are counted as light-duty vehicles due to their size and eventually part of the non-diesel-fueled vehicles category since these are gasoline-fueled. The average traffic speed was obtained to be 43 km/h during the measurements, revealing the free-flowing nature of traffic in Resalat Tunnel.

Calculation of EFs

The method to calculate EF of a given pollutant from vehicles in a traffic tunnel was previously described elsewhere (Chang and Rudy 1990; Pierson et al. 1996). Equation 1 presents distance-traveled-specific EF (mg km^{-1}) per vehicle in the total fleet for the condition that the deposition is negligible.

$$EF = \frac{(C_{\text{out}} - C_{\text{in}}) \times U \times A \times T}{N \times L} \tag{1}$$

C_{out} and C_{in} represent the pollutant concentration (mg m^{-3}) at 150 m from the entrance (inlet concentration) and 150 m to the exit portal (outlet concentration), respectively. A is the tunnel cross section (102 m^2), U is the average in-tunnel wind speed (m s^{-1}), N is the number of vehicles traversing the tunnel during time period T (900 s), and L is the distance between the two monitoring sites (0.65 km). Estimation of EFs involves simultaneous measurement of pollutant concentration at both ends of the tunnel. However, our measurements were constrained as we were only to have access to one air quality monitor at a time. For this reason, we opted to use the average concentrations of pollutants at the entrance as a proxy for inlet concentration during every time segment which would then be applied to Eq. 1 as C_{in}. In order to do so, duplicate measurements were performed at the tunnel entrance to ensure that the inlet concentration values were as much reflective of similar traffic and operating conditions to those of the outlet as possible. As a further matter, it is worth mentioning that the 15-min mean values of in-tunnel wind speed measured using the in-tunnel equipment are applied to Eq. 1 as U since these are surely more representative and accurate than those measured using the handheld air velocity meter. This is because more repetition goes into measuring the aforementioned 15-min averages as opposed to their handheld counterparts.

Equation 2 is a more inclusive and extensive form of Eq. 1 that takes the effect of deposition into account and contrary to Eq. 1 does not assume the deposition coefficient to be 0 but similar to Eq. 1 assumes the volume of air flow throughout the tunnel to be correspondingly the result of natural ventilation (i.e., the natural effects resulting in flowing of air inside the tunnel; piston effect included), and Eq. 3 presents the ratio of deposition on the tunnel surface to emission of a given pollutant that is derived for the case of natural ventilation. Full details can be found in Chang et al. (1981) and Chang and Rudy (1990).

$$EF = \left[C_{\text{out}} - \left(C_{\text{in}} \times e^{-\frac{KL}{U}}\right)\right] \times \frac{A \times T \times K}{N \times \left(1 - e^{-\frac{KL}{U}}\right)} \tag{2}$$

$$R = 1 + \left[\frac{U \times A \times T}{N \times L \times EF} \times \left(C_{\text{in}} - \frac{N \times EF}{A \times T \times K}\right) \times \left(1 - e^{-\frac{KL}{U}}\right)\right] \tag{3}$$

K is the deposition coefficient (s^{-1}) which is the product of the deposition velocity derived particularly for a pollutant, and the proportion of tunnel perimeter to its cross section. For a derived SO_2 deposition velocity of 7E−5 m s^{-1} (Chang et al. 1981), the SO_2 deposition coefficient of Resalat Tunnel was measured to be 21.7E−3 min^{-1}. Of all the deposition coefficients presented in Chang et al. (1981), SO_2 has the highest value. SO_2 was one of the few pollutants and the only one among the current three that we were able to find its deposition velocity in the literature for a tunnel condition. However, the main reason that we were interested in the deposition effect of SO_2 is the fact that it is considered a sticky gas as is the case with NO_2 as well. This is evident by various attempts that have been made on measuring the deposition velocities of both of these acidic gases in various studies, namely in Grøntoft and Raychaudhuri (2004) and even more so for SO_2 as can be figured by the relatively higher number of researches that initially attempted to measure its deposition velocity (McMahon and Denison 1979). Due to the complexity in the measuring process of deposition velocity, namely the acidity and alkalinity of a given surface (Grøntoft and Raychaudhuri 2004) or the surface saturation and regeneration which directly affect the pollutant removal rate (Judeikis and Wren 1978) and the vast selection of materials on which deposition and pollutant removal occur, we avoided to select a NO_2 deposition velocity from the literature that we thought would be close and fitting for the current case of the tunnel and decided to only apply the aforementioned SO_2 deposition velocity as it was solely derived for a tunnel condition.

Niayesh Tunnel and campaign description

Niayesh Tunnel is the longest urban tunnel in Iran with a total length of 10 km, taking into account the ramps and the two main bores. The tunnel has two bores of opposite directions with each one being about 3 km long and traffic lanes similar to those of Resalat Tunnel. The mechanical ventilation comprises a total of 60 jet fans as longitudinal ventilation and a series of axial fans that only come into service when there is an emergency. Similar to that in Resalat Tunnel, the number of activated jet fans is decided based on the in-tunnel CO sensors that are embedded along its length. As a part of the attempt to estimate the real-world traffic emissions in Tehran, along with the current study, we conducted another experimental campaign in Tehran Niayesh Tunnel. Niayesh Tunnel functions as a traffic route that connects the northeast side of Tehran to the northwest side of it. For this reason, the tunnel is of a relatively longer length (3 km) when compared with Resalat Tunnel (0.85 km). Measurements were performed between October 8 and October 17, 2016, in the south bore of Niayesh Tunnel through a method similar to that of Resalat Tunnel measurements. Along with the difference in tunnel length and layout as well as the traffic and operating conditions which are noticeable, the slight difference in the traffic fleet composition traversing the two tunnels should as well be taken into consideration. Niayesh Tunnel is solely dedicated to light-duty vehicles. While this is also the case with Resalat Tunnel, different vehicle types including motorcycles routinely traverse Resalat Tunnel. This makes the results of Resalat Tunnel to be reflective of a slightly varied fleet composition which is typical of urban areas whereas the emission factors estimated in Niayesh Tunnel are representative of emissions from light-duty vehicles. The estimated emission factors of Niayesh Tunnel campaign are compared with those of the current Resalat Tunnel study in "EFs from other tunnel studies in Tehran."

Results and discussion

Metrological data and traffic characteristics

Table 1 presents the average values of traffic volume, traffic speed, temperature, and wind speed data as well as the composition of traffic fleet that traversed Resalat Tunnel while we were performing the measurements which were all collected over 1 week of tunnel campaign.

In addition, the relative humidity varied in a range of 19–31%. Wind speed was much lower between the afternoon hours than those of other time periods. The range in which the wind speed varied was 1–2 and 1–9 m s^{-1} during the afternoon and evening hours, respectively. As mentioned in "Resalat Tunnel description," ventilation system was in operation between late afternoon and evening hours which may very well be the cause of variance in wind speed results with the broader range of variations in the evening results confirming the fan thrust impact. Therefore, it is safe to assume that in-tunnel wind speed throughout the afternoon peak especially around 12:00–14:00 period is largely attributed to the vehicle-induced piston effect since no jet fan was in service during the afternoon period. This assumption is further supported by the difference between wind speed values that were measured at different heights during the afternoon period. They were 1.35 and 2.63 m s^{-1} at the height of 8 and 4 m (from the ground level), respectively, showing that the maximum wind speed occurs near the vehicles (Chen et al. 1998). As presented in Table 1, this is very much the case with 10:00–12:00 and 14:00–16:00 periods as well when the

Table 1 Traffic and metrological data, measured during Resalat Tunnel campaign; all the data representing each parameter are mean values

In-tunnel traffic and metrological data	8:00–10:00		10:00–12:00		12:00–14:00		14:00–16:00		16:00–18:00	
Temperature (°C)	26.69		27.99		30.55		30.70		31.11	
Wind speed—8 m (m s^{-1})[a]	4.06		1.73		1.35		1.69		3.96	
Wind speed—4 m (m s^{-1})[b]	2.47		3.25		2.63		2.41		2.86	
Traffic volume (veh h^{-1})	4882 ± 957^{C}		4676 ± 957^{C}		4956 ± 304^{C}		4930 ± 460^{c}		4474 ± 725^{c}	
Traffic speed (km h^{-1})	45.29		48.66		43.54		44.14		35.94	
Traffic fleet composition	NDVs	DVs	NDVs	DVs	NDVs	DVs	NDVs	DVs	NDVs	DVs
	91.37%	6.62%	93.38%	7.28%	92.72%	5.56%	94.44%	6.00%	94.00%	8.63%

[a] Measured using the in-tunnel wind sensors at the height of 8 m

[b] Means of spot values that were measured three times during each 15-min period using the handheld instrument meter at the height of 4 m above the ground

[c] Standard deviation

ventilation system is out of operation while the exact opposite happens during 8:00–10:00 and 16:00–18:00 periods with the wind speed values measured at 8 m above the ground being greater than those measured at 4 m which is reasonable since the ventilation system was mostly in operation during those periods, hence a faster movement of in-tunnel air near the jet fans. However, as it can be deduced from the results, the effect of jet fans on the average wind speed inside the tunnel is greater than that of the vehicle motion especially since it becomes more apparent when the two sets of wind speed data obtained at 8 and 4 m above the tunnel ground are compared and the resulting correlation between the two is better during the times when the ventilation is in operation (R^2 = 0.41) as opposed to when it is not (R^2 = 0.35). Moreover, this should be considered a downside to tunnel studies for the reason that the in-tunnel air movement will no longer be only the result of your typical natural ventilation and vehicle-induced piston effect, but a result of the somewhat extra force of the mechanical ventilation which will result in a possible overestimation of the emission factors. This is not to say that the emissions from vehicles change under the influence of the ventilation system as it does not make any sense, rather in the context of tunnel studies, the process of estimating the emission factors through gathering the experimental data (e.g., pollutant concentrations and wind speed) and applying them to Eq. 1 which in itself requires precision during the measurement campaign will be affected. An example of this is the simultaneous changes in the pollutant concentration and the wind speed value during the 16:00–18:00 period under the sudden changes in the number of working jet fans with the aforementioned parameters, respectively, showing a decrease and an increase in their respective values. This will be tackled in the following subsection ("Examining the vehicular emissions and the level of air pollutants").

The majority of vehicles in Tehran are gasoline-fueled and little to no reliable statistics on the proportion of each vehicle type is available. However, based on previously made observations, there is an approximate share of 70%, 25%, and 5% of the total fleet for gasoline-fueled, bi-fueled, and diesel-fueled vehicles, respectively. Due to being located in heavily traveled highways, traffic tunnels are representative of a fleet that is for the most part typical of urban traffic composition. Still, the traffic composition of tunnel fleet differs from those of other urban areas in one particular aspect, that is, the fraction of diesel-fueled vehicles. The traffic fleet composition during the present study is presented in Table 1, and as can be gathered from Table 1, the fraction of diesel-fueled vehicles varied from 5 to 10% and at times from 5 to 15% of the total fleet between the morning and evening hours with the former presenting the smaller fraction among the two periods. This, in general, may result in a lack of data and consequently less accurate data analysis to determine the emissions from diesel-fueled vehicles through regression methods. The evening peak has an average traffic volume of 4474 ± 725 veh h^{-1} which shows a decrease of about 8% and 10% from that of the morning and afternoon peaks, respectively. This, however, is to be expected as evening peak represents the heaviest traffic condition which results in low traffic speed and traffic congestion. This reveals that despite the importance of variables such as traffic volume in the measurements of vehicular emissions, other contributing factors including traffic speed should as well be taken into account in regard to their effect on the variations of the emissions.

Examining the vehicular emissions and the level of air pollutants

One of our early ideas prior to the start of the tunnel campaign was to apply the background (ambient) concentration as the inlet value in Eq. 1 by sampling the air outside of the tunnel entrance or acquiring its equivalent street-level concentration from Tehran Air Quality Control Company. The problem with this approach is that the background concentration is not the actual inlet concentration as shown in Fig. 4.

The background concentration of CO ranged from 1000 to 4000 ppb while the inlet concentration ranged from 6000 to 14,000 ppb which is due to the backflow mixing that involves mixing of the polluted air and the fresh incoming air near the portals of two unidirectional bores (Tan et al. 2015). Figure 4 shows the variation of CO concentration with distance from 50 m before the tunnel entrance to 50 m after the tunnel exit. The concentration level increases with distance along the tunnel until it reaches its peak value near the tunnel exit which is then followed by a drop in CO level. Note that the data displayed in Figs. 4, 5, and 6 were obtained continuously under heavy traffic at different locations during periods that the ventilation system was out of operation. Therefore, the main driving force behind the in-tunnel air movement was the result of vehicle motion. Figures 5 and 6 display the spatial variations of SO_2 and NO_2 concentrations, respectively, with both showing a trend similar to that of CO. Still unlike CO and SO_2, NO_2 concentration does not drop after the exit portal and remains in a comparable range. This can be explained by the implausibility of emitted NO_2 getting transported from the

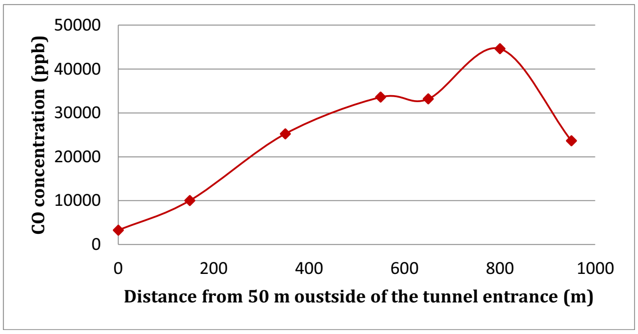

Fig. 4 Spatial variation of CO concentration

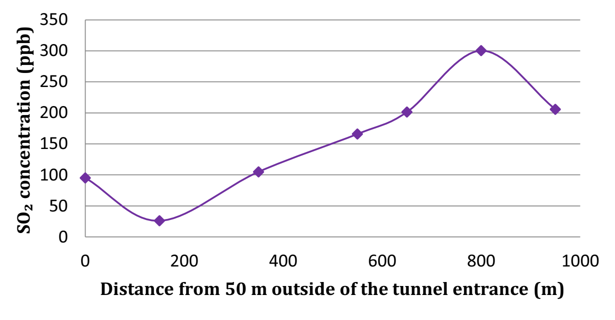

Fig. 5 Spatial variation of SO_2 concentration

source (i.e., vehicles) to higher elevation as a result of dry deposition that is more likely to occur for NO_2 when emitted close to a surface (Watson et al. 1988). In other words, vehicular emissions of NO_X are likely to remain close to the surface due to dry deposition which presumably prevents the vertical distribution of the pollutant. Also, the direction to which the prevailing wind travels is the opposite of the traffic path which in turn may prevent the horizontal distribution of the pollutants. Moreover, the contribution of fresh air outside of the tunnel exit portal to the reaction between NO and O_3 which results in secondary NO_2 production will affect the concentration level of NO_2 and should reasonably result in higher NO_2 values. Another difference between these trends presented in Figs. 4, 5, and 6 is the drop in SO_2 concentration near the entrance. One possible explanation could be the effect of SO_2 deposition on its concentration which is resulted from the sudden exposure of a polluted bulk (i.e., background inflow plus the polluted outflow of the adjacent bore) to the tunnel walls, knowing the fact that SO_2 has a relatively high deposition velocity and consequently its removal should relatively be higher than other pollutants while due to the increasing emission, its concentration eventually peaks near the tunnel exit. We cannot be certain about this explanation being the reason for SO_2 concentration drop, and it would be remiss to reach a definitive conclusion on the reasons behind these discrepancies since many factors contribute to the behavior of gas species. Still a point that can be drawn from the spatial variations of these pollutants is that they all display an inclining trend which is expected in semi-enclosed spaces such as a tunnel as vehicular emissions of these pollutants as well as both mods of natural ventilation and mechanical ventilation result in a more or less growing concentration level toward the end of the tunnel. The aforementioned factors plus other possibilities which should be further explored in tunnel studies contribute to the dispersion and behavior of a pollutant.

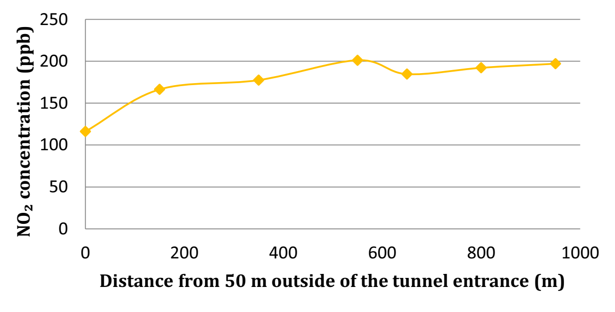

Fig. 6 Spatial variation of NO_2 concentration

Concentrations of pollutants and the EFs, as well as their overall values, are presented in Table 2 for five consecutive time segments.

Also Figs. 7, 8, and 9 show the distribution of 15-min average concentrations of pollutants at the outlet site for each of the five time segments over 1 week of measurements.

While there were instances during the 8:00–10:00 period when NO_2 concentration exceeded 200 ppb, the 12:00-to-14:00 period saw a somewhat stable distribution of relatively higher NO_2 concentrations. Although the proportion of diesel-fueled vehicles mostly remained in a similar range during all of the periods, the presence of several aged diesel-fueled minibuses during the 12:00–14:00 period for the entire duration of our campaign may explain higher levels of NO_2 concentration during the aforementioned period since diesel-fueled vehicles are considered to be highly associated with NO_X emissions (Gillies et al. 2001). CO and NO_2 concentrations are lower than the in-tunnel safe values proposed by the Permanent International Association of the Road Congress (PIARC) (PIARC 2012). They were 70,000 and 1000 ppb, respectively. However, there were occasions especially during the 12:00–14:00 period when the visibility was highly reduced and CO concentration ranged between 65,000 and 68,000 ppb at the outlet site. Although no in-tunnel safe value for SO_2 has been proposed in the literature, it is plausible to assume that the pollutant has high vehicular emissions as evidenced by the large difference between the inlet and the outlet values of SO_2 concentration. EFs were $(11.14 \pm 8.95 - 6.59 \pm 2.69)$E+3, $(2.73 \pm 2.82 - 1.42 \pm 0.84)$E+2, and (1.65 ± 2.57)E+1 $- 6.80 \pm 4.99$ mg km^{-1} for CO, SO_2, and NO_2, respectively. Depending on the time of day, EFs varied in a relatively large range which is attributed to a number of factors. The two time segments of 14:00–16:00 and 16:00–18:00 have a similar traffic condition, but the concentrations of CO and SO_2 are higher during 14:00–16:00. This is the result of the ventilation impact on the concentration level. However, the corresponding emission factors of concentrations that were measured during the 16:00–18:00 period are higher than those of other time periods. It is much in part due to the activity of jet fans, resulting in higher wind speed, hence overestimation of EFs. This also applies to some of the emission factors from the morning period. In the case of emission factors, it is best to consider scenarios representing the highest emissions. However, by excluding the emission data of periods during which the ventilation system was in-service from the total dataset, a clear decrease by 41%, 48%, and 58% in,

Table 2 Measured concentrations of pollutants and emission factors from Resalat Tunnel campaign

Pollutant	Time segment					Summary statistics[a]				
	8:00–10:00	10:00–12:00	12:00–14:00	14:00–16:00	16:00–18:00	Mean	Median	Max	Min	SD
CO										
Outlet (ppb)	4.00E+4	3.52E+4	5.20E+4	5.49E+4	3.72E+4	4.07E+4	3.94E+4	6.79E+4	1.72E+4	1.17E+4
Inlet (ppb)	8.94E+3	8.27E+3	9.58E+3	9.54E+3	1.08E+4	9.38E+3	8.67E+3	1.39E+4	6.70E+3	2.33E+4
EF (mg km^{-1})	1.45E+4	6.43E+3	7.13E+3	9.21E+3	1.74E+4	1.12E+4		4.52E+4	1.53E+3	8.94E+3
EF (mg km^{-1})[b]						6.59E+3		1.37E+4	1.53E+3	2.69E+3
SO_2										
Outlet (ppb)	3.22E+2	3.34E+2	4.78E+2	5.05E+2	4.25E+2	3.80E+2	3.15E+2	7.36E+2	1.09E+2	1.63E+2
Inlet (ppb)	2.58E+1	5.69E+1	9.83E+1	5.10E+1	1.62E+2	7.80E+1	6.15E+1	2.32E+2	1.41E+1	5.60E+1
EF (mg km^{-1})	3.16E+2	1.53E+2	1.39E+2	2.07E+2	5.36E+2	2.73E+2		1.51E+3	2.24E+1	2.82E+2
EF (mg km^{-1})[b]						1.42E+2		4.46E+2	2.74E+1	8.44E+1
NO_2										
Outlet (ppb)	1.71E+2	1.62E+2	1.88E+2	1.75E+2	1.72E+2	1.70E+2	1.70E+2	2.29E+2	9.02E+1	1.62E+1
Inlet (ppb)	1.69E+2	1.59E+2	1.58E+2	1.64E+2	1.31E+2	1.59E+2	1.63E+2	1.87E+2	6.55E_1	2.10E+1
EF (mg km^{-1})	8.44	3.02	7.81	2.49	4.40E+1	1.65E+1		1.16E+2	1.21E−1	2.59E+1
EF (mg km^{-1})[b]						6.80		2.25E+1	1.21E−1	4.99

[a] Summary statistics are calculated for the total dataset

[b] Data from periods with ventilation system in operation are excluded

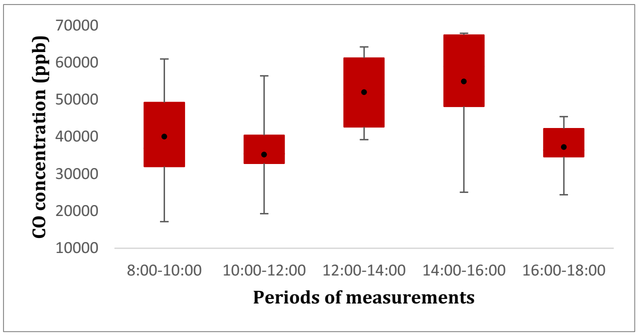

Fig. 7 Distribution of 15-min average concentrations of CO at the outlet site

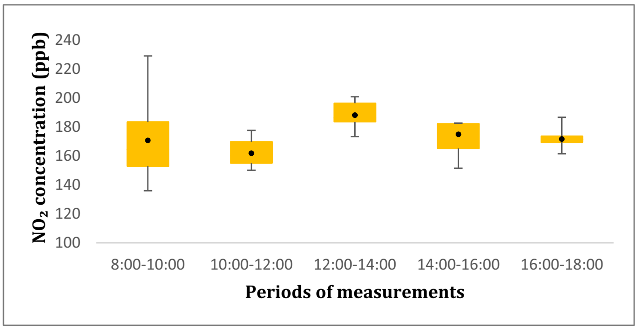

Fig. 9 Distribution of 15-min average concentrations of NO_2 at the outlet site

respectively, CO, SO_2, and NO_2 EFs was noticed. Also as tackled in "Calculation of EFs," the deposition effect on the EFs is to be accounted for. Thus, we applied Eq. 2 which makes for the deposition effect in the case of in-tunnel natural ventilation including the piston effect. Excluding the data from the periods with mechanical ventilation in service and using Eq. 2, we obtained a mean SO_2 EF value of (1.58 ± 0.88)E+2 mg km^{-1}. This shows that our SO_2 EF is about 11% underestimated when the effect of deposition is neglected which makes sense since a certain amount of emitted SO_2 gets deposited on the tunnel wall and Eq. 2 makes up for it through the coefficient *K* and the effect is not practically deducted as it is in Eq. 1. Equation 3 was applied to determine the ratio of SO_2 deposition on the tunnel walls to its emission, and the resulting mean value was obtained to be 12%. Chang et al. (1981) found the ratio to be 9% for SO_2.

Figure 10 shows the variations of 2-h average EFs and their standard deviations.

An interesting point to note is that the variation trends for CO and SO_2 are almost identical to one another whereas for NO_2, the variation deviates from the common trend around 12:00–14:00. This emission trend pretty much solidifies the concentration trend depicted in Fig. 9 since the concentration level is directly influenced by the emissions with the possible reason for its deviation around 12:00–14:00 being the ever happening presence of overage middle buses and minibuses.

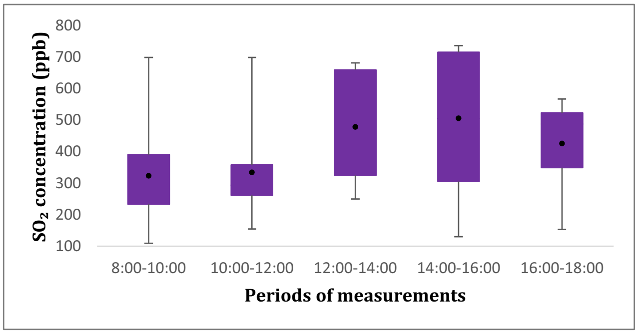

Fig. 8 Distribution of 15-min average concentrations of SO_2 at the outlet site

Dependency of EFs on traffic speed

The speed limit in Resalat Tunnel is 60 km h^{-1}. The traffic speed in the tunnel varies in a range of 20–60 km h^{-1}. Figure 11 shows the variations of 15-min average CO EFs and traffic speed for a period of 10 h.

As expected, the lowest traffic speed (20 km h^{-1}) was recorded during the evening period when the traffic volume was at its highest. The traffic speed was above 50 km h^{-1} around 10:00 and for the rest of the times ranged within 40–50 km h^{-1} range. To determine the influence of the traffic speed on vehicular emissions through total sets of our data, we organized the speed data into 4 intervals of 20–30, 30–40, 40–50, and 50–60 km h^{-1} and classified the corresponding CO EFs accordingly. Figure 12 is the boxplot representation of EFs against each speed interval.

As shown in Fig. 10, the average EFs are (3.01 ± 1.18)E+4, (20.05 ± 9.95)E+3, (9.96 ± 5.89)E+3, and (4.83 ± 2.57)E+3 mg km^{-1} at speed intervals of 20–30, 30–40, 40–50 and 50–60 km h^{-1}, respectively, showing an overall reduction in the CO emissions at higher speeds. Pierson et al. (1996) reported that unlike fuel-specific emissions, the emissions calculated on the basis of distance traveled are affected by the roadway grade which in itself influences vehicle speed. Therefore, a factor to consider when interpreting these results is fuel consumption which increases during traffic congestion situations as a result of vehicle accelerating that just occurs more frequently under lower traffic speeds. The trend of these figures confirms that for the speed range of 20–60 km h^{-1}, CO EFs have a tendency to decrease when the traffic speed is increased. Previous tunnel studies (Deng et al. 2015; Touaty and Bonsang 2000) reported similar results. Figure 13 represents the distribution of NO_2 emissions under different proportions of DVs through boxplots of NO_2 EFs against each of the four speed intervals. NO_2 emissions reveal to be decreasing with the increase in the average traffic speed as well. However comparing with CO, the reduction trend seems to be sharper. As already shown in Fig. 10 the variations of SO_2 emissions throughout different times of day is similar to those of CO, but NO_2 emissions followed a different trend during the 12:00–14:00 period which happened to be

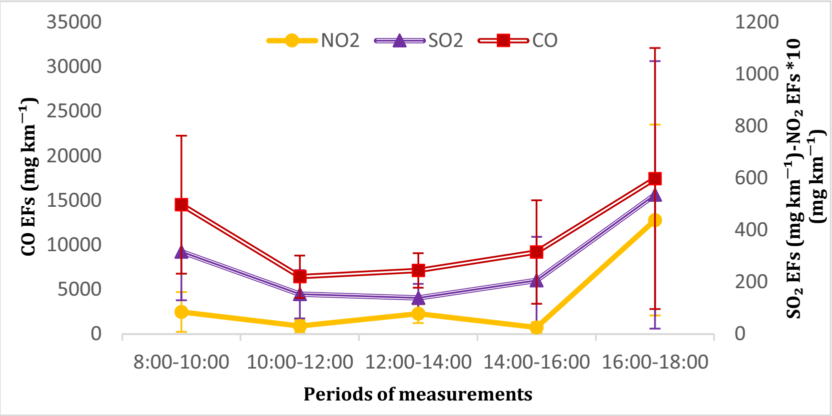

Fig. 10 Temporal variations of EFs

around the time that more DVs traverse the tunnel. As also can be observed from Fig. 13, the NO_2 emissions are of higher values under a heavier presence of DVs. Kristensson et al. (2004) mentioned that while the NO_X emissions increase under the traffic speed of more than 75 km h^{-1}, they are even higher under traffic congestion situations; more so for heavy-duty vehicles which is also the case with the results of the current study. It should be considered that the reduction trend of these emissions with the increase in the average traffic speed in the current study is for the speed range of 20–60 km h^{-1} and a road incline grade of 2.7%.

Comparison of EFs with those of other tunnel studies—general discussion

The data listed in Table 3 represent EFs for CO, SO_2, and NO_2 from different tunnel studies as well as the traffic characteristics of each study. The mean EF for CO in the present study is (1.11 ± 0.90)E+4 and (6.59 ± 2.69)E+3 mg km^{-1} for conditions with the ventilation system in and out of service, respectively. For comparison purposes, through this section, we use those of the emissions measured with jet fans switched off as they, for the most part, are reflective of vehicular emissions rather than being influenced by the impact of the ventilation system.

It also needs to be considered that although tunnel studies refer to estimation of distance-traveled-specific emission factors as in the current case, the method of estimating fuel-based emissions expressed as mass of pollutant emitted per unit of fuel consumed (Singer and Harley 1996) is an alternative approach to determining vehicular emissions which can be taken in both remote-sensing (Franco et al. 2013) and tunnel measurements (Martins et al. 2006; McGaughey et al. 2004). Despite that the fuel-based emissions are regarded as being relatively less affected by alteration in the driving mod and are even considered to be almost unaffected by the road grade (Pierson et al. 1996) when compared with those of mass per distance-traveled emission, the influence of driving speed and the road grade on fuel-based emissions has nonetheless been a subject of interest as in Kean et al. (2003). In cases that a certain fuel such as gasoline of a specific quality is widely consumed, fuel-based emissions can relatively be a more appropriate approach than the distance-traveled-specific emissions since as already mentioned, the former is regarded to be less sensitive to changes in driving condition as was the case for CO emissions in Singer and Harley (1996). However, in the current case, not all the vehicles in Tehran fleet are gasoline-fueled nor all the gasoline-fueled vehicles consume gasoline of similar quality. For this reason, in the current study, we opted for distance-traveled-specific emissions (i.e.,

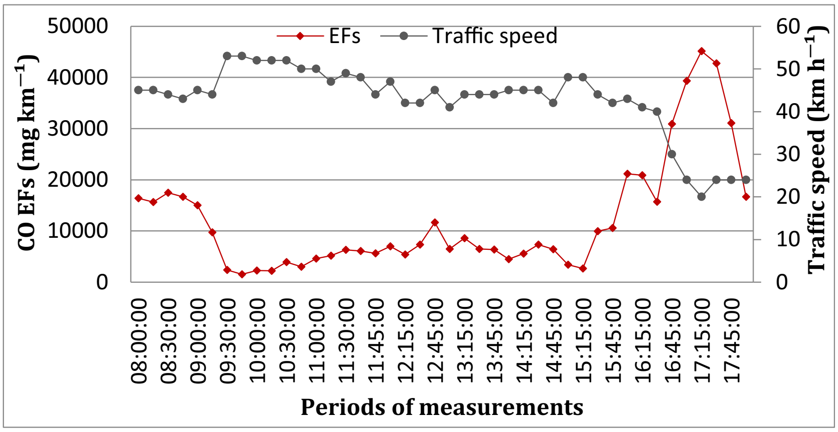

Fig. 11 Variation of CO EF with traffic speed

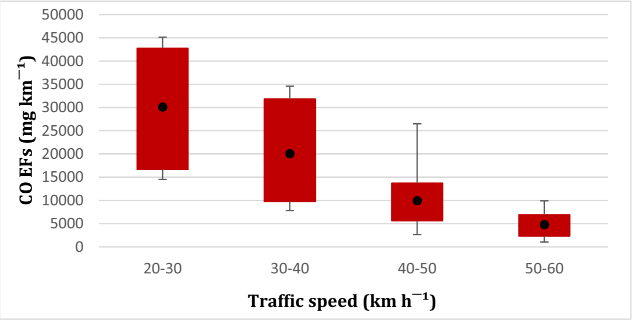

Fig. 12 Distribution of CO EFs under different speed intervals

mg km^{-1}). When compared with the results of other tunnel studies, CO EF in the present study is clearly higher than in most cases. An exception would be the CO EF of 1.12E+4 mg km^{-1} in Salim Slam Tunnel (El-Fadel and Hashisho 2000) which is 1.72 times more than that of 6.59E+3 mg km^{-1} in the present study. Based on the reports in the aforementioned study, their fleet of vehicles was 14 years of age at the time. In our case, there is very little information available on the average model year of the existing fleet in Iran. Still what we can reflect on as a fact is that the lifetime of a private passenger vehicle before its eventual scrappage under certain conditions is considered to be 20 years in Iran. Results for CO EFs from studies in Hong Kong (Cheng et al. 2006) and Southern Taiwan (Hung-Lung et al. 2007) that were conducted between 2003 and 2005 were (1.84 ± 0.43)E+3 and (1.89 ± 0.56)E+3 mg km^{-1}, respectively. These values are about 70% lower than the CO EF in the present study and are somewhat lower than the recent studies in China (see Table 3) including (1.36 ± 0.82–3.97 ± 2.19)E+3 mg km^{-1} in East Yan'an Tunnel, Shanghai (Deng et al. 2015). The study in Shing Mun Tunnel was carried out for a fleet that was composed of about 30–60% diesel-fueled vehicles which are considered to have lesser emissions of regulated pollutants (e.g., CO) than those from gasoline-fueled vehicles (John et al. 1999). The present study, however, was carried out for a fleet almost entirely consisted of non-diesel-fueled vehicles. Still, we should consider that there are reports of otherwise, pointing out to higher emissions of CO from heavy-duty vehicles (Schmid et al. 2001) which indicates that emissions, measured in a certain country, should not be applied to others. While the study in Chang-Liao Tunnel was carried out for a fleet that mainly comprised light-duty vehicles, it is worth noting that the traffic speed at which that study was carried under was 110 km h^{-1} which shows stable driving and presumably a free-flowing traffic state, resulting in lower CO emissions. CO EF in the present study is higher than that of (3.09 ± 0.68)E+3 mg km^{-1} in Zhujiang Tunnel, Guangzhou (Zhang et al. 2015). In terms of being conducted more recently for a tunnel that is located in an urban district, the results from Zhujiang Tunnel campaign are more appropriate for comparison with those from the present study. However, our results showed to be higher than those of Zhujiang Tunnel study. This can be partially explained by the difference in emission standards. The process of upgrading to euro-5 vehicle emission standard has yet to be fully set in motion in Iran as opposed to China which has already started the process in 2014. Moreover, the fundamental differences in vehicular technology in the two countries should as well be considered. Among studies that were carried out around the world, the closest CO EF to that of 6.59E+3 mg km^{-1} in the present study was obtained through a tunnel campaign (Kristensson et al. 2004) which was conducted nearly 17 years prior to the present study and was considered relatively high due to fraction catalytic converters of the Swedish fleet being lower than those in the USA at the time. The after-treatment system included in the current fleet of vehicles in Iran is the three-way catalytic converter that creates a condition in which the main exhaust emissions of CO, unburned hydrocarbons (HC), and NO$_X$ are treated into the products of complete combustion (i.e., CO$_2$ and H$_2$O). Since 2002, the use of catalytic converters has become mandatory for vehicles manufactured in Iran. The life expectancy of a three-way catalytic converter is considered 80,000 km (Moldovan et al. 2002) which on average is about the lifetime of your average passenger vehicle but as already pointed out, the life expectancy of vehicles in Iran is longer than that of developed countries and replacement of the original converter with an aftermarket converter is required at some point. It should be mentioned that a 5-year project aiming at replacing the catalytic converters of Tehran taxicabs has recently started. The initial phase of the project was carried out for 5000 taxi units (out of the total 19,000 units) with 200,000 km mileage with the results showing a significant decline in the emissions of each pollutant, namely a 93.7% reduction in the CO emissions (Esteghamat et al. 2016). The SO$_2$ EF in this study revealed to be much higher than the results from Hsuehshan Tunnel (Chang et al. 2009) and Chang-Liao Tunnel studies (Hung-Lung et al. 2007) that were 3 ± 2–6 ± 3 and 2 ± 1 mg km^{-1}, respectively. Both of these studies were carried out between 2005 and 2006 in road tunnels located in Taiwan for fleets dominated by light-duty vehicles. As listed in Table 3, the SO$_2$ emissions in all of the

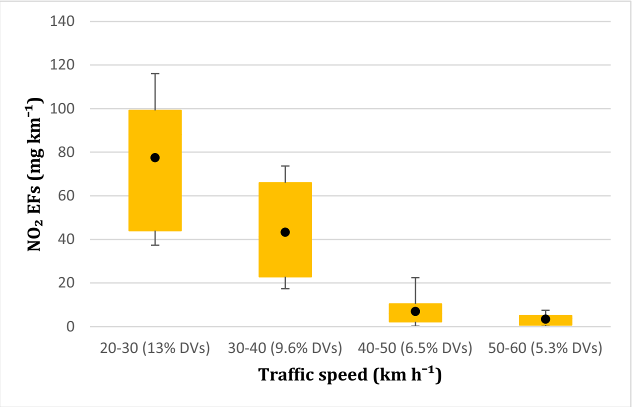

Fig. 13 Distribution of NO$_2$ EFs under different speed intervals

Table 3 Comparison of EFs from different studies around the world

Tunnel	Location	Year of the measurement campaign	Traffic speed (km h^{-1})	EF (mg km^{-1})			The composition of the vehicle fleet
				CO	SO_2	NO_2	
Resalat	Tehran, Iran	2016[a]	20–60	(6.59 ± 2.69)E+3	(1.42 ± 0.84)E+2	6.80 ± 4.99	89–95% NDVs
Zhujiang	Guangzhou, China	2014	20–47	(3.09 ± 0.68)E+3	(2.1 ± 0.3)E+1	–	61% LDVs
Yingpan	Changsha, China	2013	30	1.72E+3	–	–	97.3% LDVs
East Yan'an	Shanghai, China	2012	25–40	(1.36 ± 0.82)E+3[b]	–	–	91.6–95% gasoline
		2012	25–40	(3.97 ± 2.19)E+3[c]			91.6–95% gasoline
Grand Mare	Rouen, France	2007	≤ 70	–	3.2 ± 2.1	(2.63 ± 1.15)E+2	88% LDVs
		2009	≤ 70	–	(1.16 ± 0.84)E+1	(5.89 ± 2.89)E+2	88% LDVs
Hsuehshan	Taipei, Taiwan	2006	30–70	(9.09 ± 4.69)E+2	3 ± 2[b]	–	LDVs
		2006	30–70	(1.46 ± 0.63)E+3	6 ± 3[c]	–	LDVs
Chang-Liao	Southern Taiwan	2005	110	(6.59 ± 2.69)E+3	2 ± 1	–	90.5% LDVs
Shing Mun	Hong Kong, China	2003/2004	60–70	(6.59 ± 2.69)E+3	–	–	30–80% diesel
Salim Slam	Beirut, Lebanon	1999	40	1.12E+4	5.60E+1	1.68E+2	96% gasoline
Solderled	Stockholm, Sweden	1998/1999	70–90	(5.27 ± 0.1)E+3	–	–	95% LDVs
Tuscara	Pennsylvania, USA	1992	95	3.60E+3	–	–	6–88% HDVs

[a] Current study

[b] Downslope

[c] Upslope

Table 4 EFs from different tunnel studies in Tehran

Pollutant	Niayesh Tunnel—October 2016 (mg km^{-1})	Resalat Tunnel—present study (mg km^{-1})	Resalat Tunnel–February and May 2012 (mg km^{-1})[a]
CO	(5.95 ± 2.45)E+3	(6.59 ± 2.70)E+3	3.71E+3–1.24E+4
SO_2	(1.82 ± 0.88)E+2	(1.42 ± 0.84)E+2	–
NO_2	4.85 ± 3.50	6.80 ± 4.99	–

[a] The study was carried out by Yazdi et al. (2015)

tunnel studies are lower than those of 1.42E+2 mg km^{-1} in the present study. Aside from the present study, the highest SO_2 EF is that of 5.6E+1 mg km^{-1} Salim Slam Tunnel (El-Fadel and Hashisho 2000) which was implied to be low enough since the Lebanese fuel contained low sulfur content. Unfortunately, we have so far been unable to obtain the actual gasoline analysis results of more recently analyzed samples. However, previous attempts by Tehran Air Quality Control Company in analyzing gasoline samples from 5 gas stations in capital Tehran provide some insight into the quality of gasoline in terms of sulfur content. The most recently analyzed samples that were collected between June and November 2018 for the most commonly consumed moderate fuel ranged from about 50 to 200 ppm of sulfur content. These are above the required 10 and 50 ppm of euro-5 and euro-4 standards, respectively. This supports the presumption that we initially had, that is, the relatively high level of sulfur which points out that high vehicular emissions of SO_2 in Iran are highly associated with the unregulated level of sulfur contained in the gasoline that is being consumed in the country. This was also pointed out in Shahbazi et al. (2016) that the moderate type of fuel which is consumed in Tehran has a sulfur content of 300 ppm, exactly 6 times more than the regulated 50 ppm of the clean fuel (i.e., euro-4 requirement). The mean NO_2 EF of 6.81 mg km^{-1} in the present study is lower than that of 1.68E+2 mg km^{-1} in Salim Slam Tunnel (El-Fadel and Hashisho 2000). Even higher EFs for NO_2 were obtained during summer 2007 and winter 2009 that were 2.63E+2 and 5.89E+2 mg km^{-1}, respectively, for a fleet with an average 12% presence of heavy-duty vehicles (Ameur-Bouddabbous et al. 2012).

EFs from other tunnel studies in Tehran

The results of two separate tunnel studies in Tehran, as well as the current study, are presented in Table 4.

The EFs in Niayesh Tunnel were determined through a method similar to that in the present study. The following should be taken into consideration when reviewing the results from Niayesh Tunnel study:

- Niayesh Tunnel study was conducted over a 10-day period from October 8 to October 17, 2016, during evening peak hours of each day.
- Only light-duty vehicles are allowed to traverse the approximately 3-km Niayesh Tunnel; therefore, the results are reflective of emissions from the said type of vehicle.
- Except on one occasion during a weekend, the ventilation system was in operation throughout the entire measurement campaign in Niayesh Tunnel, with average in-tunnel wind speed varying within 1.8–4.5 m s^{-1} range.

The results from the present study and Niayesh Tunnel study are very close to one another, confirming the relatively high CO and SO_2 emissions of the current Tehran fleet. The study that was previously conducted in Resalat Tunnel in 2012 (Yazdi et al. 2015) estimated CO EFs to be in the range of 3.71E+3–1.24E+4 mg km^{-1} which is not very different from that of the current results. This though is not to dismiss the improvements in emission control policies as both fuel quality and vehicle-related aspects (i.e., vehicle emission standards and vehicle inspection services) have since improved. A notable difference between the present study and the previous Resalat Tunnel study is the methodology of measurements and data gathering. The previous study was conducted through a series of separate campaigns between February and May 2012 using floating machine method while the present study was conducted through intense measurements during the opening week of schools when the urban vehicular traffic is at its highest.

Conclusion

In this study, we estimated emission factors for three gaseous pollutants in Resalat Tunnel in Tehran. Real-world emissions for CO, SO_2, and NO_2 were for the first time studied for Iranian fleet through stationed measurements in an urban tunnel. The following are the more important points obtained through this study:

- CO and SO_2 concentrations increased rapidly along the tunnel, reaching higher levels of about 67,900 and 736 ppb, respectively, near the tunnel exit before being reduced meters down the exit portal while NO_2 that also reached a high level of about 229 ppb increased, even more, passed the tunnel exit portal which has to be taken into consideration as members of tunnel service patrol are regularly stationed just next to the exit portal.

- The CO emission factor of (6.59 ± 2.70)E+3 mg km^{-1} compared well to those of other tunnel studies while SO_2 emission factor of (1.42 ± 0.84)E+2 mg km^{-1} without deposition and (1.58 ± 0.88)E+2 mg km^{-1} with deposition effect included and NO_2 emission factor of 6.80 ± 4.99 mg km^{-1} were respectively higher and lower than those measured in other countries.
- CO and NO_2 EFs were influenced by the traffic speed as these EFs revealed a decreasing trend when the traffic speed increased within a speed range of 20–60 km h^{-1} for a road incline grade of 2.7% and NO_2 emissions reduced more drastically under a lighter presence of diesel-fueled vehicles which further highlights the direct association of NO_2 emissions and diesel-fueled vehicles.
- Diurnal variations of CO and SO_2 followed a similar trend which indicates that unlike NO_2, the two pollutants are likely to be associated with the same source of emissions, that is, gasoline-fueled vehicles, while the increase in the NO_2 emissions around the 12:00–14:00 and 16:00–18:00 periods during which the presence of diesel-fueled vehicles was more frequent shows the direct relationship between the two.
- The results indicated that the tunnel ventilation system has certain effects on both the concentration of pollutants and calculation process of EFs; these include the reduction of concentration levels and the increase of in-tunnel wind speed which in this case resulted in an overestimation of EFs; so much so that excluding the EFs of the periods when the tunnel ventilation was in operation resulted in a reduction of about 41%, 48%, and 58% for CO, SO_2, and NO_2 overall EFs, respectively; however, a precise extent of these effects remains to be determined in future works.
- Conducting the measurements in another urban tunnel through the same method resulted in similar estimated emission factor values of (5.95 ± 2.45)E+3, (1.82 ± 0.88)E+2, and 4.85 ± 3.50 mg km^{-1} for CO, SO_2, and NO_2 which shows that despite the differences in tunnel layout and operating and traffic conditions, as long as the vehicle fleet is the same, the results should not deviate from within a common range. This signifies that the method of tunnel studies is a reliable means of estimating real-world traffic emissions.

The high vehicular emissions in the present study, especially for SO_2, should be of high concerns as it is widely believed to be associated with the quality of gasoline that is consumed in Iran. These also confirm that the vehicular emissions available in databases and literature that are specific to certain cases in certain countries should not necessarily be applied to others, especially in the case of developing countries. It should also be considered that power plants and factories, as well as the presence of DVs, highly contribute to air pollution in the capital but which is the highest contributor of air pollutants is not the concern of the current study since we can only reflect on the results of vehicular emissions for a fleet that was mainly composed of gasoline-fueled vehicles. Besides the fuel quality that in itself requires the implementation of more stringent emission standards and development of vehicles that are compatible with higher fuel quality, other factors including regularity of vehicle inspections and replacement of overage vehicles should as well be taken into account.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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