Environmental Science and Pollution Research (2023) 30:80655–80675
https://doi.org/10.1007/s11356-023-27883-5

RESEARCH ARTICLE

Modeling fuel consumption and emissions by taxis in Tabriz, Iran: uncertainty and sensitivity analyses

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Received: 9 January 2023 / Accepted: 19 May 2023 / Published online: 10 June 2023

Abstract

Taxis pose a higher threat to global climate change and human health through air emissions. However, the evidence on this topic is scarce, especially, in developing countries. Therefore, this study conducted estimation of fuel consumption (FC) and emission inventories on Tabriz taxi fleet (TTF), Iran. A structured questionnaire to obtain operational data of TTF, municipality organizations, and literature review were used as data sources. Then modeling was used to estimate fuel consumption ratio (FCR), emission factors (EFs), annual FC, and emissions of TTF using uncertainty analysis. Also, the impact of COVID-19 pandemic period was considered on the studied parameters. The results showed that TTF have high FCRs of 18.68 L/100 km (95% CI=17.67–19.69 L/100 km), which are not affected by age or mileage of taxis, significantly. The estimated EFs for TTF are higher than Euro standards, but the differences are not significant. However, it is critical as can be an indication of inefficiency of periodic regulatory technical inspection tests for TTF. COVID-19 pandemic caused significant decrease in annual total FC and emissions (9.03–15.6%), but significant increase in EFs of per-passenger-kilometer traveled (47.9–57.3%). Annual vehicle-kilometer-traveled by TTF and the estimated EFs for gasoline-compressed natural gas bi-fueled TTF are the main influential parameters in the variability of annual FC and emission levels. More studies on sustainable FC and emissions mitigation strategies are needed for TTF.

Keywords Taxi · Transportation · Air pollutant · COVID-19 · Emission · Fuel consumption · Greenhouse gas

Introduction

Fossil fuel-based road transportation have a significant contribution to the greenhouse gases (GHGs) emissions and urban air pollution, leading to negative effects on the global climate, ecosystem, and human health (Goel et al. 2015). It has been reported that carbon monoxide (CO) and hydrocarbon (HC) emissions are five times higher for light-duty passenger vehicles (LDPVs) aged more than 15 years old compared to those less than 5 years old. Also, almost 20% of the LDPVs are high emitters and responsible for almost half of CO, HC, and nitric oxide (NO) emissions (Hassani et al. 2021). Taxis are believed to have higher accumulated vehicle kilometers traveled (VKT) and more fuel consumption than the typical LDPVs. This raises serious concerns over the likelihood of taxis having higher harmful emissions than new LDPVs because they do not maintain their new vehicle emission levels (Bishop et al. 2016). Therefore, it is crucial to monitor the emissions from vehicles, especially urban taxis, and compare them with the existing standards.

Responsible Editor: Philippe Garrigues

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Iran is the eighteenth highest GHG emitter in the world (World Bank 2022) and transportation is responsible for almost 25% of the emitted GHGs (ISC 2020). Iran adopted Euro 2/II emission standards for light, heavy, and semi-heavy vehicles in 2010. According to the schedule, these vehicles had to meet the Euro 4/IV standards from 2012 to 2014 (IIPRC 2005). Then, from March 2019 to March 2022, they had to meet the Euro 5/V standards, and from March 2022 onwards, the up-to-date European emission standards must be followed (IIPRC 2018). The implementation of these scheduled guidelines was not successful and was delayed due to issues such as outdated vehicles manufacturing technologies and lack of fuel in accordance with the respective Euro standards. For example, the implementation of the Euro 3 emission standard was generally cancelled; or taxis with Euro 4 and Euro 5 emission standards were added to the fleet in 2015 and 2021, respectively. This means that practical implementation of the emission standards in Iran is way behind the developed countries. For example, in 2020 around 65% of urban taxis in Tabriz, the largest economic hub and city in northwest Iran and target city of the present study, were certified as Euro 2. This calls for special attention regarding their emissions. On the other hand, unlike the USA and European countries with public accessible reference databases for emission factors (EFs), the data on vehicle emission levels in Iran is very limited. There were some studies in Iran undertaking on-road measurement (Bagheri et al. 2016, Banitalebi &Hosseini 2016, Ghaffarpasand et al. 2020), adapting International Vehicle Emissions (IVE) model (Ghadiri et al. 2017; Jamshidi Kalajahi et al. 2020; Khazini et al. 2019; Moeinaddini and Ali-Taleshi 2019; Shahbazi et al. 2016), or both methods (Pouresmaeili et al. 2018), trying to provide estimates on air pollutants and GHG emissions by vehicles.

Among the aforementioned investigations, the studies by Banitalebi and Hosseini (2016) and Bagheri et al. (2016) were the most comprehensive, but their reported fuel consumption ratios (FCRs)—fuel consumption per 100 km—and EFs for Tehran cannot reflect the precise vehicle FC and emission levels in Iran because limited speeds and slopes were considered. Therefore, there is a need for more investigations on FCR and EF inventories (EFIs) of transportation in Iran. Studies on FCR and EFs of taxis in Iran are even scarcer. Jamshidi Kalajahi et al. (2020) reported EFs of air pollutants for taxis in only one street in Tabriz using the IVE model—which is designed to estimate the emissions from motor vehicles and is recommended for developing countries. But considering the results by Bagheri et al. (2016) that used on-road measurements and reported high values for EFs of taxis compared to typical LDPVs, this model might not be a good choice for taxis in Iran.

Since there are problems with equipment availability and due to high cost of direct measurement, the present study did not use on-road measurement for estimating FCR and VKT-EFs of Tabriz taxi fleet (TTF). Besides, considering that modeling tools are mostly validated for cars with different technologies in developed countries than those in Iran—especially for taxis—the present study did not estimate the FCR and VKT-EFs of TTF by the available modeling tools. Instead, field investigations along with the results of other relevant studies were used to obtain almost real-time measurement data.

The present study was conducted in 2020 and 2021, during which mobility restrictions were adopted due to COVID-19 pandemic. This caused a sharp reduction in transportation demand, especially public transportation (Sui et al. 2020). Therefore, comparing energy consumption by average VKT-EFs can misinform decision-makers and it is unable to represent the marginal impact of changing consumption (Bigazzi 2019). For this reason, the present study also investigated the marginal FCRs and EFs, which are typically presented by FCR or EFs per passenger trip or per-passenger-kilometer-traveled (per-PKT) to give decision makers a clearer picture of marginal changes in FC and emission levels during COVID-19.

When a comparative EFI is performed with the aim of identifying which fuel or vehicle has higher emissions, understanding the variations in the results is important. Besides, when an attributional EFI is carried out, sensitivity analysis could determine which parameters need further investigation to improve model accuracy or which insensitive parameters can be fixed, or to identify areas of improvement with the greatest impact on the model output. Therefore, uncertainty and sensitivity analyses play important roles in modeling of FC and EFI of transportation (Di Lullo et al. 2020).

Various methods are available to evaluate the model output uncertainty and quantify the importance of the input factors. The selection of the appropriate method is a function of the system's uncertainty and the stakes involved. The present study used global sensitivity analysis methods involving multiple evaluations of the model where the input factors are selected according to specific sampling strategies. Here, variance-based techniques have been adopted that explore the whole range of variation of the input factors and consider the interaction effects (Kouridis et al. 2010).

On the basis of what has been mentioned, thus far, this paper presents the results of a study on the calculation of the uncertainty of TTF's road transport inventories. It introduces a methodology for cities in developing countries with lack of access or limited access to the real driving measurement tools. Thus, it contributes to establishing a model for estimating air pollutants and GHG emissions for LDVs, such as taxis in cities.

The present study was designed to test the following hypotheses: (1) Age of a taxi in Tabriz has a significant impact on its fuel consumption, (2) a significant correlation exists between the total mileage of Tabriz taxis and the amount of fuel they consume, (3) fuel consumptions by Tabriz taxis in warm and cold seasons are significantly different, (4) a significant difference exists between fuel consumption by Tabriz taxis in 2019 and 2020, (5) a significant difference exists between per-PKT-EFs by Tabriz taxis in 2019 and 2020, (6) the emission factors for air pollutants (CO, HC, and NO_X) by Tabriz taxis are higher than the respective Euro emission standards, and (7) overall emissions by Tabriz taxis in 2020 are significantly lower compared to those in 2019.

To the authors' best knowledge, this study is the first effort exploring FCRs of TTF along with their average VKT-EFs (from now on addressed as FCR and EFs), per-PKT-FCRs and per-PKT-EFs, and annual total FC and emissions considering the impact of COVID-19 pandemic on them and applying uncertainty and sensitivity analyses. Its results will provide policymakers with insights to design control strategies.

Methods

Activity data and EFs are the two main components in conducting an emission inventory. To achieve the aims and test the hypotheses, the present study took different steps. First, to obtain activity data, it used different data sources including (1) a structured questionnaire to gather operational data of TTF from taxi drivers, (2) municipal organizations in Tabriz, and (3) literature review. Modeling was then used to combine the results of the field study with the results of other relevant studies and the data sources to obtain almost real-time measurement data on FCR and EFs of TTF. These steps and more are explained in the following subsections.

Activity data collection

TTF: performance and numbers

Tabriz is the capital of East Azerbaijan province, the sixth most populated city in Iran, and located in the northwest of Iran (Fig. 1(a)). The central municipal area covers 244.53 km^2 with a population of 1.64 million in 2022. Taxis in Iran, including Tabriz, are considered semi-public transportation vehicles, and are often shared by more than one passenger on a particular route. Tabriz reached its urban taxi capacity limit in 2009, meaning there was no demand for any extra taxis in Tabriz, and after that, new taxis have been introduced to replace worn-out ones (TTO 2020).

The common taxis in Tabriz are provided with 5 seats (including the driver). The present study surveyed the operational characteristics of taxis in Tabriz in 2020, when 10,324 were in operation. A total of 10,124 of which were bi-fueled (9494 gasoline-compressed natural gas (G-CNG) and 630 gasoline-liquid petroleum gas (G-LPG) fueled) and 118 gasoline-fueled taxis. Besides, almost 58% of TTF were Euro 2 G-CNG bi-fueled taxis. All G-LPG bi-fueled TTF and 60% of gasoline fueled TTF were Euro 2, and the rest were Euro 4 certified (TTO 2020).

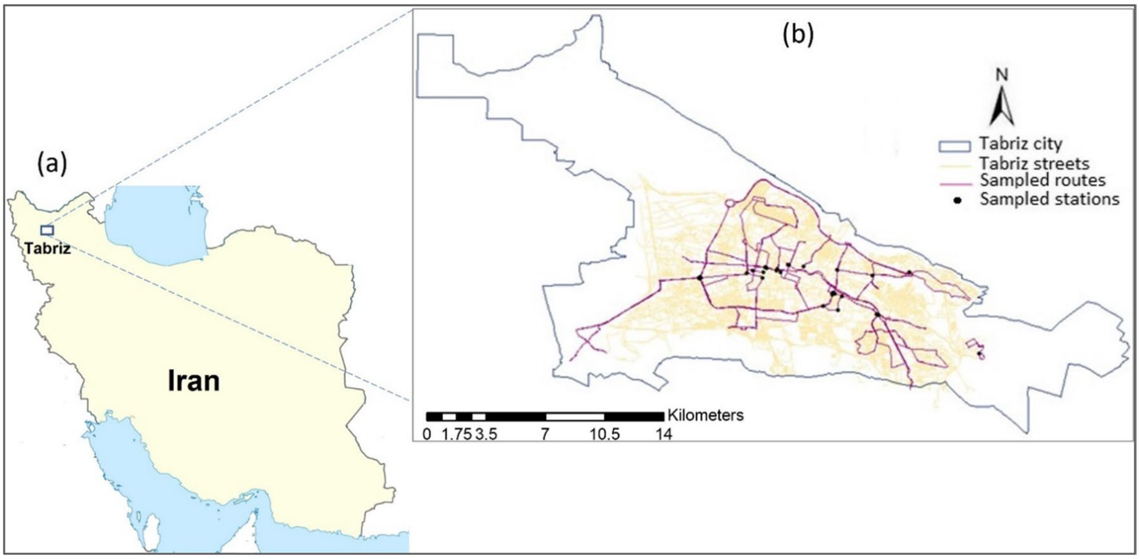


Fig. 1 **a** Tabriz on Iran map, and **b** routes and stations that samples of TTF were taken from

Field data collection

At first, a pilot study was conducted to determine the required sample size for estimating the FCR by TTF with interviewing 30 taxi drivers at five taxi stations in October 2020. Since Tabriz taxis are mostly G-CNG or G-LPG bi-fueled vehicles, to estimate the total daily gasoline-equivalent FC, the daily CNG and LPG consumptions were converted to the equivalent gasoline consumption (the details for this conversion will be elaborated in sub-section "Equivalent CO_2").

From the pilot study, the standard deviation of 6.0 was obtained for the FCR (L/100 km). Then, by employing the *t*-distribution with 95% confidence level and precision of 1.0, a sample size of 142 was obtained. The samples were randomly obtained from the TTF population to determine the mean (*M*) FCR for TTF. Using this sample size, there is a 95% probability that the mean FCR in the population lies somewhere between $M\pm1.0$ (Dhand and Khatkar 2014). Then, for the main survey, taxi drivers were interviewed using a structured questionnaire developed by the research team. The interviews were conducted at 38 taxi stations and 38 routes around the city (see Fig. 1(b)). Locations included a commercial district in the downtown of Tabriz (hosting stations for 11 routes to different districts in the city), five major traffic intersections (hosting stations for 22 routes), and five important intersections next to universities, hospitals, and promenades (hosting stations for 5 routes). These locations are all transportation hubs that are well-served by taxis; therefore, obtaining a representative sample from the overall TTF population is most likely.

During the main study period, only taxis drivers that were available at the time of the visit and volunteered to cooperate with the research team were included in the study. For this purpose, a structured data collection form was used (see Supplementary Information, Table S1). During the sampling period, samples were tried to be proportionate with the type and age of the TTF population. This led to a total sample size of 153. The characteristics of the samples are summarized in Table S2.

Since the use of public transportation was limited in 2020 due to the COVID-19 pandemic, in order to estimate the normal fuel consumption and emissions by TTF, drivers were also asked questions about the average VKT, the number of round trips, and average daily passengers before the pandemic (in 2019).

Estimation of fuel consumption by TTF

As mentioned in the sub-section "Estimation of hot running (HR) gaseous air pollutants and GHG emission factors for TTF," to estimate the total daily gasoline-equivalent FC (FC_{eq}), the daily CNG or LPG consumptions by TTF were converted to equivalent gasoline consumption using their net thermal values and then the resulted FC value was summed up with the daily gasoline consumption (see Eq. (1)).

$$FC_{eq} = FC_{CNG\ or\ LPG} \times \frac{NTV_{CNG\ or\ LPG}}{NTV_{gasoline}} + FC_{gasoline} \tag{1}$$

where, FC_{eq} is the total daily gasoline-equivalent FC volume (liter (L)) of the TTF; $FC_{CNG\ or\ LPG}$ is the daily volume of CNG (m^3) or LPG (L) consumption, $NTV_{CNG\ or\ LPG}$ is the net thermal value of CNG or LPG (34.89 Mj/m^3 for CNG or 46.49 Mj/L for LPG), $NTV_{gasoline}$ is the net thermal value of gasoline (33.10 Mj/L), and $FC_{gasoline}$ is the daily volume of gasoline consumption (L). Finally, FC_{eq} was divided by *daily VKT* (km) to estimate the total gasoline-equivalent FC ratio (*FCR*) (L/km) (see Eq. (2)).

$$FCR = \frac{FC_{eq}}{Daily\ VKT} \tag{2}$$

Modeling

Estimation of hot running (HR) gaseous air pollutants and GHG emission factors for TTF

Since the present study could not find any studies reporting hot running EFs (HR-EFs) for Tabriz taxis, HR-FCRs, and distance-based HR-EFs of gaseous air pollutants (from now on referred to as pollutants and include CO, HC, and NO_X) and GHGs (CO_2, CH_4, and N_2O) for TTF were estimated by combining the findings of following studies. Bagheri et al. (2016) had a real-road study on the models of taxis similar to the ones in the present study at limited slopes and speeds without reporting any HR-FCRs and HR-EFs in each slope/speed category. Banitalebi and Hosseini (2016) also used the same methods on the similar routes and speeds reported by Bagheri et al. (2016) but for LDPVs and indicating the HR-FCRs and HR-EFs in each slope/speed category. Also, both studies were mostly conducted in highways, making them unsuitable for operational conditions of TTF. Therefore, the results of another study by Park and Rakha (2006), which reported FCRs and EFs in various slopes and speeds, were also applied to determine the HR-FCRs, and HR-EFs for LDPVs in various slopes and speeds of Tabriz. The step-by-step procedure for the estimation of HR-FCR and EFs was explained below:

1. Slopes of the sampled routes were obtained using Google Earth Pro. Then, they were categorized as routes with positive (equal or above 1%), negative (equal or below −1%), and flat (between −1 and 1%) slopes. The portions of urban routes with positive, negative, and flat slopes from total sampled routes were 23.13%, 23.08%,

and 48.38%, respectively, while the portions of both positive and negative slopes of highways were 2.7%.

2. Average speeds in urban routes (20 km/h) and highways (47 km/h) of Tabriz were obtained from Balad (2020) and Khazini et al. (2019), respectively.
3. The HR-FCR and HR-EFs reported by Banitalebi and Hosseini (2016) for Euro 2 LDPVs at different slopes/speeds were used as the real-life rates for estimating the HR-FCR and HR-EFs in Tabriz.
4. The HR-FCR and HR-EFs at the desired slopes were obtained from the relevant models extracted from the study by Park and Rakha (2006).
5. Step by step HR-FCR and HR-EFs were calculated for the required slope/speed categories of Tabriz using Eqs. (3) to (7) in Table 1.

Final HR-FCR (L/km) and HR-EFs (g/km of pollutants or CO_2) for Euro 2 LDPVs in Tabriz (T_i) were estimated using Eq. (8) by considering the fractions of involved routes (urban/highway) at different slope categories (positive, flat, and negative):

Table 1 Equations to estimate the HR-FCR (L/km), or HR-EFs of pollutants or CO_2 (g/km) for the categorized speeds and slopes in Tabriz

Route	Slope	Eq.	no.	Parameters
Urban	Positive	$TPSU_i = \frac{a_i \times b_i}{c_i} \times C_1$	(3)	• $TPSU_i$: the HR-FCR (L/km), or HR-EFs of pollutants or CO_2 (g/km) at the positive slopes of Tabriz urban routes (TURs)- i is FC, HC, CO, NOx, or CO_2 emissions • a_i : the HR-FCR (L/km), or HR-EFs of pollutants or CO_2 (g/km) at 7.62% slope and speed of 12 km/h in the Banitalebi and Hosseini (2016) study • b_i = the HR-FCR (L/km), or HR-EFs of pollutants or CO_2 (g/km) at the positive slopes and speeds of TURs, extracted from the Park and Rakha (2006) study • c_i: the HR-FCR (L/km), or HR-EFs of pollutants or CO_2 (g/km) at 7.62% slope and speed of 12 km/h in the Park and Rakha (2006) study • C_1: the correction factor according to the HR-FCR (L/km), or HR-EFs of pollutants or CO_2 (g/km) for positive slopes
	Flat	$TFSU_i = \frac{d_i \times e_i}{f_i} \times C_2$	(4)	• $TFSU_i$: the HR-FCR (L/km), HR-EFs of pollutants or CO_2 (g/km) at the flat slopes of TURs • d_i: the HR-FCR(L/km), or HR-EFs of pollutants or CO_2 (g/km) at 0.12% slope and speed of 23 km/h in the Banitalebi and Hosseini (2016) study • e_i: the HR-FCR(L/km), or HR-EFs of pollutants or CO_2 (g/km) at the flat slopes and speeds of TURs, extracted from the Park and Rakha (2006) study • f_i: the HR-FCR(L/km), or HR-EFs of pollutants or CO_2 emissions(g/km) at 0.12% slope and speed of 23 km/h in the Park and Rakha (2006) study • C_1: the correction factor according to the HR-FCR (L/km), or HR-EFs of pollutants or CO_2 (g/km) for flat slopes
	Negative	$TNSU_i = \frac{TFSU_i \times g_i}{e_i} \times C_3$	(5)	• $TNSU_i$: the HR-FCR (L/km), or HR-EFs of pollutants or CO_2 (g/km) at the negative slopes of TURs • g_i: the HR-FCR (L/km), or HR-EFs of pollutants or CO_2 (g/km) at the negative slopes and speeds of TURs, extracted from the Park and Rakha (2006) study • C_3: the correction factor according to the HR-FCR (L/km), or HR-EFs of pollutants or CO_2 (g/km) for negative slopes
Highway	Positive	$TPSH_i = \frac{h_i \times j_i}{k_i} \times C_4$	(6)	• $TPSH_i$: the HR-FCR (L/km), or HR-EFs of pollutants or CO_2 (g/km) at the positive slopes of Tabriz highway routes (THRs) • h_i: the HR-FCR (L/km), or HR-EFs of pollutants or CO_2 (g/km) at 4.31% slope and speed of 68 km/h in the Banitalebi and Hosseini (2016) study • j_i: the HR-FCR (L/km), or HR-EFs of pollutants or CO_2 (g/km) at the positive slopes and speeds of THRs, extracted from the Park and Rakha (2006) study • k_i: the HR-FCR (L/km), or HR-EFs of pollutants or CO_2 (g/km) at 4.31% slope and speed of 68 km/h in the Park and Rakha (2006) study • C_4: the correction factor according to the HR-FCR (L/km), or HR-EFs of pollutants or CO_2 (g/km) for positive slopes in highway routes
	Negative	$TNSH_i = \frac{TPSH_i \times l_i}{k_i} \times C_5$	(7)	• $TNSH_i$: the HR-FCR (L/km), or HR-EFs of pollutants or CO_2 (g/km) at the negative slopes of THRs • l_i: the HR-FCR (L/km), or HR-EFs of pollutants or CO_2 (g/km) at the negative slopes and speeds of THRs, extracted from Park and Rakha (2006) study. • k_i: the HR-FCR (L/km), or HR-EFs of pollutants or CO_2 (g/km) at 4.31% slope and speed of 68 km/h in the Park and Rakha (2006) study. • C_5: the correction factor according to the HR-FCR (L/km), or HR-EFs of pollutants or CO_2 (g/km) for negative slopes in highway routes

$$T_i = 0.231 \times TPSU_i + 0.484 \times TFSU_i + 0.231 \times TNSU_i + 0.027 \times TPSH_i + 0.027 \times TNSH_i \tag{8}$$

6. The results of the previous step for Tabriz were divided by their relevant values for Tehran, Iran, reported by Banitalebi and Hosseini (2016), to find out the correction factors of HR-FCRs and HR-EFs. Then, the results were multiplied by their relevant values reported by Bagheri et al. (2016) for taxis. In this case, the HR-FCR and HR-EFs for each TTF would be estimated as Eq. (9):

$$TT_{i,t} = \frac{T_i}{m_i} \times n_{i,t} \tag{9}$$

Where,

$TT_{i,\,t}$	HR-FCR (L/km), or HR-EFs of pollutants or CO_2 (g/km) for TTF;
m_i	HR-FC (L/km), or HR-EFs of pollutants or CO_2 (g/km) reported by Banitalebi and Hosseini (2016) for Euro 2 LDPVs;
$n_{i,\,t}$	HR-FC (L/km), or HR-EFs of pollutants or CO_2 (g/km) reported by Bagheri et al. (2016) for taxis

Note: $n_{i,\,t}$ in the Supplementary information was numbered 1 to 7, regarding the model (Euro 2 or Euro 4) and the fuel (gasoline, CNG, or LPG). Therefore, Eq. (9) gives the HR-FCR (L/km), or HR-EFs of pollutants or CO_2 (g/km) for TTF based on their model and fuel.

Note: since HR-EFs of CH_4 and N_2O were not reported by any of the aforementioned studies, the present study used the method suggested by the Intergovernmental Panel on Climate Change (IPCC) to estimate HR-EFs of CH_4 and N_2O. Therefore, CH_4 to HC ratio of 10–25% for 4-stroke gasoline vehicles, 88.0–95.2% for natural gas, and 29.6% for LPG-fueled vehicles were applied to develop EF of CH_4 from HC data. According to IPCC, N_2O/NO_X ratios for light motor vehicles and passenger cars range from 0.1 to 0.25, which was applied to estimate EF of N_2O (Waldron et al. 2019).

Annual distance traveled by each taxi (annual VKT) was estimated based on the results of the current field study. The ratio of distance traveled by each fuel to the total distance traveled by a taxi was assumed to be equal to the ratio of consumption of that fuel to the total FC_{eq}. Therefore, the emission factor for each model and fuel from Eq. 9 was multiplied by the ratio of distance traveled by the fuel of interest. The average annual FC_{eq}, pollutants, or GHG emissions of TTF were estimated using Eq. (10).

$$O_{i,t} = \sum \left(TT_{i,t} \times AVKT \times R_F \right) \times N \times 10^{-6} \tag{10}$$

Where, $O_{i,\,t}$: annual FC_{eq} (ML), pollutants or GHG emissions (ton) by TTF of kind (Euro 2 or Euro 4); $AVKT$: the average annual distance traveled by each taxi (km); R_F: the ratio of distance traveled by the fuel of interest (gasoline, CNG or LPG); N: the number of taxis of kind in Tabriz

The values and distributions for every parameter in Eqs. (3) to (10) are tabulated in Table S3.

Estimation of excess cold emissions

In light-duty gasoline vehicles equipped with three-way catalytic converters, depending on the ambient temperature and vehicle speed, it takes about 6 to 30 min to reach its thermal stability, during which partially or not controlled tailpipe air pollutants are emitted (André and Joumard 2005). This warming-up period is known as cold start, and the emissions during this period are called excess cold emissions (ECEs). In other words, ECEs are the extra emissions obtained under the cold running period compared to the emission value that could be recorded for the same period under hot running (see Figure S1) (André and Joumard 2005). ECEs consist of two parts: the first part is excess emissions due to the starting of the engine and the second part is excess emissions during the warming-up process of the engine and the catalyst (Favez et al. 2009). The following formula was used to estimate ECEs (André &Joumard 2005).

$$\text{ECEs (T, V, δ, t)} = \omega_{20^{\circ}\mathrm{C},20km/h} f(T,V).\left\{ \frac{1 - e^{a.\delta}}{1 - e^{a}} \right\}.g(t) \tag{11}$$

Where,

$ECEs$	excess emissions for a trip (g)
V	mean speed in km/h during the cold period
T	ambient temperature ($^{\circ}C$)
t	parking time (h)

$$\delta\ :\ \text{dimensionless travelled distance} = d/d_c(T,V) \tag{12}$$

d	traveled distance
$d_c(TV)$	cold distance
$\omega_{20^{\circ}C,\,20km/h}$	reference excess emission (at 20°C and 20 km/h)
$g(t)$	parking-time influence function

The average speed in the cold exhaust period was assumed to be equal to the average traffic speed in Tabriz (20 km/h). Daily temperatures for 2019 and 2020 were extracted from AccuWeather (2019 and 2020). To compare the ECEs in cold and warm days, it was assumed that days with temperatures of 15°C and below are cold, and days with temperatures above 15°C are warm. The average annual temperature of Tabriz was used to calculate the average annual ECEs by TTF. The values and formulas presented in Table 2 were used for the remaining parameters in Eq. (11) (André &Joumard 2005).

Daily ECEs for TTF would be categorized as ECEs at the beginning of a day (ECEs$_{(B.H.W)}$), ECEs after midday break (ECEs$_{(M.H.W)}$), and ECEs due to average parking times at the first and last stations (ECEs$_{(stations)}$). Therefore, ECEs categories were estimated separately and then summed up to obtain daily ECEs (Eq. (34)).

$$daily\ ECEs = ECEs_{(B.H.W)} + ECEs_{(M.H.W)} + ECEs_{(Staions)} \qquad (34)$$

To estimate ECEs$_{(B.H.W)}$ and ECEs$_{(M.H.W)}$, the average home-work distance (d$_{H.W}$) is needed, and estimation of ECEs$_{(stations)}$ requires the average length of each round trip (d$_{trip}$). Therefore, to estimate d$_{H.W}$, daily VKT and distance traveled on a route were used, and for the estimation of d$_{trip}$ the average daily distance traveled on the route and the average number of daily trips on the route were used. The estimated d$_{H.W}$ and d$_{trip}$ were used to calculate δ in Eq. (12) for the corresponding categorized ECEs.

In the next step, to estimate g(t) for calculation of ECEs$_{(B.H.W)}$ parking time was assumed to be an overnight stop of 10 h (600 min), and to estimate g(t) for calculation of ECEs$_{(M.H.W)}$ it was assumed to be a 2-h (120-min) midday break. To estimate g(t) for calculation of ECEs$_{(stations)}$, the average parking time at the first and last stations of the route was estimated as 6.54 ± 5.4 min and 12.54 ± 7.13 min in 2019 and 2020, respectively, using Eq. (35).

Table 2 Equations and values to calculate ECEs by TTF (André and Joumard 2005)

Gas	Parameter		Model			
			Euro 2	Eq.	Euro 4	Eq.
CO	ω20°C, 20 km/h		17.060	-*	4.875	-*
	dc (T, V)		$4.409 - 0.002 \times T + 0.024 \times V$	(13)	$6.716 - 0.06 \times T$	(14)
	f (T, V)		$1.927 - 0.043 \times T - 0.003 \times V$	(15)	$6.488 - 0.274 \times T$	(16)
	a		-9.007	-*	-5.544	-*
	g(t)	t≤(720)	$4.614 \times 10^{-3} \times t - 2.302 \times 10^{-6} \times t^2 - 2.966 \times 10^{-9} \times t^3$	(17)[†]	$614 \times 10^{-3} \times t - 2.302 \times 10^{-6} \times t^2 - 2.966 \times 10^{-9} \times t^3$	(17)[†]
		(t≥720)	1	-*	1	-*
CO_2	ω20°C,20km/h		133.839	-*	64.700	-*
	dc (T, V)		$4.048 - 0.124 \times T + 0.145 \times V$	(18)	$5.398 - 0.142 \times T$	(19)
	f (T, V)		$1.454 - 0.026 \times T + 0.004 \times V$	(20)	$2.597 - 0.08 \times T$	(21)
	a		-2.563	-*	-2.686	-*
	g(t)	(t≤20)	$0.1349 \times t - 2.915 \times 10^{-4} \times t$	(22)[†]	$0.1349 \times t - 2.915 \times 10^{-4} \times t$	(22)[†]
		(21≤t≤720)	$0.136 + 0.12 \times t$	(23)[†]	$0.136 + 0.12 \times t$	(23)[†]
		(t≥720)	1	-*	1	-*
HC	ω20°C, 20km/h		4.381	-*	0.244	-*
	dc (T, V)		$5.201 - 0.037 \times T + 0.065 \times V$	(24)	$6.97 - 0.16 \times T$	(25)
	f (T, V)		$1.597 - 0.014 \times T - 0.016 \times V$	(26)	$21.246 - 1.012 \times T$	(27)
	a		-10.209	-*	-11.898	-*
	g(t)	(t≤240)	$7.641 \times 10^{-3} \times t - 2.639 \times 10^{-5} \times t^2 + 3.128 \times 10^{-8} \times t^3$	(28)[†]	$7.641 \times 10^{-3} \times t - 2.639 \times 10^{-5} \times t^2 + 3.128 \times 10^{-8} \times t^3$	(28)[†]
		(241≤t≤720)	$0.625 + 5.208 \times 10^{-4} \times t$	(29)[†]	$0.625 + 5.208 \times 10^{-4} \times t$	(29)[†]
		(t≥720)	1	-*	1	-*
NO_x	ω20°C, 20km/h		0.705	-*	0.186	-*
	dc (T, V)		$-2.515 + 0.238 \times V$	(30)	4.523	-*
	f (T, V)		$0.406 + 0.03 \times V$	(31)	1	-*
	a		-3.765	-*	-0.432	-*
	g(t)	(t≤50 min)	$7.141 \times 10^{-3} \times t + 1.568 \times 10^{-3}\ t^2 - 3.204 \times 10^{-5} \times t^3 + 1.594 \times 10^{-7} \times t^4$	(32)[†]	$7.141 \times 10^{-3} \times t + 1.568 \times 10^{-3}\ t^2 - 3.204 \times 10^{-5} \times t^3 + 1.594 \times 10^{-7} \times t^4$	(32)[†]
		(51≤t≤720)	$1.290 - 4.030 \times 10^{-4} \times t$	(33)[†]	$1.290 - 4.030 \times 10^{-4} \times t$	(33)[†]
		(t≥720)	1	-*	1	-*

The parking time *t* is in min

*Constant values, without equations

[†] Can be applied for both Euro 2 and Euro 4 models

$$t_{station} = \frac{WT - daily\ VKT \times V}{60 \times (\mathrm{RT} \times 2)} \tag{35}$$

Where, $t_{station}$ is the parking time spent at a station (min); WT is the average daily working time of a taxi (600 min (TTO 2020)); V is the average traffic speed in Tabriz (20 km/h), which was divided by 60 to obtain the speed in km per minute; RT is the number of daily round trips, which was multiplied by 2 to obtain the number of parking times that cause ECEs$_{\mathrm{(stations)}}$ at the first and last stations of the route.

After calculating the total daily ECEs, it was multiplied by the number of workdays per year to calculate the annual ECEs (Eq. (36)). Table S4 summarizes the values and their distribution for each assumption in this sub-section.

$$\text{Annual ECEs} = \text{daily ECEs} \times \text{work days per year} \tag{36}$$

Note: Since the study by André and Joumard (2005) has not considered CH_4 and N_2O emissions, the present study assumed that 10–25% of ECE estimated for HC can be assigned to ECE of CH_4 (Waldron et al. 2019). As for N_2O, according to Li et al. (2009) and Li et al. (2010), it does not show any obvious peak during cold start period. Therefore, no ECE was estimated for N_2O.

Note: ECEs were calculated for gasoline only (usually hot and cold start and the process of heating the car is done by gasoline as the fuel); besides, the relevant formulas and coefficients are only for gasoline. It is worth mentioning that the hot running emissions (HREs) which were calculated by considering the HR-EFs for the whole route and the ECEs were added up to attain the total emissions.

Equivalent CO_2

The equivalent CO_2 (CO_2-eq) is calculated by taking into account the latest global warming potential (GWP) values for 100-year time horizon relative to CO_2 according to the fifth assessment report (AR5) by considering the contribution of the three species (CO_2: 1, CH_4: 28, N_2O: 260) (Myhre et al. 2013). Multiplying these values by the respective GHG emission from TTF gives their operational CO_2-eq (Eq. (37)).

$$CO_{2\text{-}}\mathrm{eq} = CO_2 + CH_4 \times (\mathrm{GWP}) + N_2O \times (\mathrm{GWP}) \tag{37}$$

Per-passenger kilometer travelled (PKT) emission factors

During the field study, taxi drivers were asked about the number of their daily passengers and round trips in 2019 and 2020, which were used to estimate per-PKT emissions. In the scope of this study, the per-PKT-EF is defined as Eq. (38):

$$E_{pkt} = EF_i / pass \tag{38}$$

where, E_{pkt} is the per-PKT emission factor for the i^{th} pollutant or GHG; EF_i is the emission factor for the i^{th} pollutant or GHG; and $pass$ is the average passenger occupancy of a taxi per trip (excluding the driver), which was calculated using Eq. (39).

$$\mathrm{pass} = \frac{\mathrm{DP}}{\mathrm{RT} \times 2} \tag{39}$$

where, DP is the average daily passengers, and RT is the number of daily round trips, which was multiplied by 2 to obtain the total number of daily trips.

Uncertainty and sensitivity analyses

Monte Carlo simulation was applied in all steps using R software version 4.1.0. Easyfit software was used to fit the distributions to input data and select the best model (normal distribution was preferred when it was ranked among the best fitting statistically significant distributions) (McMurray et al. 2017).

The uncertainty and sensitivity analyses were conducted for the input data (FCR and EFs, etc.). The sensitivity analysis was performed using a variance-based analysis technique, quantifying the importance of the influential inputs that drive the uncertainty of the TTF emissions. About 10^6 runs were conducted for the quantitative analysis, but those runs that resulted in output values lower than 0 were filtered. Using a filter may lead to a decreased but more realistic uncertainty. For HR-EFs of air pollutants, 95% confidence interval (95% CI) was reported; however, the final outputs for FC$_{\mathrm{eq}}$ and emissions were reported by considering a 99% CI.

Statistical analyses

The Kruskal-Wallis test was used to compare the total FCR of TTF with different car age groups (below 5, between 5 and 10, and above 10 years of age). Mann-Whitney *U* test was used to compare daily FC$_{\mathrm{eq}}$ in warm and cold seasons. Wilcoxon signed rank test was used to compare the results between years 2019 and 2020, to see the possible effects of the COVID-19 pandemic. Pearson correlation was conducted to see if there is any significant relationship between the total mileage of a taxi and the amount of fuel it consumes. 95% CI for HR-EFs of air pollutants were obtained from uncertainty analysis and were used to see if the difference between the estimated HR-EFs and the relevant standard limits is significant.

Results and discussion

FCR and EFs

Adopting Eqs. (3) to (9), HR-FCR and HR-EFs for pollutants and GHGs were estimated through modeling. Table S5 represents sensitivity indices from variance-based sensitivity analysis for HR-FCR and EFs of HC, CO, NO_X, and CO_2. The HR-FCR/EFs reported by Bagheri et al. (2016) influence the variability of the HR-FCR and all HR-EFs the most, especially for CO, HC, and NO_X. The HR-FCR reported by Banitalebi and Hosseini (2016) was the second influential factor in the estimated HR-FCR. Correlation value for NO_X is +0.2 that means weak correlation among the uncertainties of the parameters for this pollutant. Correlations for HR-FCR and other EFs show values below +0.11, which indicates a very weak correlation among their uncertainties.

Total FCR was estimated by field study and using Eq. (2). The total emissions were estimated by summing up HREs and ECEs. Table S6 tabulates the estimated HR-FCR and HR-EFs for pollutants and CO_2 at different routes and slopes of Tabriz for Euro 2 LDPVs. It also represents their correction factors to be used for TTF. It was assumed that the correction factors can be applied to all TTF with different fuels and Euro emission standards. Table 3 shows the HR-FCR and HR-EFs for TTF. According to the findings when G-LPG fueled TTF use gasoline, they have the highest FCR, NO_X, and N_2O, and when they use LPG, they have the highest EFs for HC. As for Euro 2 TTF, when they use gasoline, they have the highest EFs for CO, and when they use CNG, they have the highest EFs for CH_4. Euro 4 gasoline-fueled TTF have the highest EFs for CO_2 but lowest EFs for other gases.

FCR

Total FCRs and HR-FCRs were estimated using different methods. The total FCRs were estimated by field study (asking TTF's drivers) and HR-FCRs were estimated through modeling (see Table 3). To estimate the total FCRs, 153 taxi drivers were interviewed for the daily FC. Given that the gasoline price is higher than CNG, and drivers benefit from half-priced gasoline quota of 250 L per month since November 2019, it is possible that some of the drivers overreported their gasoline consumption to prevent a gasoline quota reduction. To overcome such bias, the extreme FC_{eq} values were determined using SPSS software version 27 and omitted from further analysis.

The combined HR-FCR for each model of taxi was calculated considering the HR-FCR reported in Table 3 and the fraction of distance traveled by each fuel for each model. Figure 2 represents the total FCR and combined HR-FCR for TTF. It is obvious that G-LPG bi-fueled TTF have the highest FCR. Moreover, bi-fueled TTF with Euro 4 emission standards have higher FCR than those with Euro 2 emission standards that could be due using low-tech engines.

The mean total FCR obtained from the field survey on TTF was 18.68 L/100km (95% CI=17.67–19.69 L/100km), meaning that the mean FCR in the TTF population lies somewhere between mean±1 L/100km, which confirms the assumption made in this study when determining the sample size (see sub-section "Estimation of hot running (HR) gaseous air pollutants and GHG emission factors for TTF").

The results of statistical analyses showed no significant difference among the total FCR calculated for TTF with different age groups (p=0.698). Also, no significant correlation was observed between the total mileage of TTF and FCR (p>0.05). One reason for these results could be the taxi drivers' practice regarding the maintenance and inspection procedures set for taxis, which may affect FCR. According to our findings, almost all of the interviewed taxi drivers followed the taxi's routine services in terms of changing vehicle's oils or filters, tire replacement, etc., and about 91% of them followed the schedule for periodic technical inspection (PTI) test.

Table 3 The HR-FCR (L/100km) and HR-EFs (g/km) for TTF

Model	Fuel type	FCR	CO	HC	NO_x	CO_2	CH_4	N_2O
E2	G1	16.19±4.00	20.71±12.92	1.046±1.116	4.467±3.369	333.69±87.93	0.184±0.195	0.782±0.589
	CNG1	16.82±4.01	12.97±8.97	1.312±0.629	4.765 ±3.679	270.65±71.79	1.198±0.574	0.832±0.641
	G2	30.56±6.39	20.69±12.90	1.045±1.117	7.582±6.371	332.00±87.82	0.184±0.195	1.327±1.111
	LPG	28.50±5.66	7.04±2.24	1.866±1.147	7.475±5.710	260.38±52.89	0.552±0.339	1.308±1.000
E4	G3	16.41±3.42	16.09 ±6.81	0.220±0.112	0.200±0.148	348.68±77.39	0.039±0.020	0.036±0.025
	CNG2	16.12±3.25	1.83±1.15	0.336±0.135	0.230±0.177	243.39±50.79	0.307±0.125	0.041±0.030
	G4	16.03±3.33	0.64±0.36	0.171±0.050	0.095±0.069	363.79±76.03	0.03±0.009	0.017±0.014

G1, Euro 2 G-CNG fueled TTF when using gasoline

G2, Euro 2 gasoline fueled TTF; and Euro 2 G-LPG fueled TTF when using gasoline

G3, Euro 4 G-CNG fueled TTF when using gasoline

G4, Euro 4 gasoline fueled TTF

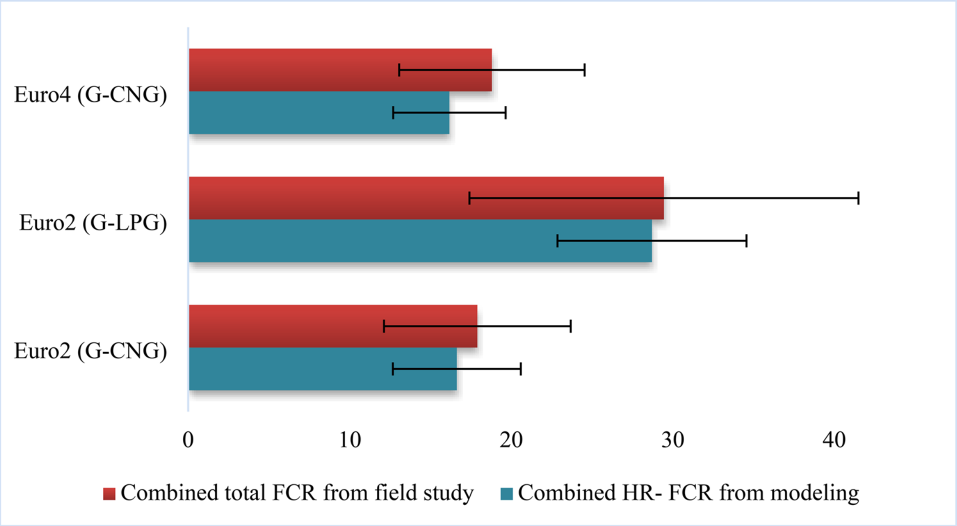


Fig. 2 Total FCR and combined HR-FCR for different TTF (L/100km)

The results of statistical analyses also showed that the difference between daily FCeq by TTF in warm and cold seasons was not significant (p=0.954). Despite the fact that cold seasons may increase fuel consumption, in warm seasons drivers have relatively longer work hours in a day; this makes the daily FC_{eq} by TTF almost the same in both seasons.

HR-EFs

Various levels of estimated emissions of bi-fueled TTF are shown in Table 3, and Table S7 shows the 95% CI of HR-EFs of air pollutants. Euro 2 emission standards for CO and HC+NO_X are 2.2–5.0 and 0.5–0.7 g/km, respectively, and Euro 4 emission standards for CO, HC, and NO_X are 1.0–2.27, 0.1–0.16, and 0.08–0.11 g/km, respectively. The average HR-EFs estimated by the present study do not follow these standard limits, except for CO emission from Euro 4 gasoline fueled TTF and Euro 4 bi-fueled TTF in the period of using CNG.

However, considering Table S7, only the 95% CI for HR-EFs of CO estimated for Euro 4 bi-fueled TTF in the period of using gasoline does not include the Euro 4 emission standard limit for CO; thus, HR-EFs of CO estimated for this model are significantly higher than the CO emission standard limit. The 95% CIs for HR-EFs of air pollutants estimated for other models include the limits of the respective emission standards; thus, at the 95% CI the differences between the estimated HR-EFs for air pollutants and the respective standard limits are not significant for those models.

There is also a further point to be considered. The measured values by Bagheri et al. (2016) and estimated values reported in Table 3 are only for HR-EFs without including the levels of ECEs, which if included may lead to higher emission rates. The reason for such high values is for further investigations focusing on country-specific factors (Banitalebi and Hosseini 2016), some of which are discussed below.

Iran requires taxis to be scrapped after 10 years of service and has set more inspection and maintenance procedures for taxis older than 10 years, in which they need to be inspected once every 3 months, while younger taxis do it twice a year. Our findings showed that 51% of TTF were older than 10 years in 2020. Besides, as mentioned earlier, about 91% of interviewed taxi drivers followed the schedule for PTI test. Therefore, the high emissions estimated by the present study would raise some doubts such as inefficiency of PTI tests for TTF.

The PTI test in Iran is performed as a load-free test only at idle speed, and technical inspection limits are set for the concentration of CO and unburned HC in the exhaust gases. This method does not measure NO_X emission nor the efficiency of the three-way catalyst (TWC), which is one of the most important components in reducing vehicle's pollution.

Moreover, none of the old taxis in Tabriz has their catalyst renewed. On the other hand, a majority of the bi-fueled TTF and their catalysts are designed for gasoline. In other words, internal combustion engines that run on gasoline are adapted for CNG or LPG, which could affect TWC efficiencies for some exhaust gases (Winkler et al. 2013). Table 4 tabulates HR-EFs and HR-FCR reported by different studies for taxis tested in different cities under various conditions (speeds and slopes). Comparing the results of the present work with those in Table 4 shows higher values for all the parameters in the present study.

Two out of the eight studies presented in Table 4 were conducted in Iran. Ghaffarpasand et al. (2020) reported lower HR-EFs compared to the ones by the present study because their investigation was performed at an urban flat highway near the city of Isfahan with a light traffic, unlike

Table 4 HR-EFs and HR-FCR from taxis tested in different studies

#	Author	Speed (km/h)	Pollution standard	Fuel	CO (g/km)	HC (g/km)	NOx (g/km)	CO_2 (g/km)	FCR* (L/100km)
1	(Ghaffarpasand et al. 2020)	19.5	Euro 4	G†	3.289±0.422	0.280±0.032	0.051±0.007	-	-
		41.1	Euro 4	G†	3.624±0.410	0.285 ±0.031	0.057±0.007	-	-
		61.6	Euro 4	G†	3.182.4±0.392	0.289±0.029	0.066±0.008	-	-
2	(Bagheri et al. 2016)	Urban roads: 23 km/h and 12 km/h; highways:65 km/h and 54 km/h	Euro2	G†	18.13±11.96	0.61±0.60	3.27±3.71	288.9±49.1	14.66±3.76
			Euro2	CNG	9.91±9.33	0.92±0.45	2.50±1.86	235.5±40.2	14.38±1.96
			Euro4	G†	16.31	0.11	0.13	296.5	13.77
			Euro4	CNG	0.99	0.19	0.12	231.0	13.31
3	(Yao et al. 2014)	40.7	Euro 2	CNG	1.0±1.1	1.37±0.53	2.13±0.77	144±13	-
4	(Huo et al. 2012)	Instantaneous vehicle speed	Euro 2	G†	8.2±0.3	1.06±0.09	0.54±0.20	222±68	-
5	(He et al. 2019)	Instantaneous vehicle speed	Euro 4 (gasoline-fueled taxis)	G†	2.855 ±3.524	0.227±0.387	0.598 ±0.9	191.1±17.5	-
			Euro 4 (bi-fueled taxis)	G†	3.771±3.781	0.066±0.096	0.422±0.477	191.4±24.8	-
			Euro 4	CNG	1.181±1.093	0.16±0.276	0.376±0.422	133.1±6.4	-
6	(Goel et al. 2015)	Instantaneous vehicle speed averaged 22 km/h	Average of Euro 2,3&4	G†	8.467±37.360	-	0.240 ± 0.443	-	-
				CNG	8.499±37.36	-	1.206 ± 2.218	-	-
7	(Papadopoulos et al. 2018)	Instantaneous vehicle speed	preEuro4 (Euro2,3)	LPG	6.72±0.94	1.12±0.96	3.98 ± 2.84	-	24.39±0.58
8	Present study	20 km/h	Euro 2	G†	20.71±12.92	1.046±1.116	4.467±3.369	333.69±87.93	16.19±4.00
			Euro 2	CNG	12.97±8.97	1.312±0.629	4.765 ±3.679	270.65±71.79	16.82±4.01
			Euro 2	G†	20.69±12.90	1.045±1.117	7.582±6.371	332.00±87.82	30.56±6.39
			Euro 2	LPG	7.04±2.24	1.866±1.147	7.475±5.710	260.38±52.89	28.50±5.66
			Euro 4	G†	16.09 ±6.81	0.220±0.112	0.200±0.148	348.68±77.39	16.41±3.42
			Euro 4	CNG	1.83±1.15	0.336±0.135	0.230±0.177	243.39±50.79	16.12±3.25

1: Was performed at urban flat highway near the city with light traffic in Isfahan, Iran

2: Was performed at flat urban/uphill urban/flat highway/uphill highway in Tehran, Iran

3: Was performed at the main urban roads and a highway in Yichang, China

4: Was performed at inter-city highways, urban freeways, arterial roads, and residential roads in three cities of China

5: Was performed at arterial roads, sub-arterial roads, and freeways in seven cities of China

6: Was performed at chassis dynamometer in Delhi, India

7: Was performed at urban network of Hong Kong

8: was simulated for urban network of Tabriz, Iran

*CNG and LPG FCR were converted to gasoline equivalent FCR

†Gasoline

the present study that took a wider look at the Tabriz roads and their slopes, which gave a more comprehensive picture of fuel consumption and emission inventory of TTFs.

Bagheri et al. (2016) was one of the main references of the present study and was used for modelling. They studied four different speeds at flat/uphill urban and highway roads in Tehran; however, the HR-EFs and HR-FCR estimated by the present study were higher. Actually, Bagheri et al. (2016) conducted 50% of real driving measurements on urban roads and 50% on highways. However, taxi trips in Tabriz mainly take place in urban roads with higher traffics, leading to higher HR-EFs and HR-FCR.

Jamshidi Kalajahi et al. (2020) have used IVE model and not real measurements for emission inventory of taxis in Iran. They investigated the EFs of taxi fleets in a flat highly crowded street of Tabriz. The EFs for CO, CH_4, NO_X, CO_2, and N_2O had the values of 175.58, 20.72, 5.38, 480, and 5.5×10^{-3} g/km respectively, which are different from what were estimated in the present study. This is due to adopting different sampling methods, assumptions, and modeling by the two studies.

Combined emission factors for different models are presented in Table 5. It can be said that despite having the highest combined HR-EFs for CO_2, Euro 4 gasoline fueled TTF have a lower combined HR-EFs for other gases. Euro 2 G-CNG fueled TTF have the highest combined HR-EFs for CH_4. Euro 2 gasoline fueled TTF have the highest combined HR-EFs for CO and Euro 2 G-LPG fueled TTF have the highest combined HR-EFs for HC, NO_X, and N_2O. These two groups of TTF are the oldest ones and need to have a priority in TTF's renovation plan.

To address environmentally and economically feasible options for replacement of worn-out taxis, Khazini et al. (2023) examined some scenarios regarding cost and potential reduction in air pollutants emitted by them in Tabriz. Their findings, based on results from IVE emission model, showed that the emission reduction due to replacement of worn-out taxis with Euro 4 taxis, CNG fueled taxis, and hybrid taxis is almost equal. But considering replacement costs, the cost of hybrid vehicles is much higher than their counterparts for an almost equal reduction of the emissions (125.9 $MM for hybrid taxis compared to 18.4 $MM for Euro 4 taxis and CNG fueled taxis each). Therefore, it is suggested that the renovation plan for worn-out TTF focuses on their replacement with new taxis with Euro 4 or higher Euro standard emissions or CNG fueled ones.

Per-PKT-FCR/EFs

The result of the field study showed that the average passenger occupancy of a taxi in Tabriz per trip was 4.3±0.8 in 2019. The maximum capacity of taxis in 2019 for each trip was 4 passengers, but in routes with long distances, passenger(s) may get off taxis somewhere on the way and taxis may pick up new passenger(s), which makes the number of passengers in a trip in 2019 exceed 4 people. The average passenger occupancy of a taxi in Tabriz per trip in 2020 was found to be 2.89±0.60.

Using the estimations for passenger per trip and HR-EFs levels, the per-PKT-EFs in 2019 and 2020 were estimated and the results are presented in Fig. 3. From Fig. 3, it can be said that per-PKT-FCR/EFs are 47.9–57.1% higher in 2020 than those in 2019, and Wilcoxon signed rank test results showed that this increase in per-PKT-EFs in 2020 is significant ($p<0.001$). The reason for this would be a significant decrease in the number of taxi passengers during the COVID-19 pandemic ($p<0.001$), from 131±72 in 2019 to 65±32 in 2020 (50.4% decrease).

Such results can be discussed by considering special conditions introduced by COVID-19 pandemic. As mentioned earlier, before the COVID-19 pandemic, the maximum capacity of a taxi was 4 passengers (excluding driver), while during the pandemic, and to follow the social distancing rules, they were allowed to carry a maximum of 3 passengers. On the other hand, the closure of schools, universities, and some businesses, teleworking in some businesses and reduced working days in some others, and the use of private cars to create social distance reduced the number of taxi passengers. Therefore, the taxis traveled with fewer passengers and sometimes empty.

Besides, although the target taxis in the present work were those that are only allowed to move passengers in special lines, by comparing their reported daily VKT and the frequency of their rounds per day in their special lines, it can be said that they take other paths to find passengers.

Figure 3 shows that Euro 2 G-LPG fueled TTF have higher per-PKT-FCR/EFs for HC, NO_X, and N_2O, and Euro 2 gasoline-fueled TTF have a higher CO per-PKT-EFs than the other TTF. Euro 2 G-CNG fueled TTF have the highest CH_4 per-PKT-EFs. In spite of having the highest CO_2 per-PKT-EFs, Euro 4 gasoline fueled TTF have lower per-PKT-EFs for other gases compared to the other taxis.

ECE levels

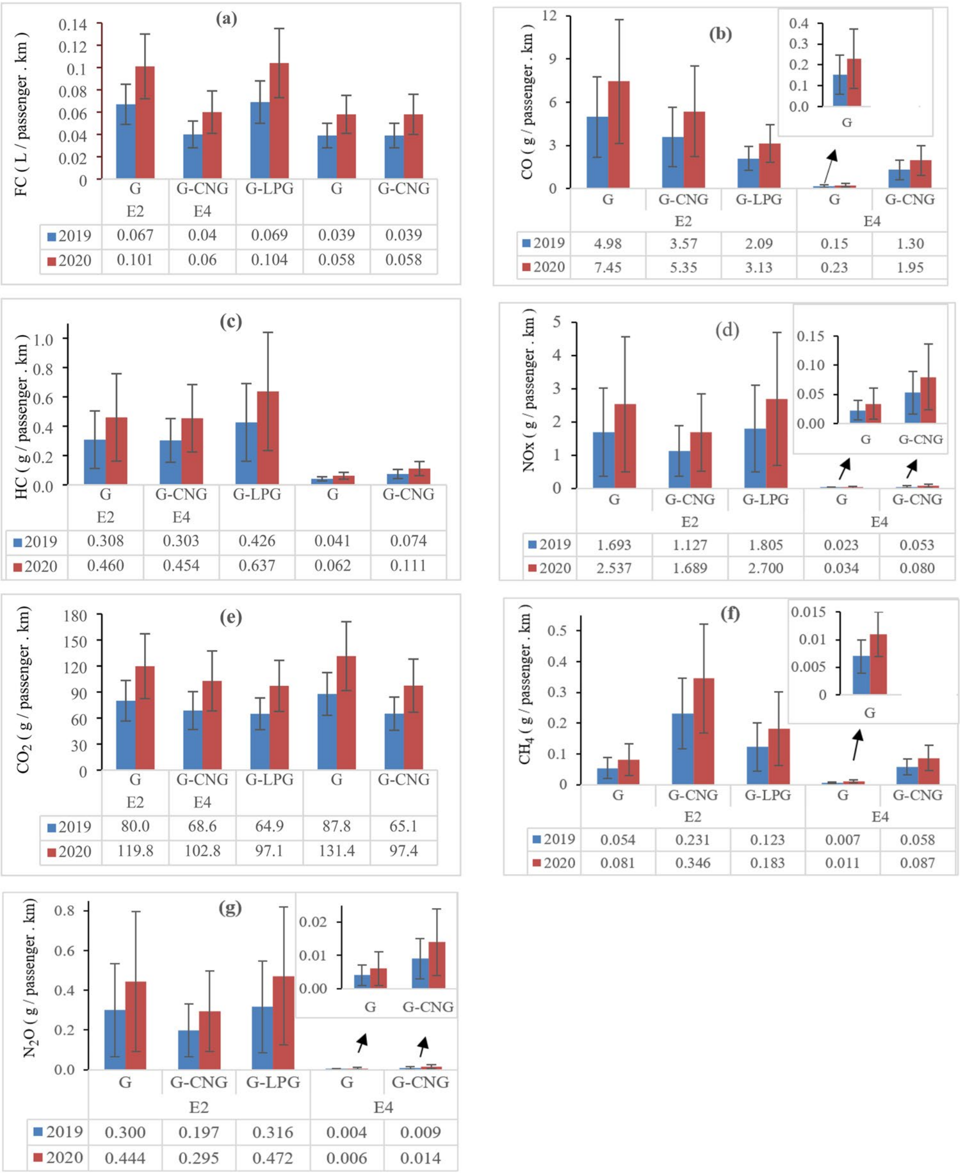
Figure 4 presents the temperature-related daily ECEs of pollutants and GHGs from a Euro 2 and a Euro 4 taxi in Tabriz in 2019 and 2020. ECEs of CO, HC, CO_2, and CH_4 in cold days are higher than those in warm days. Despite having the longest cold distance and time spent on the cold period (see Table S8), ECEs of NO_X in cold and warm days for both models and years are the same because distance traveled in cold start period for ECEs of NO_X is not temperature dependent (see Table 2).

When comparing the ECEs from Euro 2 and Euro 4 taxis, a Euro 4 taxi in warm days has way lower ECEs than those in cold days. The reasons for this would be the decrease in cold distance in warm days, which causes a Euro 4 taxi to travel a less cold distance than it did in cold days (17%, 48%, and 56% decrease in 2019, and 16%, 46%, and 54% decrease in 2020 for CO, HC, and CO_2, respectively). However, for a Euro 2 taxi, although ECEs are lower in warm days, the difference is small (1%, 10%, and 0.35% for CO, HC, and CO_2, respectively, for both years).

Despite the decreased cold distance traveled by TTF in 2020 compared to 2019 (see Table S8), ECEs from both models in

Table 5 The combined HR-EFs (g/km) for TTF

Model	Fuel type	CO	HC	NO_x	CO_2	CH_4	N_2O
Euro 2	Gasoline	20.67±10.83	1.276±0.764	7.024±5.286	332.3±73.8	0.224±0.134	1.229±0.916
	G-CNG	14.84±7.97	1.260±0.564	4.687±2.99	285.4±72.6	0.960±0.437	0.819±0.522
	G-LPG	8.68±3.08	1.769±1.035	7.492±5.183	268.9±56.7	0.508±0.303	1.311±0.909
Euro 4	Gasoline	0.64±0.36	0.171±0.050	0.095±0.069	363.8±76.0	0.03±0.009	0.017±0.013
	G-CNG	5.40±2.59	0.308±0.113	0.222±0.143	269.7±61.0	0.241±0.098	0.040±0.025



(a)

	G	G-CNG	G-LPG	G	G-CNG
	E2	E4			
🟦2019	0.067	0.04	0.069	0.039	0.039
🟥2020	0.101	0.06	0.104	0.058	0.058

(b)

	G	G-CNG	G-LPG	G	G-CNG
	E2			E4	
🟦2019	4.98	3.57	2.09	0.15	1.30
🟥2020	7.45	5.35	3.13	0.23	1.95

(c)

	G	G-CNG	G-LPG	G	G-CNG
	E2	E4			
🟦2019	0.308	0.303	0.426	0.041	0.074
🟥2020	0.460	0.454	0.637	0.062	0.111

(d)

	G	G-CNG	G-LPG	G	G-CNG
	E2			E4	
🟦2019	1.693	1.127	1.805	0.023	0.053
🟥2020	2.537	1.689	2.700	0.034	0.080

(e)

	G	G-CNG	G-LPG	G	G-CNG
	E2	E4			
🟦2019	80.0	68.6	64.9	87.8	65.1
🟥2020	119.8	102.8	97.1	131.4	97.4

(f)

	G	G-CNG	G-LPG	G	G-CNG
	E2			E4	
🟦2019	0.054	0.231	0.123	0.007	0.058
🟥2020	0.081	0.346	0.183	0.011	0.087

(g)

	G	G-CNG	G-LPG	G	G-CNG
	E2			E4	
🟦2019	0.300	0.197	0.316	0.004	0.009
🟥2020	0.444	0.295	0.472	0.006	0.014

Fig. 3 **a** per-PKT-FCR (L/pas·km) and **b** to **g** per-PKT-EFs (g/pas·km) for TTF. E2, emissions from Euro 2 TTF; E4, emissions from Euro 4 TTF; G, gasoline-fueled TTFs; G-CNG, gasoline-CNG bi-fueled TTF; G-LPG, gasoline-LPG bi-fueled TTF

2020 increased compared to 2019 (see Fig. 4). ECEs of CO_2 from a Euro 2 taxi in warm days had the lowest increase (13%) and those of NO_X from a Euro 4 taxi in cold days had the highest increase (111%) in 2020 compared to 2019.

Figure S2 illustrates the contribution of each categorized ECEs to total daily ECEs presented in Fig 4. The $ECEs_{(B.H.W)}$, resulting from home to work trip in the morning after a soak time of 10 h, had the highest contribution to the total ECEs of CO and CO_2 from both Euro 2 and Euro 4 taxis in both 2019 and 2020. However, its contribution to the total ECEs of CO decreased for both warm and cold days and from both models in 2020 compared to 2019. The reason for this was a 52% increase in the share of $ECEs_{(stations)}$ resulted from increased parking times at the stations in 2020.

As for CO_2, the contribution of $ECEs_{(stations)}$ to the daily ECEs from both models increased by 64% in cold days and 63% in warm days in 2020 compared to 2019, causing a decrease in the contribution of both $ECEs_{(B.H.W)}$ and $ECEs_{(M.H.W)}$ to the total daily ECEs. For other gases, $ECEs_{(stations)}$ had the highest contribution to the daily ECEs from both models and increased in 2020 due to the same reason discussed for those of CO and CO_2.

Table 6 tabulates the annual ECEs of pollutants and GHGs from total Euro 2 and Euro 4 TTF in 2019 and 2020. It shows that Euro 2 vehicles are responsible for higher annual ECEs than the Euro 4 ones and the annual ECEs have increased in 2020.

Annual FC_{eq} by TTF

Annual FC_{eq} of a Euro 2 and a Euro 4 taxis in Tabriz were 10.91±4.64 and 10.68±4.72 m^3 in 2019, and 9.22±4.35

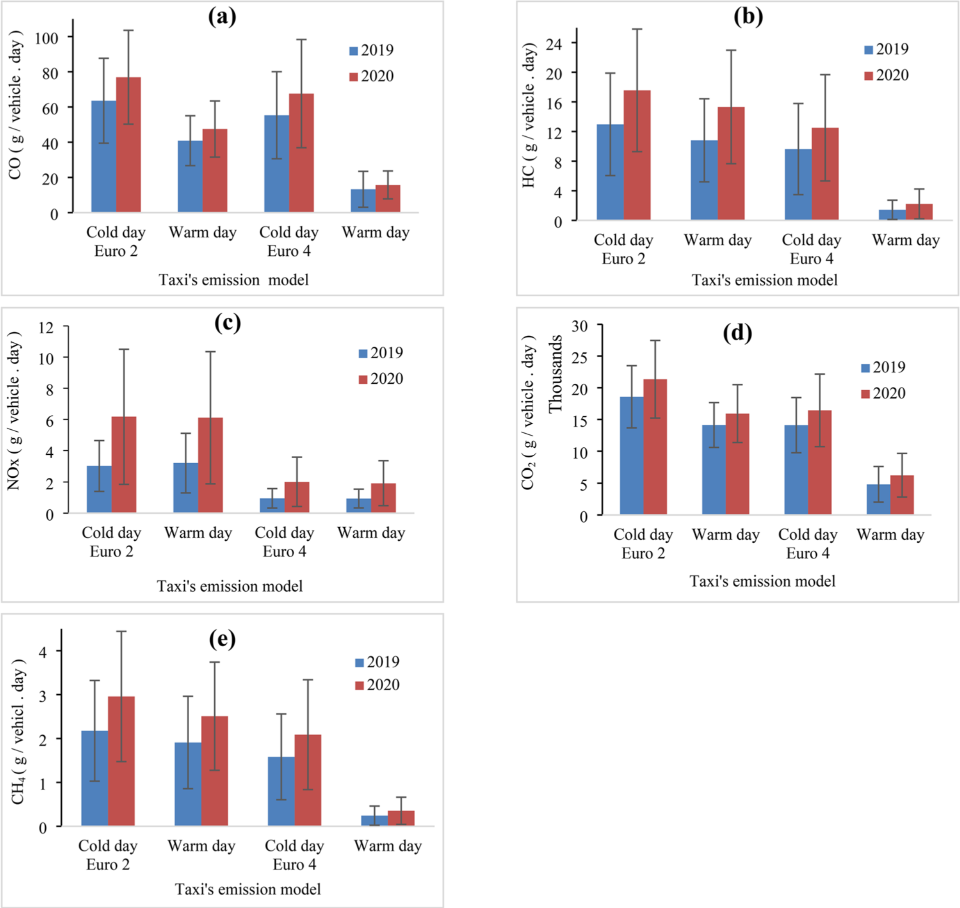


Fig. 4 Estimated temperature-related daily ECEs for **a** CO, **b** HC, **c** NO_x, **d** CO_2, and **e** CH_4 from a Euro 2 and a Euro 4 taxi in Tabriz in 2019 and 2020

and 9.03±4.40 m^3 in 2020, respectively. Adopting Eq. (10), annual HR-FC_{eq} and total FC_{eq} for all TTF were estimated. The output statistics and sensitivity indices from Monte Carlo simulation are given in Table 7 and Table S9, respectively. From Table 7, it can be said that the total annual FC_{eq} in 2019 is higher than 2020. By analyzing the data from the field study, it was found that the decrease in FC_{eq} during COVID-19 in 2020 was significant ($p<0.05$).

Table S.9 shows that the annual VKT is the most influential factor in the annual total FC_{eq} variability for all the

Table 6 Annual ECEs for pollutants and GHGs from TTF in 2019 and 2020 (tons)

Gas	Model	2019				2020			
		Mean	SD	U (99%)	99% CI	Mean	SD	U (99%)	99% CI
CO	E2	117.60	49.16	114.26	28.47–256.98	146.07	60.82	153.89	42.74–350.52
	E4	53.03	31.44	72.04	5.35–149.42	64.72	39.03	91.38	8.97–191.72
HC	E2	24.02	12.76	30.19	0.82–61.20	33.41	16.05	42.9	5.99–91.79
	E4	8.82	6.73	15.18	0.04–30.40	12.45	9.72	23.88	0.19–47.95
NOx	E2	6.02	3.52	7.82	1.77–17.40	11.87	8.29	17.89	2.22–37.99
	E4	0.93	0.61	1.28	0.24–2.80	1.97	1.50	3.265	0.31–6.84
CO_2	E2	34,953.79	10,895.06	27,035.47	13,088.06–67,159.00	38,862.70	13,295.58	36,801.69	13,353.63–86,957.01
	E4	13,976.99	5909.59	14,125.90	3850.41–32,102.20	16,051.43	7002.59	17,474.98	4098.06–39,048.01
CH_4	E2	4.25	2.38	5.59	0.14–11.31	5.54	2.72	6.36	1.00–13.72
	E4	1.51	1.16	2.42	0.01–4.84	2.02	1.55	3.35	0.04–6.74
CO_2-eq	E2	35,282.63	11,252.79	29,189.28	13,243.12–71,621.68	38,878.74	13,104.39	35,821.65	13,472.62–85,115.91
	E4	13,969.01	5867.12	13,918.21	3809.64–31,646.05	16,190.90	7186.12	18,846.89	4107.05–41,800.83

U (99%), expanded uncertainty for 99% CI; *E2*, Euro 2 TTF; *E4*, Euro 4 TTF; *T*, total TTF outputs in both 2019 and 2020, especially for HR-FC$_{eq}$. The FCR of Euro 2 G-CNG fueled taxis was the second most influential factor.

The uncertainty of the total annual FC$_{eq}$ by TTF is presented in Fig. 5, which shows that having a slight skewness, the total annual FC$_{eq}$ by TTF have gamma distribution in both 2019 and 2020.

Annual emissions of pollutants, GHGs, and CO$_2$-eq

The results of Monte Carlo simulation for annual emissions of single taxi and total taxis based on their emission models in Tabriz are presented in Fig. 6 and Table 8, respectively. Figure 6 shows that a Euro 2 taxi emits higher pollutants than a Euro 4 taxi (from 2.6 times for CO in both 2019 and 2020 to 22.4 and 21.9 times for NO$_X$ in 2019 and 2020, respectively). From a climate change perspective, it seems that CO$_2$ emission by a Euro 2 taxi in Tabriz is only 10% higher than that of a Euro 4 taxi, and CO$_2$-eq emission by a Euro 2 taxi is 1.8 and 1.7 times of those by a Euro 4 taxi in 2019 and 2020, respectively. This means that although pollutants' emissions decreased in Euro 4 taxis compared to Euro 2 taxis, GHGs control calls for more attention.

The annual emissions of pollutants and GHGs are higher in 2019 than 2020. Applying the EFs from Table 3 to the annual VKT (in 2019 and 2020) of each investigated taxi in this study, it was observed that the decrease in the emissions of all pollutants and GHGs and CO$_2$-eq in 2020 compared to 2019 was significant (p<0.001), meaning that the COVID-19 pandemic had caused a significant decrease in the emissions of pollutants and GHGs by TTF.

The results of the present study showed that HREs were responsible for 97.5, 94.4, 99.6, 77.0, and 98.5% of total emissions of CO, HC, NO$_x$, CO$_2$, and CH$_4$ in 2019, respectively, while their contributions to total emissions of CO, HC, NO$_x$, CO$_2$, and CH$_4$ in 2020 were 96.3, 91.1, 99.2, 71.6, and 97.7%, respectively. These results indicate that HREs of pollutants decreased by 13.1% in 2020 compared to 2019, while their ECEs increased by 28.5%.

In 2019, ECEs were responsible for 2.3% of pollutants (210.4 tons), while in 2020, they were responsible for 3.4% of pollutants (270.5 tons). This may be due to fewer trips, leading to longer parking times in stations, waiting for passengers. Regarding the ECEs of CO$_2$ and CH$_4$, they both increased in 2020, having a share of 22.9% and 0.003% from the total GHG emissions in 2020 compared to 28.3% and 0.004% in 2019, respectively.

Figure 7 shows the contribution of each GHG to CO$_2$-eq emission from TTF in 2019 and 2020. The contribution of CO$_2$ to CO$_2$-eq is the highest, especially in ECEs of CO$_2$-eq (99.6%<). However, CH$_4$ had the lowest share of ECEs of CO$_2$-eq (0.33% and 0.38%, for 2019 and 2020, respectively) and HREs of CO$_2$-eq (4.14% and 4.10% in 2019 and 2020, respectively).

Li et al. (2009) studied the impact of real-world driving cycles of gasoline-fueled vehicles on the emission of GHGs, and used GWP values from the second assessment report, where the contribution of the three species is as CO$_2$: 1, N$_2$O: 310, CH$_4$: 21 (Myhre et al. 2013). They

Table 7 Annual HR-FC$_{eq}$ and total FC$_{eq}$ (ML) by TTF in 2019 and 2020

Model	FC$_{eq}$	2019				2020			
		Mean	SD	U (99%)	99% CI	Mean	SD	U (99%)	99% CI
E2	Hot	69.0	26.0	67.8	12.9–148.5	58.4	24.9	64.5	5.8–134.7
	Total	73.8	31.4	80. 5	10.7–171.6	62.3	29.4	74.8	5.3–154.9
E4	Hot	32.7	12. 6	32.7	6.0–7.5	27. 7	12.0	31.0	2.7–64.7
	Total	38.0	16.8	42.9	4.9–90.7	32.2	15.7	39.8	2.6–82.1
T	Hot	101.8	28.9	74.5	43.4–192.5	86.0	27.6	71.5	32.1–175.2
	Total	111.8	35.7	92.0	42.0–226.0	94.5	33.3	86.3	31.2–203.8

U (99%), expanded uncertainty for 99% CI; *E2*, Euro 2TTF; *E4*, Euro 4 TTF; *T*, total TTF

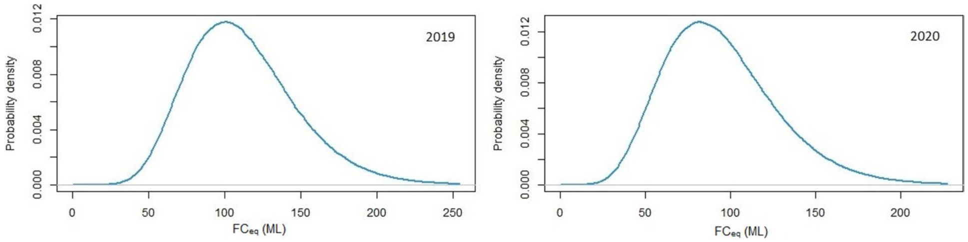


Fig. 5 Uncertainty analysis of the annual total FC$_{eq}$ by TTF in 2019 and 2020

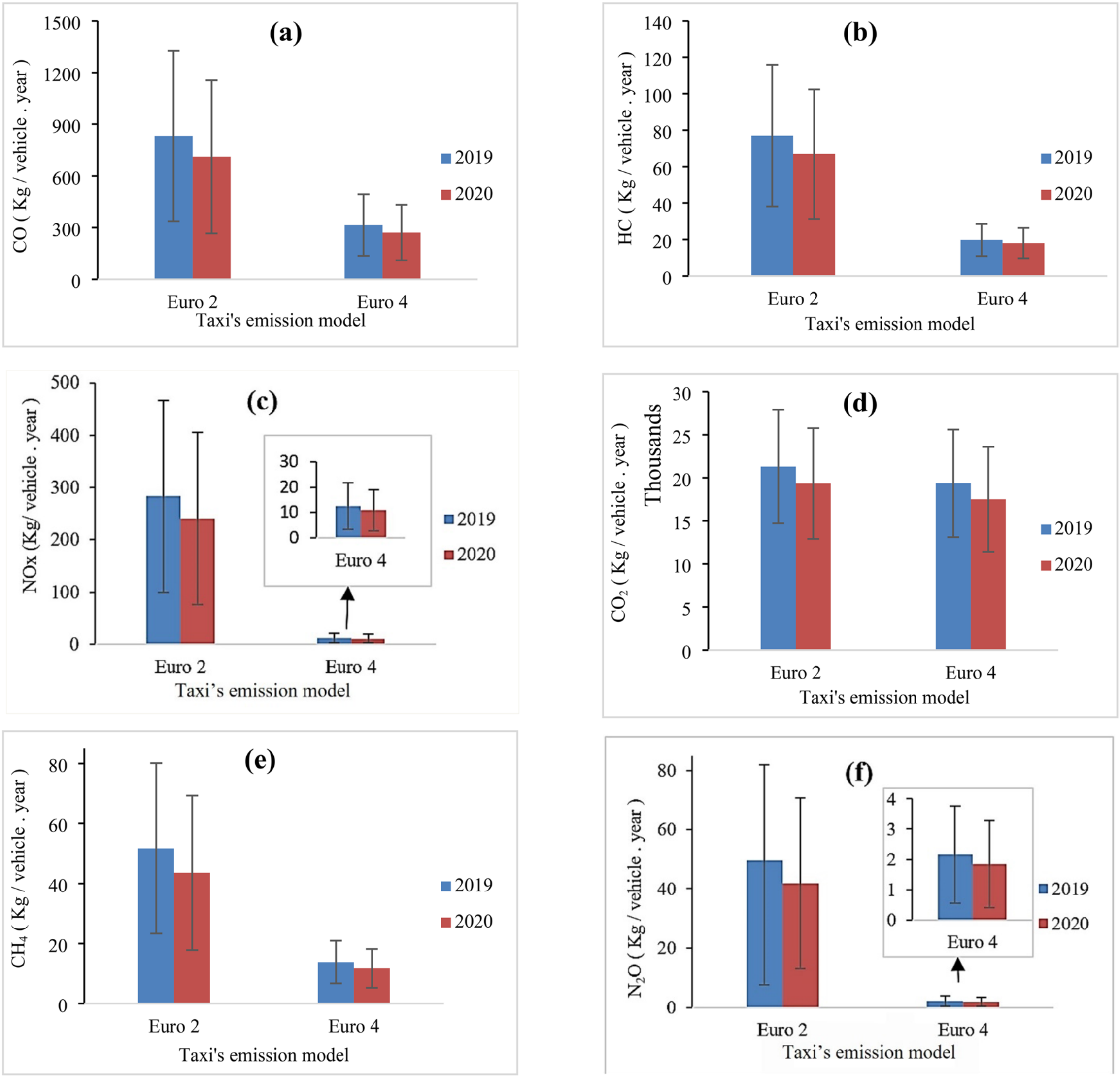


Fig. 6 Annual emissions of (**a**) CO, (**b**) HC, (**c**) NOx, (**d**) CO_2, (**e**) CH_4, and (**f**) N_2O by one taxi in Tabriz in 2019 and 2020

found that the contributions of three GHGs to CO_2-eq were approximately 90±3%, 10±3%, and 0.3–0.4% for CO_2, N_2O, and CH_4, respectively (Li et al. 2009). Comparing these results with the results of the present study shows that CH_4 and N_2O emitted by TTF have higher concentrations in the exhaust, which gives them higher fractions in the total CO_2-eq. The reason for this is that the bi-fueled taxis in Tabriz mostly use CNG (75% of the total VKT) or LPG (88% of the total VKT) instead of gasoline. Therefore, given that EFs of CH_4 and N_2O for CNG and LPG fuels are higher than those of gasoline, this gives CH_4 and N_2O emissions a higher fraction in the total CO_2-eq emission.

According to the sensitivity indices in Table S10, the annual VKT influences the variability of the emissions for the outputs of HC and CH_4 emissions the most (39.2% and 67.9% in 2019 and 47.0% and 72.4% in 2020, respectively). As for NO_X and N_2O, they were mostly influenced by the variability of EFs estimated for Euro 2 G-CNG bi-fueled taxis in Tabriz when they use CNG (56.1% and 56.4% in 2019 and 49.4% and 49.4% in 2020, respectively). The outputs of CO and CO_2 emissions in 2019 were mostly influenced by the EFs estimated for the Euro 2 G-CNG bi-fueled taxis in Tabriz when they used CNG (39.5% and 50.6%, respectively), and in 2020 they are mostly influenced by annual VKT (39.7% and 43.0%, respectively). Correlations among the variables show values below ±0.1, indicating a very weak correlation among their uncertainties.

Table 8 Annual emissions of pollutants, GHGs, and CO_2-eq form TTF in 2019 and 2020 (tons)

Gas	Model	2019				2020			
		Mean	SD	U (99%)	99% CI	Mean	SD	U (99%)	99% CI
HC	E2	521.0	263.1	680.6	44.1–1405.1	451.8	240.1	616.6	33.2–1266.4
	E4	70.3	31.2	80.8	10.7–172.4	64.5	29.6	77.3	6.6–161.1
	T	589.6	278.7	721.8	71.8–1515.4	514.7	256.2	660.5	52.3–1373.4
CO	E2	5626.7	3343.1	9367.3	850.1–19,584.7	4803.0	3003.7	8460.7	457.7–17,379.1
	E4	1120.1	632.6	1709.2	144.7–3563.0	966.7	572.6	1548.8	90.6–3188.2
	T	6750.7	3647.2	10,210.4	1098.7–21,519.4	5767.3	3310.6	9270.2	580.5–19,120.9
NO_X	E2	1918.7	1241.1	3595.5	260.3–7451.3	1628.5	1109.7	3233.6	132.0–6599.1
	E4	45.1	32.9	95.5	5.6–196.5	39.3	29.1	85.2	3.6–173.9
	T	1964.9	1254.8	3643.1	273.0–7559.2	1799.8	1177.5	3423.1	182.0–7028.1
CO_2	E2	144,151.7	44,600.5	116,494.7	49,004.0–281,993.3	130,699.0	43,422.8	113,805.9	36,058.3–263,670.0
	E4	68,893.0	22,233.6	58,095.6	20,922.1–137,113.3	62,391.8	21,703.6	56,863.7	14,587.7–128,315.0
	T	212,978.3	62,807.6	164,790.7	73,204.8–402,786.2	193,110.5	61,371.6	161,329.1	541,12.8–376,770.9
CH_4	E2	350.0	192.2	489.3	17.2–995.7	294.4	174.0	441.2	10.5–892.8
	E4	49.2	25.3	65.3	3.7–134.2	41.8	23.1	59.0	2.3–120.3
	T	396.8	204.6	525.9	29.6–1080.8	333.9	186.7	475.6	16.9–967.2
N_2O	E2	335.3	218.8	633.9	44.8–1312.5	283.2	195.0	566.6	22.2–1155.3
	E4	7.7	5.7	17.0	0.9–34.9	6.6	5.1	14.8	0.4–30.0
	T	343.2	219.1	622.7	67.4–1312.7	289.7	194.4	556.2	52.7–1165.0
CO_2–eq	E2	241,148.2	44,950.5	115,699.8	125,394.3–356,793.8	212,591.5	66,949.9	192,755.7	71,994.7–457,506.1
	E4	72,354.5	22,215.4	56,886.5	15,808.1–129,581.1	65,406.8	21,598.4	55,107.2	11,165.5–121,379.9
	T	313,501.1	85,051.2	236,508.0	121,976.2–594,992.2	277,772.4	79,700.5	221,690.6	95,063.4–538,444.2

U (99%), expanded uncertainty for 99% CI; E2, Euro 2 TTF; E4, Euro 4 TTF; T, total TTF

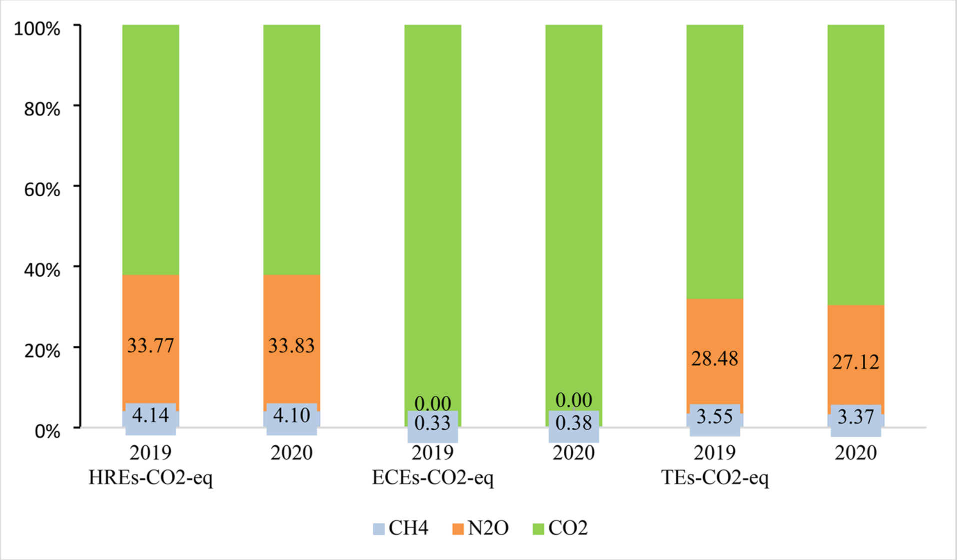


Fig. 7 Contribution of each GHG to CO_2-eq by the operation of TTF in 2019 and 2020. HREs-CO_2-eq: hot running emissions of CO_2-eq; ECEs-CO_2-eq: excess cold emissions of CO_2-eq; TEs-CO_2-eq: total emissions of CO_2-eq

The uncertainty of the annual emissions of CO, HC, and NO_X in 2019 and 2020 is presented in Fig. 8 and the uncertainty analysis of the annual total GHGs and CO_2-eq emissions in 2019 and 2020 is presented in Fig. 9. Apart from the uncertainty of CO_2 and CO_2-eq that are best fit by a normal distribution, the uncertainty for other emissions is better represented by a lognormal distribution.

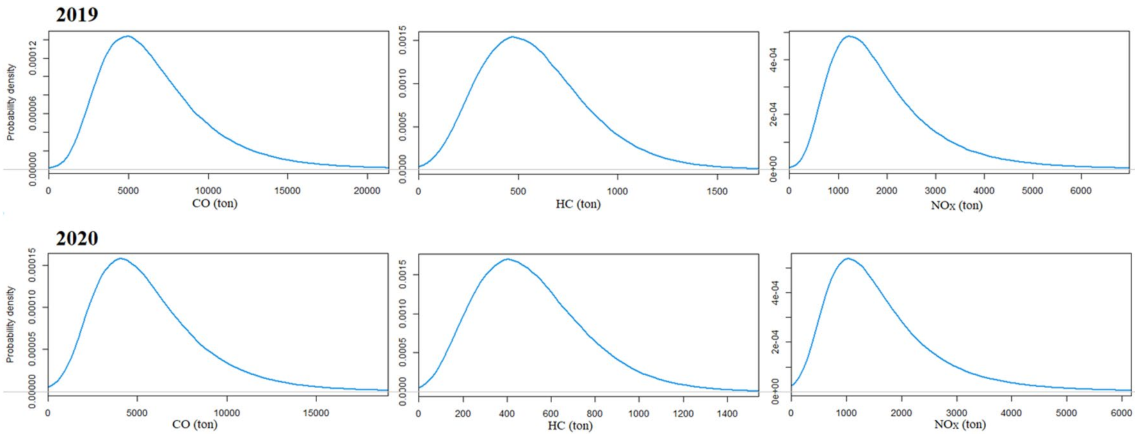


Fig. 8 Uncertainty analysis of the annual emissions from operation of the urban TTF in 2019 and 2020

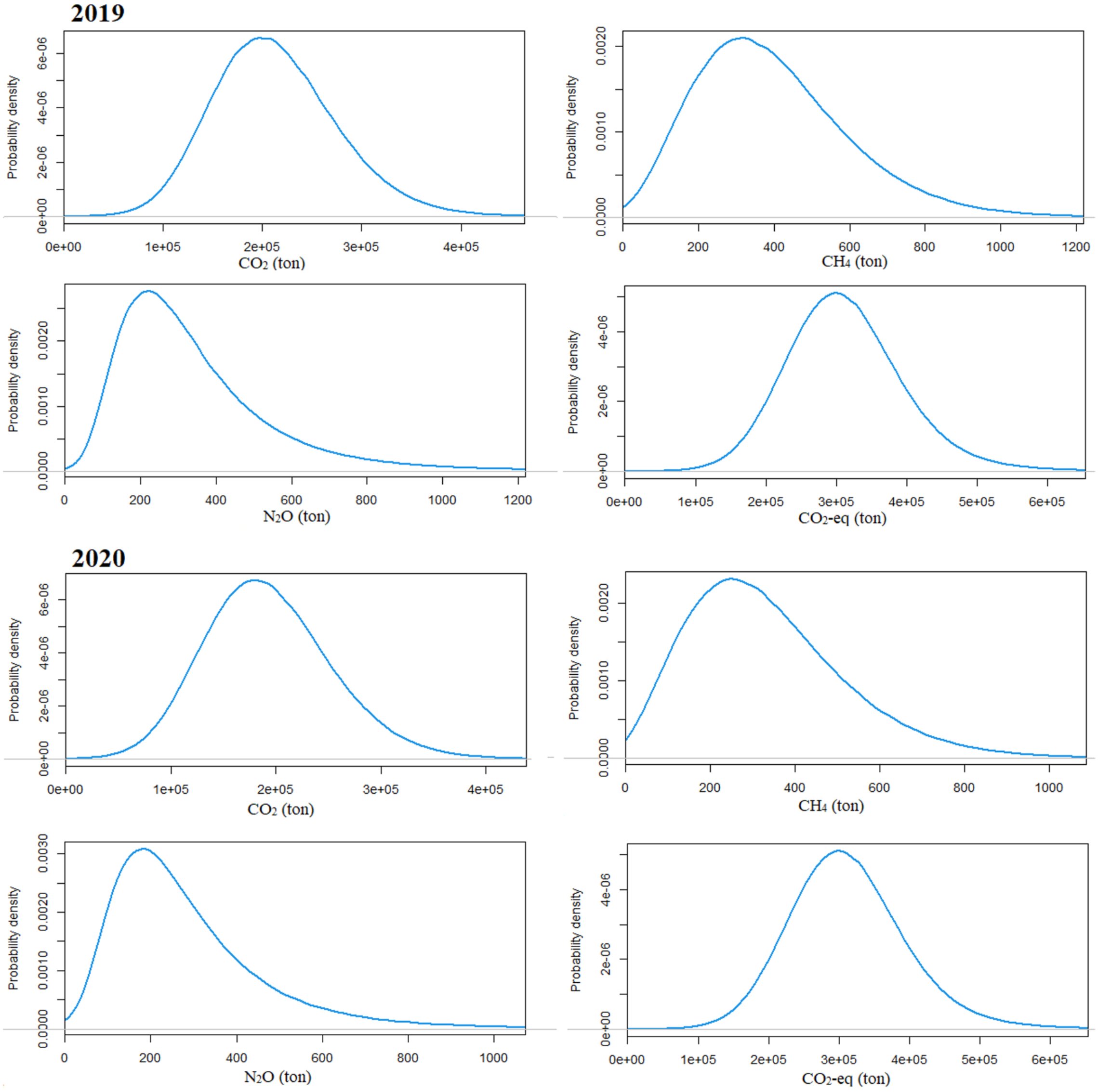


Fig. 9 Uncertainty analysis of the annual total GHGs and CO_2-eq emissions from operation of the urban TTF in 2019 and 2020

Conclusion

Taxis are one of the main sources of air pollutants and GHG emissions in cities, especially in developing countries. To conduct a fuel consumption and emission inventory on taxis in Tabriz, activity data was gathered through a field study using a structured questionnaire by interviewing taxi drivers. Relevant municipal organizations and literature review were other data sources. The present study then combined the results of its own with those of different sources through modeling to estimate FCRs, EFs, PKT-FCRs, and PKT-EFs of pollutants and GHGs and CO_2-eq for TTF. For this purpose, uncertainty and sensitivity analyses were conducted.

It was found that season has no impact on daily FC_{eq} by TTF. FCRs of TTF are high and no significant differences existed between FCRs of the TTF regarding the age or mileage. The present study considered the effect of COVID-19 pandemic on PKT-FCRs/EFs and total annual FC_e and emission levels. The results showed that in spite of significant decrease in emissions by TTF, PKT-EFs increased significantly during the COVID-19 pandemic due to declined passengers. The ECEs also increased during this period. It was revealed that the HR-EFs of taxis in Tabriz are higher than the respective Euro standards, but only the estimated HR-EF of CO for Euro 4 bi-fueled TTF in the period of using gasoline was significantly higher than the respective Euro emission standard limits.

High HR-EFs estimated for TTF call for special attention by policymakers to design sustainable control strategies for a series of follow-up implications of urban taxi management. These strategies could include applying stringent methods for PTI, which test more air pollutants and the efficiency of TWC, and taking supportive measures such as renewal of catalytic converter at discounted prices, or providing financial support for those who have old taxis to buy new ones. Other strategies would be providing taxis with higher technologies that use low-carbon fuels or fuels with enhanced quality. Infrastructure improvements and providing standard roads are other ways that will help in FC control and emission reduction.

However, economic shortages in Iran could make all these suggestions too slow or impossible to implement. Therefore, it is recommended that in order to find the best FC and emission mitigation strategies for taxis, future investigations analyze their feasibility considering economic and social factors.

One of the main strengths of the present study is its methodology that can be applied for the estimation of FC and EFs of vehicles, where the real-time measurements tools are not available or are expensive, and typical modeling tools are inefficient, especially in cities of developing countries like Iran. Although this study provides a detailed understanding of FC and emission characteristics of taxis in Tabriz, there are several limitations; since the data to conduct this study were not provided by the real-world driving measurements, this may introduce some sort of biases to the results of the present study. For example:

1. Although close to reality, the daily averages of FC, VKT, passengers, and round trips reported by taxi drivers may not be completely accurate.
2. In the study by Bagheri et al. (2016), which was one of the main references used for the modeling of FCR and EFs of taxis in Tabriz, almost all the taxis were below 10 years of age. Given that their emission could be lower than those above 10 years of age, using the EFs reported by them can be a source of underestimation of emissions of taxis in Tabriz, especially considering that they are the main influential factor in variability of the EFs of NO_X, N_2O, and CH_4 from taxis in Tabriz.
3. The ECE models, which were applied for estimation of ECEs of taxis in Tabriz, were originally developed for personal cars (not taxis). Thus, given that taxis have higher emissions than personal cars, it is possible that ECEs in the present study are underestimated.

To overcome these limitations, it is suggested that on-road measurements be conducted on vehicles, especially taxis, in Tabriz City to provide more realistic results.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11356-023-27883-5.

Acknowledgements This is a report of database from PhD thesis registered in Tabriz University of Medical Sciences with the Number 65230. The authors would like to thank Tabriz University of Medical Sciences for its support and Tabriz Taxi Organization for providing the required data. Cooperation of taxi drivers during the field study is also appreciated.

Author contribution All the authors contributed to the study conception and design. The field study and data collection and analysis were performed by Pari Teymouri. Data analysis was performed by Parvin Sarbakhsh. The study was supervised by Reza Dehghanzadeh. The first draft of the manuscript was written by Pari Teymouri, and all the authors commented on previous versions of the manuscript. All the authors read and approved the final manuscript.

Funding This work was supported by Tabriz University of Medical Sciences.

Data availability Not applicable.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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