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Real-world and bottom-up methodology for emission inventory development and scenario design in medium-sized cities

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ABSTRACT

Efficient management of air quality requires a comprehensive emission inventory to support decision-making on air quality improvement. This article presents a comprehensive framework for detailed emission inventory development in cities with low-quality basic data, which examines the emission of primary criteria pollutants (CO, NO_x, SO_2, $PM_{2.5}$, PM_{10}, and VOC) from mobile sources, residential, commercial, and public services, fuel stations, transport terminals, energy conversion sections, and industries. This research was applied to Tabriz in Northwest Iran, one of the polluted medium-sized cities with a population of 1.77 million. Results show the city daily emission per capita is 569.8 g of CO, 68.6 g of NO_x, 38.6 g of VOC, 17.6 g of SO_x, and 3.7 g of PM. Vehicular emissions accounted for 98% of CO, 91% of VOCs, 61% of NO_x, and 56% of PM; meaning alternative policy strategies in vehicles would reduce emissions rapidly. Fifteen applicable and effective scenarios in transport and one concerning stationary sources were proposed and reduction potential of them was evaluated. Effectiveness of the public transport improvement and replacement of old passenger cars were founded the key scenarios. These two alternatives decrease 14 and 2 tons of SO_2 and 6797 and 2394 tons of NO_x annually with the cost of $99.5 MM and $366.5 MM, respectively. The findings of this study provides the choice of travel method by each citizen is a function of cost, speed, comfort and safety of travel; therefore, all the requirements of any scenarios must be fully considered in the implementation step.

Introduction

The world's population has been steadily multiplying throughout history. Economic growth and rising living standards result in growing urbanization and a high concentration of population in urban areas in almost all countries. The world's urban population rose from 1.7% in the mid-19th century, to 33.8% percent in the 1960s, 50.4% by 2006, and 55.3% by 2018 and is expected to reach about 6.4 billion (68%) by 2050 (Alonso et al., 2010; United Nations, 2018). The urban population of Iran was about 27% of the total population in 1950. In the 1970s, the share was 47%, and it has reached

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68% by 2006 and 74.9% by 2018. It is projected to reach 80% by 2030 (Assari and Mahesh, 2011; Worldometers, 2018; World Bank, 2018).

Increment of the urban population has led to increased urban activities such as intensive energy consumption (in particular fossil fuels), domestic, industrial, and energy production activities, high automobile dependency, and transportation demand (Shahbazi et al., 2017; Mishra and Goyal, 2014). Growing population and urban activities lead to severe air pollution problems in most of the populated cities all over the world (Zhou et al., 2020; Simayi et al., 2020). Although mobile (vehicular) sources are recognized as major air pollution sources, there are also other sources that are responsible for poor urban air quality. Domestic and commercial sources, industries, terminals, and fuel stations, are other air pollution emission sources that exacerbate air pollution levels at the urban scale (Maes et al., 2019; Zhang et al., 2008; Pinto et al., 2020).

Exposure to a high level of air pollution increases a person's risk of contracting a disease and it is recognized as the fourth leading cause of death in the world, behind metabolic risks, dietary risks, and tobacco smoke; that is ranked third in low and lower-middle-income countries. The emitted pollutants and their oxidation products have a direct effect on human health and increase mortality and morbidity rates. Cardiovascular diseases, strokes, infections, cancers, and chronic obstructive pulmonary diseases such as bronchitis and emphysema, are some of the diseases caused by air pollution (World Bank Group, 2016; World Bank and IHME, 2016).

According to the Clean Air Acts, there are six criteria air pollutants in urban space; Carbon Monoxide (CO), Ground-level Ozone (O_3), Lead, Nitrogen Oxides (NOx), Particulate Matter (PM), and Sulfur Dioxide (SOx). Annually about 7 million deaths could be attributed to air pollution on a global scale. The $PM_{2.5}$ (particulate matters with an aerodynamic diameter of less than 2.5 micrometers) is responsible for 2.9 million of this (World Bank and IHME, 2016; Pinto et al., 2020). The total deaths of 19,644 have been attributed to air pollution in Iran in 2013 (28 out of 100,000 deaths), which represents a 49% increase compared to 2002. PMs have a considerable effect on this mortality rate. In 2002, it was estimated that only by controlling this pollutant, 8540 deaths could be prevented in major Iranian cities (Tehran, Mashhad, Isfahan, Shiraz, and Tabriz) (World Bank, 2005; World Bank Group, 2016).

Studies show that the reduction of air pollution could be beneficial from human health and also economic perspectives. Air pollution reduces the quality of life, productivity, and incomes in cities by causing illnesses and premature deaths and imposing massive economic costs on societies (Bhanarkar et al., 2018). Ambient and indoor air pollution cost the world's economy some $5.11 trillion and $225 billion as welfare and labor income losses in 2013, respectively. The economic burden of air pollution in Iran was estimated to be $13 billion in 2013 (World Bank and IHME, 2016; World Bank Group, 2016).

Besides health and economic effects, air pollution has myriad impacts on human beings and their surroundings. Poor air quality, climate change, formation of secondary pollutants (ozone and secondary particulate matters), environmental and ecological systems damages, and reduction of visibility and scenic beauty are some of these impacts (Simayi et al., 2019; Simayi et al., 2020; Metia et al., 2020).

The building block of air pollution studies is the development of high-quality emission inventories. An emission inventory is an accurate database that identifies and categorizes the main air pollution sources and emissions from each source by pollutant types, which is defined for a specific region and time (Metia et al., 2020). High-quality emission inventories provide experts, policymakers, and legislators with detailed information on the emission from each source and the temporal and spatial distribution of it. It should be noted that the emission inventories for underdeveloped and developing countries are limited due to the scarcity of information, and in the best case, only the total emission amount is available for a region (Maes et al., 2019). Emission inventories should systematically be updated due to the substantial changes in population, metropolitan structures, fuel quality and types, industrial activities, manufacturing processes, emission standards, replacement of the most polluting technologies, the addition of control equipment, vehicle number, and fleet composition over time. An accurate, comprehensive, and updated emission inventory results in a realistic record of pollutants emitted to the atmosphere in a specific area (Vallero, 2014).

Emission inventories could also be used in legislation and development of air pollution control and mitigation policies, efficient air quality management, and provision of required input data for forecasting and dispersion models. Besides, emission inventories are used as a tool to predict future emissions, apply air pollution control and mitigation strategies, and determine their effectiveness, as well as cost-benefit analysis and prioritization of various solutions. The fact that emission inventories are an integral part of air pollution management justifies the extensive efforts to provide them (D'Angiola et al., 2010; Baltar de Souza Leão et al., 2020).

Due to the importance of compiling the emission inventories in air pollution studies, many studies have been done in this regard, but most of these studies require a vast amount of data and enormous infrastructures that make their use difficult and in some cases impossible for underdeveloped and developing countries.

Maes et al. (2019) developed a vehicular emissions inventory in the Florianópolis Metropolitan Area (FLMA), in Santa Catarina, Brazil. They used a probabilistic bottom-up approach to develop high-resolution spatial and temporal emission inventories. Through this study, the impact of vehicle categories and their emission distributions, major contributors of each pollutant, and most pollutant roads and regions have been determined.

Majumdar et al. (2020) studied the major air pollution emission sources of Kolkata Metropolitan City, India, including transportation, power, industry, domestic (residential and commercial activities), waste, agriculture, and construction and their detailed activities. They developed an emission inventory of anthropogenic particulate matters and gaseous pollutants, for baseline years 2010 and 2015. Emissions were projected for the near future, 2020, 2025, and 2030 under current policy and three alternative policy and technological scenarios using Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS)-City model. Similar studies have been done for Delhi- India for baseline years 2005 – 2010 and the industrial, residential/commercial, and transportation sources are considered as major air pollution sources. The impact and reduction potential of current policy and three alternative technology and policy scenarios were studied using a modified version of the GAINS model (Bhanarkar et al., 2018).

In a comprehensive emission inventory study in Tehran – Iran, Shahbazi et al. (2016a, 2016b) studied CO_2, CO, NOx, SOx, PM, and Volatile Organic Compound (VOC) emissions from mobile, industrial, residential, commercial, and public service, energy conversion, terminal, and gas station sources for the baseline year 2013.

To provide tools for the chemical weather forecast in South America, a vehicular emission inventory for the metropolitan area of Buenos Aires, Argentina has been developed using a bottom-up method. In this inventory, the emissions of CO_2, CH_4, N_2O, CO, NOx, NMVOC (non-Methane VOC), PM, and SO_2 for the baseline year of 2006 have been studied. Due to the unavailability of local vehicle emission factors, measuring data from different researches in Argentina, Brazil, Chile, and Colombia were used to define a data set of regional emission factors, which are representative of Latin American fleets and driving conditions. Results showed that older technologies on average are responsible for 80% of emissions of all species (D'Angiola et al., 2010). In another study for the South American continent, a methodology has been developed for the construction of an urban vehicle emission inventory, with emphasis on its application in regional atmospheric chemistry modeling. In this study, available inventories were extrapolated to the locations without inventories based on the vehicle density ratios (Alonso et al., 2010).

Zhou et al. (2020) developed a comprehensive source profile database and highly accurate spatial and temporal anthropogenic emission inventory of VOCs in Sichuan Province – China to provide the required input data for air quality models. Eight categories of VOC emission sources, fossil fuel burning, industrial process, transportation, solvent use, biomass burning, gas storage and transportation, waste disposal, and cooking, are considered in this study. In another study, Zhao et al. (2020) investigated the source apportionment of VOCs and their contributions to the formation of photochemical ozone in the Yangtze River Delta (YRD) – China.

Due to the major share of mobile sources in urban air pollution, a large number of vehicular emission inventory studies have been conducted using conventional computer-based models. Computer Program to Calculate Emission Road Transport (COPERT) (Song et al., 2016; Choudhary and Gokhale, 2019; Dey et al., 2019), Multi-scale Motor Vehicle and Equipment Emission System (MOVES) (Amirjamshidi and Roorda, 2015; Sun et al, 2017; Perugu, 2019), Comprehensive Modal Emission Model (CMEM) (Pathak et al., 2016; Kan et al., 2018), Emission Factor model (EMFAC), and MOBILE (López-Martínez, 2017) models are among the most commonly used models for obtaining mobile source emissions. Another common model is the International Vehicle Emission (IVE) model, which is widely used in many countries, including China (Guo et al., 2007; Zhang et al., 2008; Zhou et al., 2019), Nepal (Shrestha et al., 2013), India (Mishra and Goyal, 2014), Iran (Shafie-Pour and Tavakoli, 2013; Shahbazi et al., 2016a, 2016b), Vietnam (Dung et al., 2015), and Pakistan (Hussain Shah and Zeeshan, 2016).

Based on studies conducted in the world, emission inventory studies have also started in Iran. Iran passed its first National Clean Air Regulations in 1975. The country adopted its Clean Air Act in 1995 and updated it in 2017 with parliamentary approval (Heger and Sarraf, 2018). The first emission inventory in Iran was developed by JICA (Japan International Cooperation Agency, the study on an integrated master plan for air pollution control in the Greater Area in the Islamic Republic of Iran.) for Tehran in 1997. Despite some measures taken to reduce air pollution in Iran, pollution levels in some cities are still higher than standard (World Bank Group, 2016).

The most important problem in the implementation of emission inventory in developing countries is the lack of required data in different organizations or in some cases the lack of cooperation of various organs in providing available information; to address these needs, Tabriz, NW of Iran, one of the most populated and polluted megacities of the country was chosen to develop emission inventory of urban air pollutants. The methods and analysis performed in this study could be used or adapted to develop emission inventories in any other cities in developing countries with limited data sources.

Despite the high air pollution level in the Tabriz, there are not any accurate and detailed emission inventory studies in recent years. Under the scope of this study anthropogenic and primary sources of air pollutants including CO, SOx, NOx, volatile organic compounds (VOCs), and PM have been surveyed within 35 km of the city for one year period (April 2017 – April 2018). In continue, different hypothetical mitigation and control strategies are also proposed and their economic costs and potential emission reduction have also been examined.

In continue, section two briefly presents the emission estimation methodology for each source; section three provides information about the study area and data sources for each pollution sector; in section four emission results and distribution maps of Tabriz are presented followed by air pollution mitigation scenarios and their effectiveness.

1. Methodology

Two essential building blocks for compiling an emission inventory are emission factors and activity data for each source. It is necessary to review the valid literature and databases to find reliable emission factors for each source and each pollutant (Mishra and Goyal, 2014). So first step for establishing a reliable emission inventory is a scientific classification of emission sources. Major sources considered in this study were mobile sources (vehicles), residential, commercial, and public services, industries, energy conversion industries (power plant, refinery, and petrochemical complexes), bus terminals, airport and railway, industries, and fuel stations.

Pollution inventory relies on a wide range of methods including mass balance calculations, engineering calculations, sampling or direct measurements, and the use of emission factors to estimate emissions. All of these methods require long and expensive costs to be able to use at any time. The US Environmental Protection Agency (EPA) therefore created a set of emission factors in AP-42 documents for various pollutants from various sources. Activity data, amount of activity that leads to emission of pollutants and has a different meaning for each pollution sector, could be obtained through an actual count, or by means of some estimating technique.

In this study, Eq. (1) is used to estimate emission from different sources:

$$E_i = \Sigma AD \times EF_i \tag{1}$$

where, E_i is the estimated emission of pollutant *i*, AD is activity data, and EF_i refers to emission factor of pollutant *i*. Correlation of an emission source with its activity data in geographical terms is required to spatially allocation of emission inventory (Vallero, 2014; Olaguer, 2017).

Uncertainty of emission factors normally ranges from approximately ± 10% to two times (Frey, 2007). Emission factors are graded from A to E to give the user an indication of how "good" the factor is, with an excellent "A" and a poor "E". The criteria used to determine the emission factor rating can be found in the emission factor documentation for AP-42 Section 1.4 and the introduction to the AP-42 document (EPA, 1998).

1.1. *Mobile sources*

Road transport is an important emission source in cities. Therefore, it is crucial to accurately calculate real-world vehicle emissions, which is associated with some difficulties due to the involvement of many factors. Given the fact that vehicle emission factors strongly depend on the vehicle driving pattern, traffic conditions, fleet composition, and other site-specific environmental factors, the emission model which has the required capability and flexibility to capture the updated situation for each site, should be used. In this methodology, emission of exhaust pollutants and non-exhaust particulate matter (PM) due to vehicle tire and brake wear and road surface abrasion are estimated respectively using IVE model and European Monitoring and Evaluation Programme (EMEP)/European Environment Agency (EEA) guidebook (Ntziachristos and Boulter, 2016). The IVE model is the most accurate computer-based model, and the availability and relative simplicity of obtaining input data are some of its advantages. It has the required flexibility to consider any local fleet composition and driving and start cycle in developing and underdeveloped countries for determining vehicle emission levels. It calculates the emission factor of pollutants not using existing statistical data but using dynamic data related to driving behavior and fleet composition in the city (Zhang et al., 2008).

The emission estimation process in this model is to multiply the base emission rate for each technology by a series of correction factors which are categorized into local (temperature, relative humidity, altitude, inspection and maintenance (I/M) classes), fuel specification, power, and driving variables (driving and start-up patterns, road grade, and air conditioner (A/C) use). Three categories of information are required as input for the IVE model; fleet, location, and base emission rate data. The last one is optional in the model and the first two should be site-specific and are mandatory to accurately calculate the emissions (Lents and Davis, 2009).

PMs are also produced as a result of the interaction between the vehicle's tires and the road surface, applying of brakes to decelerate the vehicle, and evaporation of material from surfaces at the high temperatures developed during contact. A wide range of particles from TSP to $PM_{0.1}$ (TSP, PM_{10}, $PM_{2.5}$, PM_1, and $PM_{0.1}$) are produced by these interactions. According to the EMEP/EEA guidebook and availability of detailed activity data of different vehicle categories (vehicle traveled-kilometer disaggregated by speed), the Tier 2 methodology has been used in this study (Ntziachristos and Boulter, 2016). For detailed information and equations for estimating exhaust and non-exhaust pollutants from mobile sources see the Appendix A Supplementary data.

1.2. *Residential and commercial buildings, and public service sources*

Energy consumption in residential and commercial buildings, and public services (schools, religious places, charities, etc.) sources are the other sources of urban air pollution. In this section Eq. (1) was also used EF is the emission factor of fuel combustion of these buildings and AD is the amount of consumed fuel. The requirements to use this equation are information such as the number of consumers, fuel quality, fuel type, fuel consumption, and any fuel exclusive emission factor. Emission factors of natural gas fuel, dominant fuel in Tabriz (gram per consumed fuel), or other fuel types have driven from the EPA- AP42 (EPA, 1998).

1.3. *Urban and service bus terminals*

Terminals of urban and intercity buses were considered as stationary sources in urban air pollution. The emission of pollutants from each terminal is obtained from Eq. (1), in which AD is the exact stopping time of buses in the idle operation mode at each terminal. Urban and intercity bus emission factors per minute of stop at each terminal can be obtained using the IVE emission model. The input information and equations of this model is the same as Sections 1.2 and Appendix A.

1.4. *Railways*

Railway station is one of the air pollution sources in the urban area. The following equations, Eqs. (2) and (3) are used to calculate the emission of pollutants from locomotives which is a modified form of Eq. (1).

$$EF_i = \sum_{n=idle}^{8} t_n \, EF_{i,n} \tag{2}$$

$$Ei = N \times HRS \times HP \times LF \times EF_i \tag{3}$$

where, EF_i is the emission factor of pollutant *i* during a trip, t_n is the spent time at notch position *n*, $EF_{i,n}$ is emission factor of pollutant *i* at notch position *x*, E_i is emission amount of pollutant *i* emitted by locomotives, *N* is the number of locomotives, *HRS* is total hours of activity, HP is average horsepower, and *LF* is load factor (Graver and Frey, 2016).

A design feature unique to railroad locomotive engines is the design and operation of the throttle. Engines can operate at only eight distinct power levels (throttle position), notch 1-8, for propulsion, and idle and dynamic brake. A different combination of engine speed and HP output is associated with each notch position. Depending on the time spent in each notch and notch position over an entire trip, the emission factors for each trip are determined (EPA, 1998). Emission factors of different locomotive engines can be obtained from reliable databases.

1.5. *Airports*

Research organizations such as International Civil Aviation Organization (ICAO) and Experimental Aircraft Association (EEA) have provided guidance and reports on the emission inventories of various airports all around the world. The choice of every method depends on the available data and resources and required accuracy. In each of these methods, the emission rate of an airplane is examined in two major operation phases, the Landing and TakeOff cycle (LTO) and cruise phase. All activities performed at an altitude less than 900 km are known as LTO and activities that take place above it are called cruise, therefor only LTO phase emissions are considered in the development of the emission inventory.

For detailed information and equations for estimating amount of pollutants emitted during the landing, takeoff, and LTO phase and emission of non-exhaust PM (as a result of abrasion) see the Appendix A. Information on emission factors of different types of airplanes is obtained from the ICAO database and for airplanes with no data, emission factors of similar models are used (ICAO, 2011).

1.6. *Fuel stations*

Gasoline has more volatile compounds than other fuels due to its high vapor pressure and low boiling point, which has made it one of the main sources of VOCs emission in the urban area. Two main sources in fuel stations are underground tanks (including tank breathing losses and emission during tank filling) and vehicle refueling (including losses during fuel refueling and spillage from the nozzle). Again Eq. (1) is used to calculate the monthly and annual emissions of VOCs, in which EF is VOCs emission factor and AD is the amount of sold fuel. For more information for estimating emission factors for these sources refer to the Appendix A.

1.7. *Industries*

Emission inventory of industries comprised of combustion and process emission. Due to each process and detailed specifications of them, EPA- AP42 tables were used. To calculate the total emission amount the Eq. (1) is used, in which the EF is emission factors of pollutants from polluting industries and AD is the amount of consumed fuel.

In the case of combustion sources, emission factors could be based on heat value (MMBtu/hr) rather than the volume of consumed fuel (MMscf/hr). In this case, AD in Eq. (1) is calculated using Eq. (4) (Olaguer, 2017).

$$\mathrm{AD} = V \times H \tag{4}$$

where, V is the volume of consumed fuel and H is the heating value of the intended fuel type.

1.8. *Energy conversion section*

In this section Powerplants, Petroleum refineries, and Petrochemical complexes are considered. The petrochemical company and the refinery with large chimneys, storage tanks, and large wastewater tanks emit a variety of pollutants into their surrounding atmosphere. Losses from fixed roof tanks, including standing and working loss, and losses from floating roof tanks, including standing and working (withdrawal) losses, the former includes the rim seal, deck fitting, and deck seam losses, are considered in this paper. More information on losses form fixed roof and floating roof tanks is provided in Appendix A.

Thermal power plants as electricity providers play an important role in the energy conversion sector. Power plants, as a stationary source of pollution, emit a wide range of pollutants into the atmosphere as a result of using a variety of fuels, raw materials, and products. The emission rate of a power plant is calculated using Eq. (1) as well, in which EF is the emission factors of consumed fuel in a large-sized boiler and AD is the amount of it driven from EPA- AP42 (EPA, 1998).

2. Case study

2.1. *Study area*

Tabriz, as the capital of East Azerbaijan province, is the most populated city and the largest economical and industrial hub in NW of Iran. Its population was 1,191,043 in 1996 (World Bank, 2005) and has reached over 1.77 million in 2016 with a population density of 7780 per square kilometer and the fourth populous city of Iran with 134 districts, 10 municipal areas, and 325 km^2 surface area (National Census data of 2006 and 2016).

Tabriz is enclosed by long ridges of volcanic mountains to the north, east, and south like a valley, which is opened up to Tabriz plain where the industrial belt is located. It has a semi-arid climate with regular seasons. The average annual temperature and annual rainfall are 12.3°C and 348 mm, respectively (World Climate, 1963–1990).

Topographic Geographical and meteorological characteristics conditions of Tabriz such as low wind speed, a high percentage of calm winds, and low temperature in cold seasons, consequently result in air stagnation and inversion, affecting the diffusion, dispersion, and accumulation of pollutants in the atmosphere, lead to intensification of air pollution in this city.

The high population growth in recent years has led to an increase in the number of vehicles in the city. Besides, narrow streets due to old texture, heterogeneous development of the city, and focus of demand centers in the central area of the city increase vehicle traffic, which has led to high pollution concentration in the city; therefore risk of exposure for residents with air pollutants becomes higher.

The presence of more than 0.6 million vehicles in the city and stationary sources such as residential, commercial, and public service, gas stations, railway, airport, bus terminals, and major industrial centers (power plant, petrochemical complex, oil refinery, and hundreds of industrial and manufacturer complexes), is the factors that have made Tabriz one of the polluted cities in Iran.

Air quality in Tabriz is far away from clean air standards. Tabriz city experienced 97 days (32%) with good, 170 days (56.3%) with moderate, 27 days (8.9%) unhealthy for sensitive groups, and 8 days unhealthy quality during April 2017–April 2018; which in some cases it led to the suspension of schools, universities, and offices (No information is available for other days).

2.2. *Data collection methods*

In this study, CO, NOx, SOx, VOCs (VOC and VOCevap.), and PM pollutants used as Tabriz emission inventory pollutants, call after TEIPs, for the baseline year of 1396 Solar Hijri calendar (April 2017–April 2018) has been developed. Tabriz pollution sources have been classified into two major categories: mobile and stationary sources. In the case of mobile sources, nine subcategories of mobile sources within the city boundaries and in case of stationary sources, residential, commercial, and public services, fuel stations, bus terminals, railway, airport, petrochemical complex and refinery, thermal power plant, and small and medium scale industries within the radius of 35 km of the city, have been considered.

2.2.1. *Mobile sources*

In mobile sources for all TEIPs, average emission factor and rate for different categories of vehicles, total vehicle emission, the share of each fleet, and link-based emissions in different areas of Tabriz have been studied. Three categories of exhaust, cold start, and also non-exhaust pollution (tire and brake wear and road surface abrasion) production were considered. In all, nine vehicle categories were considered, including PCs (Passenger Cars), taxis, and pickups as light-duty vehicles (LDV), urban buses, service buses, minibuses, light trucks, and trucks as heavy-duty vehicles (HDV), and two-wheelers (motorcycles) were the target fleet of this study. Different fuel types (gasoline, diesel, and Compressed Natural Gas (CNG)) and four street types, residential, arterial, highway, and bypasses were considered in this research too.

The accuracy of emission inventory depends upon the availability of reliable local data such as the fleet characteristics, driving and start-up patterns, vehicle flux, etc. Due to the lack of these data, primary surveys were necessary. Surveys and questionnaires were conducted to collect required data on fleet composition in this city. According to information obtained from the East Azerbaijan Traffic Police, there are 629,654 vehicles in the city of Tabriz by 2018. These sources consume about 1.25 million liters of gasoline, 0.37 million liters of diesel, and 0.79 million cubic meters of CNG on a daily basis in Tabriz, according to sales fuel data in 2017–2018.

To identify fleet composition and IVE technology indexes, more than 15,000 distinct vehicle technologies with all the details (engine volume, fuel type, usage, fuel delivery system, evaporative control system, and exhaust control system/standard) were examined.

Iran adapted European Emission and Fuel Regulations for vehicles from the year 2003. In the year 2003, the emission standard for vehicles was equivalent to Euro1. Euro2 standard implemented in 2005, Euro4 in 2014. As a benchmark, European countries adapted Euro6 in 2014. Euro3 standard was not implemented in domestic vehicles in Iran. Despite the implementation of the Euro4 standard in the country, heavy-duty vehicles (HDV) hardly meet Euro 3 standard or less. In Euro3 and lower standard, there is no requirement to use the after-treatment technologies in the exhaust, such as Diesel Particulate Filters (DPF), Selective Catalytic Reduction (SCR), and Diesel Oxidation Catalyst (DOC). Therefore, vehicles production year was considered as a representative for determining the vehicle emission level in the IVE model (Heger and Sarraf, 2018).

Field studies were conducted to determine the age parameter of technology indexes and the amount of accumulated mileage versus production year data was collected. This information was collected using the database of Tabriz inspection and maintenance (I/M) centers, questionnaires, and available literature information. Then, the accumulated mileage of vehicles in each fleet was plotted against the age of vehicles, and a quadratic polynomial curve was adopted to fit the relationship between accumulated mileage and ages. According to curves, an age-dependent annual mileage was assumed for each model year. Using this information, appropriate technology indexes were determined for all technologies available in the city. The vehicle classification based on age and emission standards is shown in Fig. 1.

Surveys, field studies, and questionnaires were also conducted to collect required data on driving and start patterns in this city. To prevent the scattering of results, sample streets and days were chosen for the study. Therefore, nine sample residential, arterial, and highway streets in low-income, high-income, and commercial parts of the city, and two bypass belt roads in the south and north were considered to measure the driving pattern. The study was conducted for twelve weekdays (two consecutive weeks) in February of 2018, from 6:00 a.m. 8:00 p.m. in each day. Speed, acceleration, and altitude change profiles measured by GPS-equipped vehicles.

The profiles obtained for the sample streets extended to all streets based on their classification. For this purpose, three PCs, buses traveling on the intended streets, and a motorcycle (due to the specific driving pattern of motorcycles) equipped with a GPS device were used. The measurements were performed for 20 minutes in an hour and extended to one hour. The driving pattern of other fleets (except PCs, buses, and motorcycles) was considered as that of PCs, as all vehicles were traveling with the same traffic conditions. There were not any specific traffic conditions such as accidents, VIP visits, constructions in driving pattern measurement to represent the real driving conditions in the city.

The recorded speed and acceleration profiles were examined using Eqs. (2)–(5) so the percentage of time that has been spent in each VSP/ES Bin was determined. For night hours and weekends, assumptions were made according to observations. The driving patterns of different fleets assumed the same throughout the year. Non-exhaust pollutant emission factors were obtained using driving pattern data and Eqs. (6) and (7).

For the start cycle, a 14-day questionnaire was prepared based on the time and type of the street on which the vehicle was turned on and off and distributed among local drivers from all different lifestyles, so the number of daily and hourly

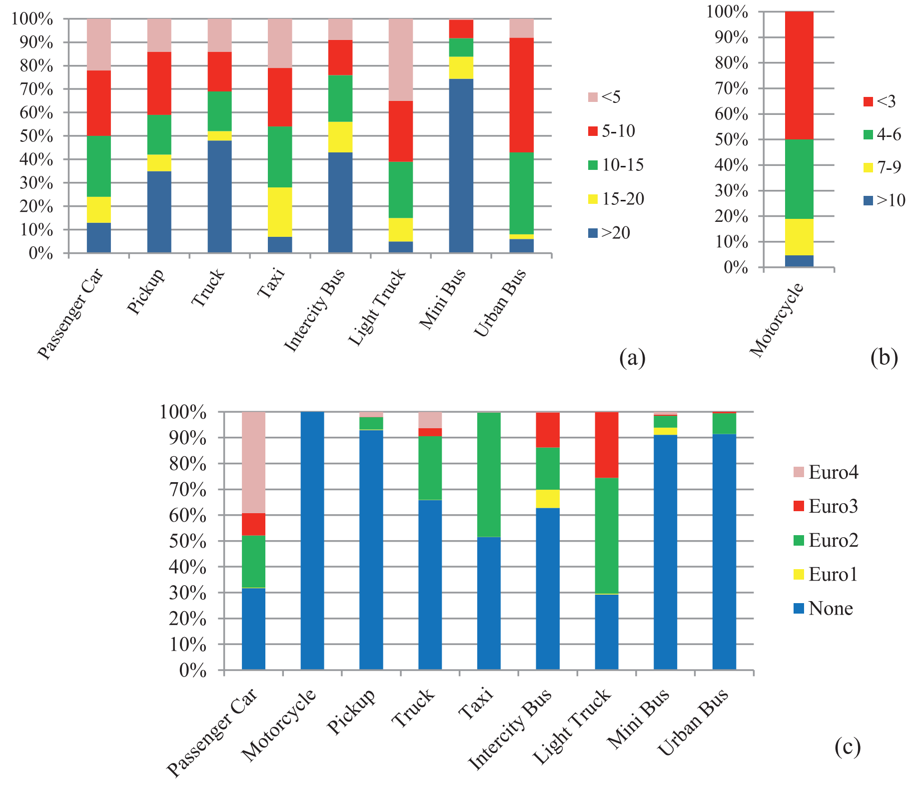

Fig. 1 – Vehicle classification based on (a) and (b) age and (c) emission standards.

startups and hourly soak time distribution were extracted over 138 traffic zone of Tabriz.

LDVs use EURO4 gasoline and also CNG while urban buses use diesel and other HDVs use gasoil with high sulfur content (more than 5000 ppm). The benzene content of gasoline fuel was assumed to be more than 2.5% and its oxygenate content more than 2%. In the case of CNG fueled vehicles the dominant fuel is CNG due to the high cost of gasoline in comparison with CNG.

Gasoline vehicles respectively form 87%, 41%, 67%, and 100% of PCs, taxis, pickups, and motorcycles. 13%, 59%, and 29% of PCs, taxis, and pickups use CNG as fuel almost all the time. While, only 4% of pickups are diesel-fueled, and all of the urban buses, intercity buses, minibuses, light trucks, and trucks are diesel-fueled (Appendix A).

In Iran, the inspection and maintenance (I/M) tests on chassis dynamometer are mandatory for all types of vehicles except motorcycles, so loaded centralized I/M class has been considered.

To get the total emission amount (according to Eqs. (8) and (9)) number of plying vehicles and the length of links are required. Since the traffic model of Tabriz is out of date (for the year 2005), counting was used to determine the vehicular flux. The number of on-road vehicles, based on the hourly monitored number of vehicles on different types of streets, was extended to the entire streets of the city. This information was corrected using monthly fuel sale data. Tabriz road network information, including coordinates of the beginning and end nodes of the links, length, type, and slope of the links acquired through the information of Tabriz Traffic Center. Roads were classified in bypass, highway, arterial, and residential (local streets and collectors), and also flat, uphill, and downhill. The total length of streets sums up to 1,089 km that bypasses, highways, arterials, and residentials account for 15.1%, 24.9%, 24.5%, and 35.5% of total road length in Tabriz, and uphill, downhill, and flat roads account for 44.5%, 34.9%, and 20.6% of total road length, respectively (Appendix A).

As there is no local emission factors for vehicles in Tabriz therefor the IVE model default values were used. Average start-up and running emission factors of TEIPs of all types of fleets and streets are given in Table 1.

In bypass streets: the start-up emission factor of pollutants was considered to be zero, since it is forbidden to stop vehicles next to these streets; emission factors of urban buses were assumed to be zero, because they are not allowed on these streets. In the case of service buses, which are not allowed on urban roads (except on bypasses), and since the terminals of these buses are located along the bypasses, start-up, running, and non-exhaust pollutants from this fleet were allocated to these streets. Studies on the driving pattern of motorcycles on residential, arterial, and highway streets have shown that it is almost the same on these streets, so the emission factors of motorcycles on these streets are the same.

2.2.2. *Stationary sources*

Residential and Commercial Buildings, and Public Service Sources: According to formal data, natural gas is the only source of energy in residential, commercial buildings, and public service sources; therefor monthly gas consumption in five gas fields of the city and different consumption categories, residential and commercial buildings, and public services, was

Table 1 – Average startup, running, and non-exhaust emission factors of all types of fleets and streets.

Fleets	Streets	Exhaust												Non-Exhaust	
		running (g/km)						Start-up (g/start-up)						(g/km)	
		CO	NOx	SOx	VOC	$VOC_{evap.}$	$PM_{exha.}$	CO	NOx	SOx	VOCs	VOCevap.	$PM_{exha.}$	$PM_{2.5}$	PM_{10}
Passenger cars (PCs)	Residential	39.93	2.89	0.0059	2.02	0.3746	0.02	39.11	1.40	0.0009	2.35	0.5066	0.02	0.02	0.03
	Arterial	40.66	2.62	0.0063	2.22	0.4557	0.01	39.11	1.40	0.0009	2.35	0.5066	0.02	0.02	0.03
	Highway	24.23	2.81	0.0050	1.67	0.2556	0.02	39.01	1.40	0.0009	2.34	0.5054	0.02	0.01	0.03
	Bypass	18.98	2.55	0.0045	1.68	0.1733	0.03	0	0	0	0	0	0	0.01	0.02
Taxis	Residential	52.68	5.32	0.0039	2.05	0.4308	0.01	39.65	1.96	0.0006	1.06	0.6163	0.02	0.02	0.03
	Arterial	53.12	4.86	0.0042	2.22	0.5230	0.01	39.65	1.96	0.0006	1.06	0.6163	0.02	0.02	0.03
	Highway	31.67	5.14	0.0033	1.71	0.2940	0.02	39.55	1.97	0.0006	1.05	0.6149	0.02	0.01	0.03
	Bypass	25.09	4.53	0.0030	1.64	0.1995	0.03	0	0	0	0	0	0	0.01	0.02
Pickups	Residential	51.62	4.34	0.0193	2.47	0.4124	0.02	38.73	1.86	0.0026	1.86	0.5563	0.03	0.02	0.03
	Arterial	52.40	3.96	0.0215	2.75	0.5011	0.02	38.73	1.86	0.0026	1.86	0.5563	0.03	0.02	0.03
	Highway	31.12	3.74	0.0120	1.98	0.2813	0.02	38.64	1.55	0.0015	1.86	0.5550	0.03	0.01	0.03
	Bypass	24.49	3.71	0.0130	1.88	0.1909	0.04	0	0	0	0	0	0.00	0.01	0.02
Urban Buses	Residential	4.21	12.77	0.0098	0.90	0	3.06	0.93	1.54	0.0001	0.09	0	4.44	0.06	0.10
	Arterial	5.65	13.75	0.0112	1.12	0	3.50	0.93	1.54	0.0001	0.09	0	4.44	0.06	0.10
	Highway	2.58	10.31	0.0077	0.58	0	2.33	0.93	1.54	0.0001	0.09	0	4.44	0.06	0.10
	Bypass	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Service buses	Residential	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Arterial	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Highway	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Bypass	2.08	12.13	0.7012	0.37	0	3.50	0.97	2.41	0.1452	0.37	0	10.09	0.05	0.09
Minibuses	Residential	2.41	4.26	0.4587	0.54	0.0063	0.95	2.14	0.47	0.0263	0.63	0.0038	1.63	0.11	0.17
	Arterial	2.61	4.59	0.5213	0.65	0.0077	1.09	2.14	0.47	0.0263	0.63	0.0038	1.63	0.11	0.17
	Highway	1.48	3.44	0.3607	0.37	0.0043	0.72	2.13	0.47	0.0262	0.63	0.0038	1.62	0.10	0.15
	Bypass	1.10	2.72	0.2934	0.27	0.0029	0.59	0	0	0	0	0	0	0.09	0.14
Light trucks	Residential	28.29	5.29	0.2931	0	0.2010	0.34	26.80	1.25	0.0283	1.40	0.2656	0.51	0.11	0.17
	Arterial	28.20	5.37	0.3329	0	0.2443	0.39	26.80	1.25	0.0283	1.40	0.2656	0.51	0.11	0.17
	Highway	17.27	4.58	0.2306	0	0.1371	0.26	26.74	1.25	0.0282	1.40	0.2651	0.51	0.10	0.15
	Bypass	13.75	3.81	0.1877	0.37	0.0930	0.22	0	0	0	0	0	0	0.09	0.14
Trucks	Residential	3.86	14.54	0.9034	0.70	0.0004	3.38	0	0	0	0	0	0	0.06	0.10
	Arterial	4.43	15.67	1.0266	0.87	0.0005	3.87	0	0	0	0	0	0	0.06	0.10
	Highway	2.37	11.75	0.7103	0.45	0.0003	2.58	0	0	0	0	0	0	0.08	0.10
	Bypass	1.65	9.29	0.5778	0.28	0.0002	2.10	0	0	0	0	0	0	0.05	0.09
Motor cycles	Other streets	28.02	1.00	0.0016	3.06	0.0985	0.32	34.86	2.93	0.0001	5.89	0.3359	0.26	0.01	0.01
	Bypass	11.30	0.70	0.0011	1.58	0.0452	0.49	0	0	0	0	0	0	0.01	0.01

inquired from Tabriz Gas Company. The annual gas consumption in the baseline year was 1685 million cubic meters in all in which the residential, commercial, and public service sectors consumed 1432.53, 182.4, and 69.36 million cubic meters, respectively. The gas consumption in some industrial sector that is located in the city was excluded and considered in the industrial section.

Urban and Service Bus Terminals: Fifteen urban and two service bus terminals are located in the city. The idle time at each of the urban and service bus terminals was taken from Tabriz Bus Organization. The average idle time for each urban and intercity bus on a weekday was 9 and 16 min, respectively. Idle times for weekend and semi-weekend days were also considered. Regardless of the season, they were the same throughout the year. Due to the technical defect of the ignition systems of urban buses which fail in a certain number of start-ups, they are not turned off during work hours and are working in-situ. The number of daily buses entering the Central Service Bus Terminal was 413 while it was 158 for the West Service Bus Terminal. The average emission factor of CO, NOx, SOx, VOCs, and PM pollutants in idle mode for each urban bus is 0.049, 0.2077, 0.0017, 0.0155, and 0.052 g/min, respectively; which is respectively 0.0394, 0.1754, 0.0013, 0.0163, and 0.076 g/min for each intercity bus, obtained from the IVE model (Additional information is provided in the Appendix A.).

Railway: Tabriz Railway Station is one of the air pollution sources in the western part of the city. In this study, the traffic of locomotives was studied within the station area and city boundaries. Information on the fleet composition of locomotives, fuel consumption, their activity profile, and idle time was obtained through correspondence with Tabriz Railways and provided brochures and catalogs. Based on the active locomotives, there are five GT26CW maneuver two-stroke locomotives, which have never been turned off except during maintenance and inspection, four Siemens Passenger locomotives (ER24PC), and two Railbus locomotives. The Railbus locomotives were considered to be similar to Siemens locomotives. Emission factors for two-stroke and four strokes locomotive engines were extracted from EMEP/EEA (Norris and Ntziachristos, 2016) and MTU corporation brochure (2014). Due to the high sulfur content of gasoil in Tabriz (more than 7,000ppm) real-world SOx emission factor was corrected using a mass balance (Additional information is provided in the Appendix A.).

Airport: Tabriz Airport located in the northwest part of the city, is considered one of the busiest airports in the country due to its geographical location. With the expansion of constructions and urban development, this airport has been gradually located in the urban area of Tabriz. The information of the airplane types and flight schedule of the airport, including the number of landings and takeoffs, the technology of airplanes were inquired for the baseline year; therefor hourly, daily, monthly, and annual emissions were calculated. Due to some limitations, only passenger flight information was provided. In all, there were 15,725 flights, including 7853 landings and 7872 takeoffs, in the baseline year.

Fuel Stations: There are 28 gasoline fuel stations in Tabriz, which are equipped with 532 gasoline nozzles. The fuel loading operation was considered to be submerged and uncontrolled. The monthly VOCs emission factor has been calculated using monthly average temperature and pressure information. With increasing temperature, the emission factor has also increased. Based on inquired data, nearly 460 million liters of gasoline have been sold by the stations in the urban area of Tabriz in the baseline year.

Industries: The total number of existing industries is 1813, of which 749 are located in the eight industrial parks on the outskirts of Tabriz and 1,064 are located outside the parks. Industrial units located around the city are divided into eleven subdivisions according to the type of processes: chemical, food, metal, textile, cellulose, non-metallic mineral, electricity and electronics, machine building, leather, pharmaceuticals, and other industries. One of the most important polluting industries is the cement industry, which supplies almost 3% of the country's cement needs; for this reason, it was examined separately from the industries. Almost all of the small and medium industries of the city use natural gas (about 99% of all the industries) and only combustion sources (boiler or furnace) are involved in emission estimation; except in the cement industry in which process PMs are calculated either due to its high pollution. Emission factors of the industrial and cement sectors were obtained from the AP-42 (AP-42-Chapter 11, Tables 11.6-1, 11.6-3, 11.6-7) and are given in Table 2 (Additional information is provided in the Appendix A.).

Energy Conversion Section: Southwestern part of Tabriz Industrial Zone with large industries such as petrochemical company and petroleum refinery is one of the main sources of air pollution in Tabriz and surrounding areas.

The emission of volatile organic compounds from the tanks was obtained using parameters such as vapor pressure, the molecular weight of fluid inside the tank, tank capacity, and the annual number of filled and emptied tanks inquired from the petrochemical company and the refinery. Overall, there are 74 fixed roof tanks, 41 external floating roof tanks, and 6 internal floating roof tanks in the refinery and the petrochemical company.

The emission of pollutants from furnaces was calculated using the concentrations of pollutants reported in the self-declared reports of the refinery and the petrochemical company and chimney parameters (such as velocity and flow rate of discharge gas and diameter and cross-section of each chimney). There are 25 chimneys in the refinery and 8 in the petrochemical company. Emissions from gas turbines and flares were also obtained using inquiry information and AP-42 emission factors (EPA, 1998).

Thermal Power Plant: Tabriz Combined Cycle Power Plant is located 16 km away from Tabriz city and has a practical capacity of 764 MW. The power plant has two steam units, each with a capacity of 350 MW, and two gas units with a capacity of 32 MW each. Pollutants are emitted from two long chimneys of the power plant. The plant's fuel is natural gas most of the year.

3. Results and discussion

This section provides the emission results from nine pollution sources introduced before. First, the results of emission from different categories of vehicles and emission modes

Table 2 – Emission factors of industrial units and cement industry.

Section	CO	NOx	SOx	VOCs	PM
Industries (g/m^3)	1.344	1.6	0.0096	0.122	0.088
Furnaces of Cement Factory (g/m^3)	1.344	3.048	0.0096	-	0.1216
Clinker Cooler with ESP (kg/Mg)	-	-	-	-	0.048
Raw Mill with Fabric Filter (kg/Mg)	-	-	-	-	0.0062
Finish Grinding Mill with Fabric Filter (kg/Mg)	-	-	-	-	0.0042

(running, start-up, evaporative, and non-exhaust) and then, sectoral distribution of the emissions from stationary sources is examined and the emission amount of each section is studied in detail. In the third section, the overall emission inventory of the Tabriz for the baseline year is studied, and also the emission distribution maps in the urban area are given. Finally, a number of emission reduction scenarios are proposed and their financial and reduction potential are analyzed.

3.1. *Data collection methods*

According to the studies, the total annual traveled distance throughout the city is 7562 million kilometers for the baseline year. Since PCs are the most abundant fleet, they have the highest traveled distance, around 77.7%. Taxis, pickups, motorcycles, minibuses, urban buses, light trucks, trucks, and service buses account for 9.5%, 5.3%, 2.6%, 1.3%, 1.2%, 1.2%, 1%, and 0.1% of the total traveled distance, respectively.

The mobile sources of Tabriz annually emit 412,000 tons of pollutants into the atmosphere, including CO, NOx, VOC, SOx, and PM account for 87.5%, 6.7%, 5.5%, 0.04%, and 0.3%. Fig. 2 presents the contribution of each fleet to the total emission by pollutant type. Due to their high number and traveled distance, PCs have the highest total emissions, followed by taxis, pickups, and motorcycles. PCs, taxis, and pickups had the highest emission of CO, NOx, and VOC pollutants. In the case of VOCs, motorcycles have a significant amount of emissions. Studies on the active fleet in the city showed that 99.2% of motorcycles have a carburetor fueling system. According to Heger and Sarraf (2018), 40% of fuel in carburetor motorcycles burn incompletely, which is the reason for the high emissions of VOCs and PMs from motorcycles.

Diesel-fueled vehicles have the lowest CO and VOC emissions and relatively high NOx emission (11%). Although they make up only 9.1% of the total vehicle and about 3.5% of the total annual traveled distance, heavy-duty vehicles are among the major sources of SOx and exhaust PMs. Trucks, minibuses, and light trucks are responsible for the emission of more than 70% of SOx pollutants. It should be noted that the diesel used by urban buses has low sulfur content, less than 50 ppm (contrary to gasoil with more than 5000 ppm sulfur content for other HDV), which reduces the emission of this pollutant from this fleet.

Urban buses, PCs, and trucks are the main sources of exhaust and non-exhaust PMs. Both weight of vehicles and traveled distance affect non-exhaust PM emissions. PCs, minibuses, taxis, and urban buses have the highest non-exhaust emission.

Two main reasons for the high emission rate of the vehicles of Tabriz are worn-out fleet and stressful driving conditions (low driving speed and the high number of decelerations and accelerations). More than 28% of vehicles in Tabriz are more than 15 years old (18% over 20 years old) and 19% of motorcycles are more than 7 years old in the baseline year. Minibuses, trucks, urban buses, and pickups are the most worn-out fleet respectively with the share of 74.4%, 48%, 43%, and 35% with over 20 years old, which have a higher emission rate normally.

Fig. 3 presents the distribution of emission according to running, start-up, evaporative, and non-exhaust modes. Vehicles have emissions in start-up and running (driving modes) and evaporative VOC emission (due to fuel combustion), and also non-exhaust PM emissions. Start-up emissions are a function of the start-up pattern, while exhaust, evaporative, and non-exhaust emissions are a function of the driving cycle (speed changes). Generally, running, start-up, non-exhaust, and evaporative modes contribute to 79.9%, 19.3%, 0.7%, and 0.1% of total emissions, respectively. Running CO, NOx, and SOx have the largest share and only evaporative emission is related to VOCs. About 26% of PM emission is related to non-exhaust PMs. To control and reduce emissions in each mode, it is necessary to modify the start and driving cycle separately.

3.2. *Emission inventory of stationary sources*

The stationary sources of Tabriz produce 38,700 tons of pollutants, annually CO, NOx, VOCs, SOx, and PM account for 18.8%, 5.9%, 43.8%, 28.9%, and 2.67% of total emission, respectively. Fig. 4 presents the sectoral distribution of emissions from stationary sources.

Annually 7200 tons of CO emit to the atmosphere by stationary sources and industries, petrochemical company and refinery, power plant, and households (also commercial and public services) are the main sources.

Stationary sources produce 16,900 tons per year of NOx pollutants and petrochemical company and refinery, industries, and households (also commercial, and public service) are next in the line. In the case of VOC pollutants with annual 2300 tons emission amount, fuel stations and petrochemical company, and refinery are the major emitters, almost equal in share.

Stationary sources are responsible for 11,200 and 1000 tons of SOx and PM emissions, respectively. Petrochemical and refinery are the main sources. Industries and railway, respectively are in the next ranks, and emissions from other sources are too low. Industries, households (also commercial and public services), and power plant accounted for 66.6%, 20.7%, and 11.5% of the total PM emissions, respectively.

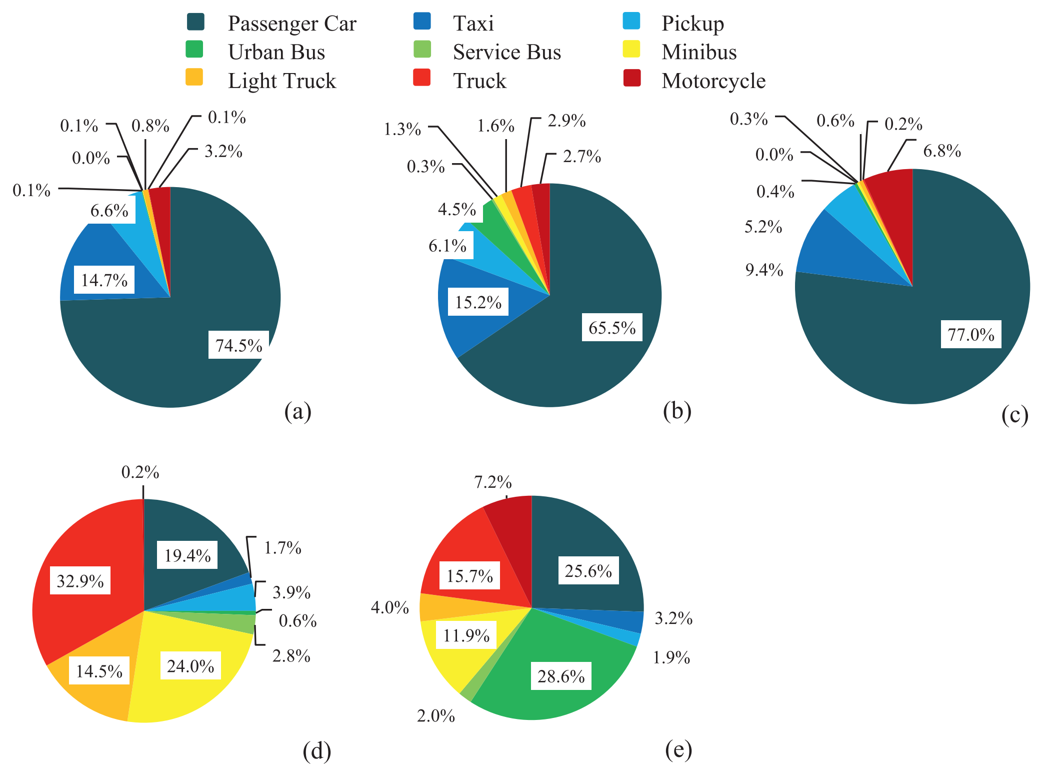

Fig. 2 – Fleet contribution in mobile sources emissions. (a) CO, (b) NOx, (c) VOC, (d) SOx, and (e) PM.

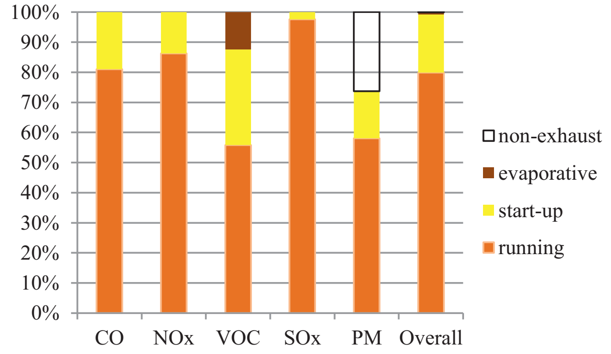

Fig. 3 – Contribution of each emission mode to total emission of pollutants.

Annually 4000 tons of pollutants are emitted by the household, commercial, and public service sectors. The highest amount of gas consumption and consequently emission amount occurs in December, January, and February, and reaches its maximum in January. This amount reaches its lowest level in July and September.

The annual emission of urban and service bus terminals is estimated to be 138 tons per year. Although the number of services and idling times at the Central Terminal is approximately 2.5 times that of the West terminal, the emission rate of them is approximately the same, due to the worn-out service bus fleet of the West terminal.

Based on the results, the railway emits 810 tons of pollutants into the atmosphere annually and SOx has the highest share. Two-stroke locomotives are responsible for a significant amount of NOx and SOx pollutants emission. They contribute to about 90% of total emissions from the railway, while four-stroke locomotives have a lower emission rate. The emission rate of the four-stroke locomotives at idle mode is almost twice traveling mode. The annual emission amount of the airport is estimated to be 341 tons, with a high emission amount of NOx and CO.

The annual VOC emission rate from fuel stations was estimated to be about 950 tons, 55.2% of which from the refueling activity of vehicles, 35.3% from filling underground tanks, 5.7% from breathing losses, and 3.8% from spillage loss. The highest VOC emission was occurred in July, August, and September due to high gasoline consumption in holidays and travel times of the country.

Industrial sources with natural gas fuel emit 6.6 thousand tons of pollutants into the atmosphere annually, with a high share of CO and NOx pollutants. In the industry section, the cement industry has the highest emissions, with 89.9% of total emissions from the industrial sector. The non-metallic and metallic industries are in the next levels while pharmaceutical and electronics industries have the lowest emissions.

In the energy conversion section, 28,600 tons of pollutants were emitted in the baseline year. As the refinery produces Euro4 gasoline and also Euro5 diesel, the emissions of SOx increase from the refinery itself.

Annually 18,300 tons of pollutants enter the atmosphere from refinery and petrochemical company, 84.6% of which is related to the refinery. SOx pollutants have the highest emission rate, and NOx, CO, and VOC are ranked next. The sulfur recovery unit (SRU) of refineries has the highest SOx emissions. The tail gases of SRU are highly contaminated, even under optimal operating conditions. Hazardous pollutants such

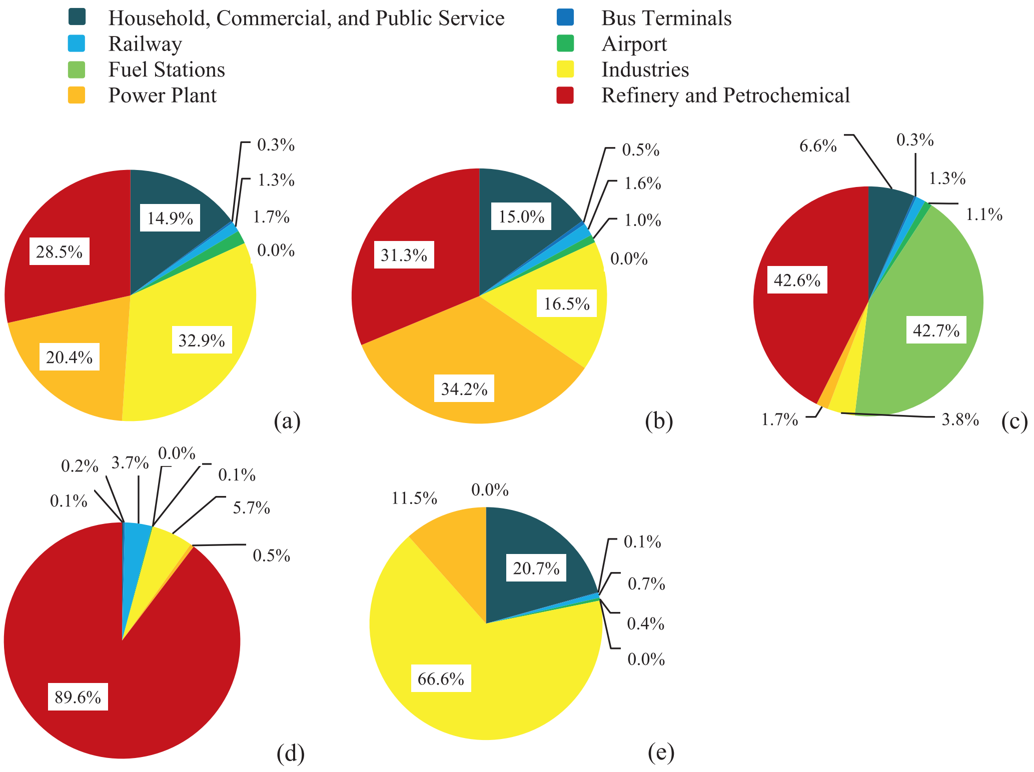

Fig. 4 – Sectoral distribution of emissions from stationary sources. (a) CO, (b) NOx, (c) VOC, (d) SOx, and (e) PM.

as sulfur dioxide and hydrogen sulfide flow to the SRU and there they are converted to sulfur dioxide by passing through a waste incinerator unit and entering into the atmosphere (Khazini et al., 2009). PM emission from these sectors was negligible. The refinery emits 18,300 tons of pollutants annually, of which 63.8% were related to SOx.

Petrochemical company is also responsible for the emission of 2,800 tons of pollutants. Storage tanks contribute to all VOC emissions from the refinery, while storage tanks accounted for 25% of the total VOC emissions from the petrochemical company. On the other hand, fixed roof tanks due to their high number, higher storage capacity, type of stored liquid, and the number of filling and emptying, emit more VOC emissions than floating roof tanks.

The combined cycle power plant with natural gas fuel annually emits 7,500 tons of pollutants, with a high share of NOx pollutants. The amount of natural gas consumption and consequently emission amount is the highest in August and the lowest in February.

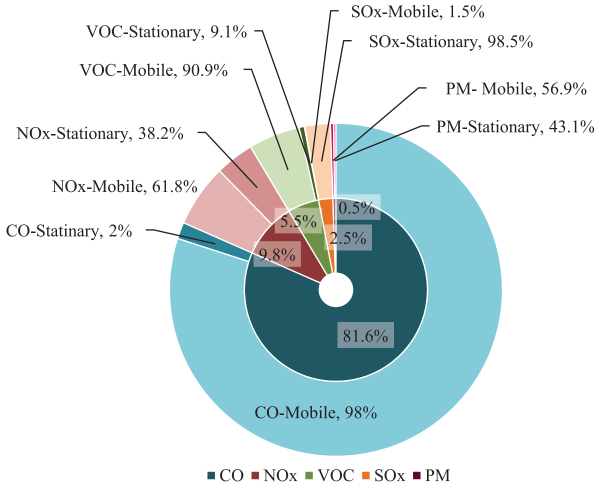

Fig. 5 – Tabriz emission inventory by mobile and stationary sources.

3.3. *Overall emission inventory*

Fig. 5 illustrates the emission inventory of TEIP including CO, NOx, VOC, SOx, and PM pollutants through stationary and mobile sources. Mobile sources remained the dominant source of CO, NOx, VOC, and PM pollutants, whereas stationary sources made the largest contribution to SOx emissions.

Fig. 6 presents the detailed sectoral distribution of Tabriz emission inventory. As mentioned earlier, mobile sources are the major sources of CO and VOC. Mobile sources, power plant, petrochemical company, and refinery are the main emitters of NOx in this city. Mobile sources, industries, and households (also commercial and public service) are responsible for most of the PM emissions. Petrochemical company and refinery with a share of 88.3% of the annual emission have the highest SOx emission. Industries and railway are ranked second and third. The emission per capita in Tabriz is 698.2 g per day, which includes 569.8 g of CO, 68.6 g of NOx, 38.6 g of VOC, 17.6 g of SOx, and 3.7 g of PMs.

Fig. 7 illustrates the emission distribution GIS maps of pollutants from all pollution sources within the urban area. Information of sources outside the city boundaries was not included in Fig. 7. The maps have been gridded with a 500m × 500m grid resolution.

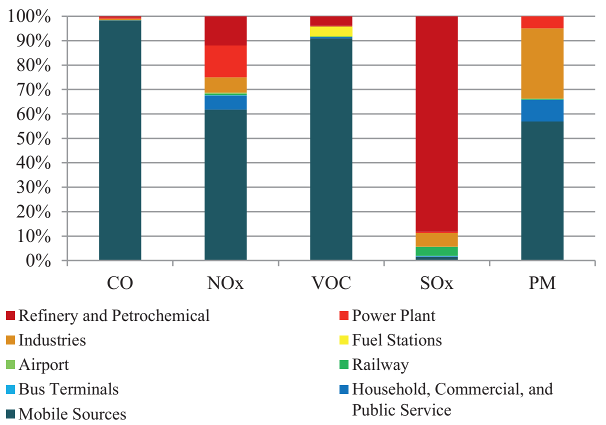

Fig. 6 – Sectoral distribution of the Tabriz emission inventory.

Due to the high share of mobile sources in CO and VOC emissions, especially LDV, the distribution of these pollutants has been spread throughout the city. These pollutants have the focus in agreement with the traffic intensity of the city. In the case of VOC emissions, fuel stations are one of the main sources, so at the fuel station geographical point, there are spots of pollution (Fig. 7**a** and 7**c**).

Fig. 7**b** reveals a hotspot of NOx emission in the location of the airport and the railway. The share of diesel vehicles in the emission of NOx emissions could not be neglected and its concentration is high along the busy streets, in the eastern and southeastern parts.

The emission distribution of SOx at the site of the airport, railway, and some busy streets, mainly with high traffic of gasoil fueled vehicles, is denser. Higher distribution is seen in the northwest and southeast parts of the city, due to the high traffic of high duty vehicles (such as service busses and trucks) (Fig. 7**d**).

In the case of PM pollutants, similar conditions are observed, due to the high share of mobile and household sources, it is scattered throughout the city. The distribution of pollutant emissions from the airport and the railway of Tabriz in small areas have led to the formation of emission hotspots in their site (Fig. 7**e**).

The emission inventory maps (Fig. 7) can be used to locate hospitals, schools, parks, etc., and also used for effective urban management. Proper location of new streets and specific buildings is very effective in reducing the effects of air pollution impact, consequently health effects and could be utilized for quality improvement of urban life.

3.4. *Scenario design and assessment*

Definition and evaluation of effects of different scenarios require accurate emission inventory for the specific location and period, which has been developed in this study. The purpose of this section is to develop applicable and effective scenarios according to the emission inventory of Tabriz and the major pollution sources. Potential reduction and financial analyses of each scenario (total cost, fuel saving revenue, and decreased social damage) are also performed.

Scenario planning is a structural process that involves the development of narratives that describe future alternatives, designed concerning important stimuli. After compiling the emission inventory in Tabriz metropolis, formulating policies to reduce air pollution and evaluating these policies were on the agenda. The purpose of this section is to determine applicable and effective policies.

The selection of air pollution mitigation scenarios has been done according to accurate literature studies and various examined options and strategies all over the world. In this section, fifteen scenarios for the major source of air pollution, mobile sources, and one scenario considering the main source of SOx pollution, the refinery, are proposed and TEIP emission change percent, total cost, revenue from fuel-saving due to fleet renovation and public transport development, and reduced social damage of pollutants for each scenario are also evaluated.

In Tabriz, because of inefficient public transport, people use PCs more than usual, therefore public transport system improvement can encourage people to shift from PCs to public transportation, and consequently a reduction in fuel consumption and air pollution. People also use taxies as a semi-public transport. Based on field studies in this city, the average daily number of passengers transported is 3 for a PC, 65 for a taxi, and 750 for a bus. Therefore, by adding a taxi and a bus to the Tabriz urban transportation system, 21.7 and 250 PCs are removed from the system on a daily basis, and as a result, the amount of pollution caused by these PCs is eliminated. It is also necessary to prepare the social and cultural infrastructure for the implementation of these types of scenarios.

The total cost is defined as the total amount of the initial investment for the implementation of each scenario. It is including the cost of new a vehicle and required infrastructure for implementing the scenario minus the amount of money earned by selling worn-out vehicles, which is calculated using Eq. (5).

$$T = (N_\mathrm{i} \times C_\mathrm{N} + C_I) - (M_\mathrm{i} \times C_w) \tag{5}$$

where, T is the total cost, N_i is the number of replaced or added vehicles, as well vehicles equipped by DPF, C_N is the cost of new vehicles or in case of DPF installation is the cost of the DPF, C_I is the cost of the required infrastructure for implementing of each scenario, M_i is the number of worn-out vehicles which have been scrapped, C_w is the cost of scrapped vehicles (in case of replacement of vehicles), and i is the fleet type (PCs, taxis, urban buses, trucks, and motorcycles). C_N and C_w are obtained based on local information. C_I is zero for all the scenarios except scenario 15, concerning the replacement of carburetor motorcycles with electric ones which is $5.5MM (million dollars). The construction cost of the tail gas treating unit (scenario 16) is estimated at $2.3MM.

By renovation of the fleet, the amount of fuel consumed by each fleet is reduced (the difference between the fuel economy of new and old vehicles), and the income from the sale of this surplus fuel at the Persian Gulf free on board (FOB) price generates an annual income for the government.

Fuel saving by implementing each scenario is the product of income from selling surplus fuel minus fuel used by new

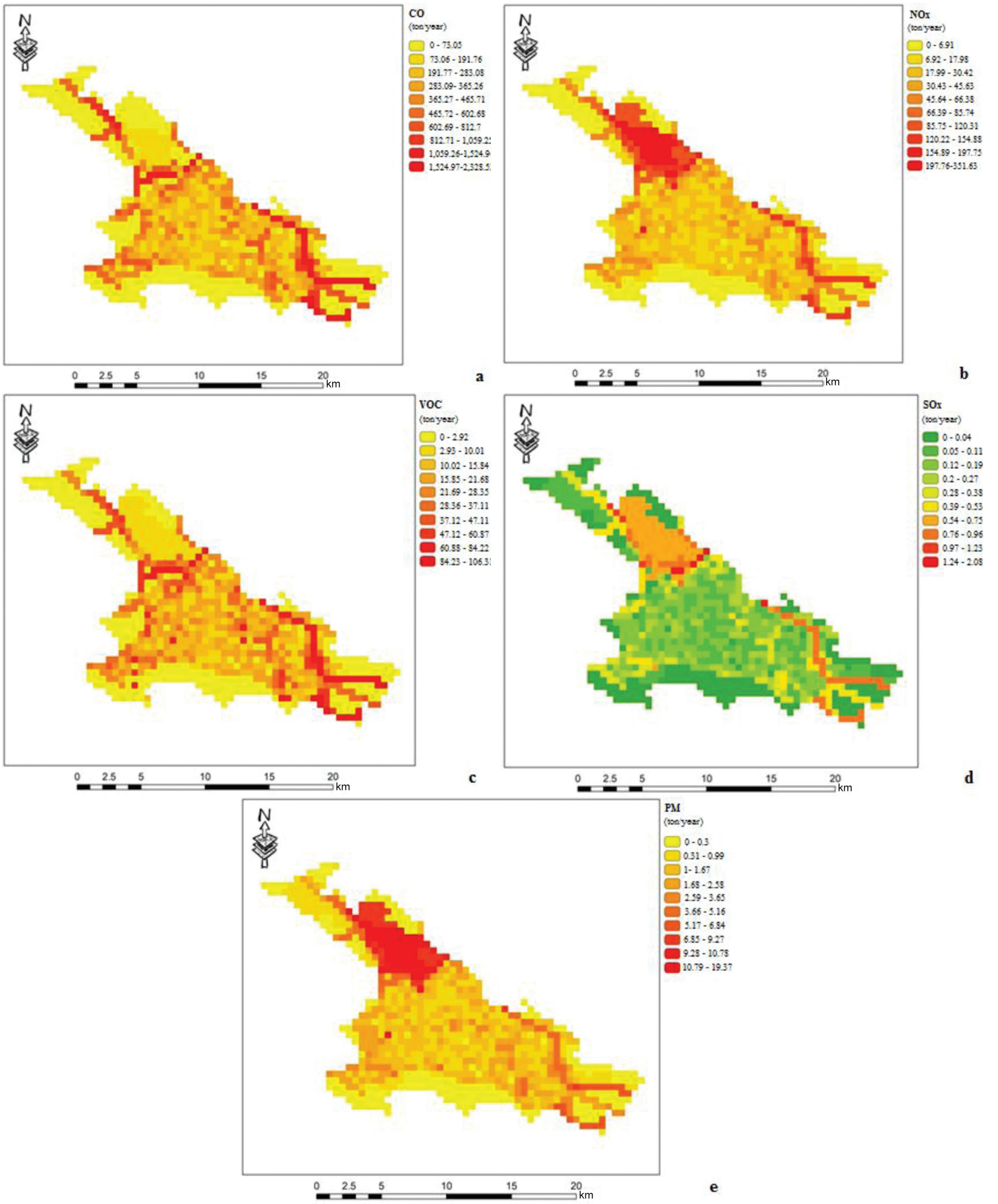

Fig. 7 – Emission distribution maps of (a) CO, (b) NOx, (c) VOC, (d) SOx, and (e) PM pollutants within urban area.

vehicles added to the fleet and is calculated by Eq. (6).

$$FS = N_i \times VTK_i \times \Delta FE_{i,j} \times FOB_j - N_{add,i} \times VTK_i \times FE_{i,j} \times FOB_j \qquad (6)$$

where, VTK_i is annual vehicle traveled kilometer by fleet i, ΔFE_i is fuel economy difference between new and worn-out vehicles, FOB_j is the Persian Gulf FOB price of gasoline or diesel which is \$0.26 per liter of gasoline and \$0.27 per liter of diesel, $N_{add,i}$ is the number of vehicles of the fleet i which is added to the urban transportation system, and j is fuel type. The cost and fuel economy of new and worn-out vehicles of each fleet studied in the scenario design section are presented in Table 3.

By implementing each scenario the emission amount of each pollutant is changed. Each pollutant has social damage which reflects damages and risks to society. In this study, the reduced social damage (RSD) which is concerning the reduced damage by reducing the emission amount of each pollutant in each scenario is evaluated using Eq. (7).

$$RSD = \sum_k \Delta E_k \times D_k \qquad (7)$$

where, ΔE_k is the reduced emission of pollutant k in each scenario, k is pollutant type (CO, NOx, VOC, SOx, and PM), and D_k

Table 3 – Cost and fuel economy of new and worn-out vehicles of each fleet.

Fleet	Fuel	C_N ($)	C_w ($)	FE_{New} (L/100 km)	FE_w (L/100 km)
PC	Gasoline Euro4	6330	400	11	8
	CNG	6330	400	-	5.5
	Hybrid	41000	400	-	4
Taxi	Gasoline Euro4	6330	400	11	8
	CNG	6330	400	-	5.5
	Hybrid	41000	400	-	4
Urban Bus	DPF	5133	-	-	-
	Diesel Euro4	124000	5600	49	41
	CNG	149000	5600	-	0*
Truck	DPF	5133	-	-	-
	Diesel Euro4	124000	5600	63	59
Motorcycle	Fuel	550	133	3.5	2.5
	Electric	1413	133	-	0

* Depend on the fraction of time that vehicle uses CNG (It is assumed to be zero and the bus which is equipped by a CNG tank uses CNG throughout the trip.)

is the social cost of pollutant k, which is considered to be $26.1 per ton of CO, $10,391 per ton of NOx, $2489.9 per ton of VOC, $10,783.1 per ton of SOx, and $63,522.4 per ton of PM (Lee et al., 2002)

Details of designed scenarios concerning mobile sources as the main source of CO, NOx, VOC, and PM pollutants and stationary sources as the main source of SOx and their TEIP emission change percent, total cost, fuel-saving revenue, and reduced social damage of pollutants are presented in Table 4.

Studies show that phasing out old vehicles and shifting to new vehicles with high emission standards and alternative fuels would be an obvious step in the emission reduction process. Scenarios 1 and 2 examine the replacement of PCs with Euro 4 PCs and hybrid PCs, with a significant reduction in CO, NOx, and VOC.

The emission reduction of TEIP is almost the same in scenarios 3 to 5, which examine the replacement of worn-out taxis with Euro 4 taxis, CNG fueled taxis, and hybrid taxis, respectively. According to the conducted survey by the IVE emission model on the replacement of PCs and taxis and special driving pattern of Tabriz (low speed and the high number of accelerations and decelerations), hybrid vehicles reduce the emissions by almost equal to their counterparts with Euro 4 standard, or CNG fuel, while the cost of hybrid vehicles is much higher than their counterparts.

In scenario 6, adding 3,000 Euro 4 taxis to the urban transportation system is examined and a significant amount of reduction of CO, NOx, and VOC is observed, while reduction of SOx and PM is lower.

In the case of replacement of worn-out buses with Euro 4 and CNG fueled buses (scenarios 7 and 8); there is no change in CO, VOC, and SOx, however, NOx and PM emissions decreased. In the case of scenarios 9 and 10, respectively 50% and 85% increase in the number of urban buses, higher emission reduction is observed compared to the other scenarios related to urban buses. Replacing urban buses is no more economical than increasing the number of city buses by 50% and 85%. In the case of DPF (Diesel Particulate Filter) installation on urban buses, the only noticeable reduction is in PM emissions (Scenario 11).

According to studies on the trucks, including replacement of worn-out trucks with Euro 4 trucks (scenario 12) and installation of DPF on worn-out trucks (scenario 13), the only major reductions are observed for PM and NOx pollutants and they are not economically viable.

In the replacement of carburetor motorcycles with motorcycles with fuel-injection systems, a decrease in CO, NOx, VOC, and PM pollutants is observed, while the SOx emission rate does not change at all. In the replacement of carburetor motorcycles with electric motorcycles, CO, VOC, and PM pollutants decrease, while NOx and SOx pollutants increase.

Scenario 10, in which an 85% increase in the number of urban buses is examined, has the highest emission reduction rate. It can be considered in the short-term mitigation programs and significant emission reduction from mobile sources could be achieved. Scenarios such as 1, 3, 4, 6, 9, and 14, which have emission reduction in the range of 0.7% to 8.45% and moderate cost, could be considered as medium-term air pollution mitigation programs (4 to 7 years). Scenarios that have a very high cost despite their low emission reduction potential, such as scenarios 2, 5, 7, 8, 11, 12, 13, and 15, are not economically viable, and their implementation at a high cost does not significantly change the emission amount. Despite their high cost, the replacement of city buses and trucks does not significantly reduce urban air pollution.

The refinery is the main source of SOx pollution, accounting for about 90% of the city's SOx emissions. In scenario 16, construction of Tail Gas Treating Unit for the sulfur unit of the Tabriz Refinery is considered, respectively with a 55% and 10% reduction in SOx and CO emissions.

An important issue that should be considered by planners in this section is that the choice of travel method by each citizen is a function of the four parameters of "cost, speed, comfort, and safety of travel"; therefore, in the implementation of any scenario, the requirements of that scenario must be fully seen. For example, in the discussion of developing and improving the public transport fleet, the necessary measures should be taken, such as choosing appropriate routes, increasing the cost of private car traffic in the city, etc., so that citi-

Table 4 – Proposed scenarios and their financial and potential reduction analyses.

Scenario	Description	Total Cost ($MM)	Fuel saving revenue ($MM/year)	Decreased social damage ($MM/year)	Emission Changes (%)*				
					CO	NOx	VOC	SOx	PM
1	Replacement of PCs with an age of more than 20 years old with Euro4 PCs (replacement of about 55000 PCs)	326	6.1	32.8	-8.28%**	-8.74%	-11.33%	-1.15%	-0.88%
2	Replacement of PCs with an age of more than 20 years old with hybrid PCs (replacement of about 55000 PCs)	2232	11.2	32.8	-8.28%	-8.74%	-11.33%	-1.15%	-0.88%
3	Replacement of worn-out taxis with an age of more than 15 years old with Euro 4 taxis (replacement of about 3100 taxis)	18.4	1.6	2.7	-0.49%	0.12%***	-5.2%	-1.33%	-0.07%
4	Replacement of worn-out taxis with an age of more than 15 years old with CNG fueled taxis (replacement of about 3100 taxis)	18.4	3.7	2.7	-0.48%	0.11%	-5.19%	-1.33%	-0.07%
5	Replacement of gasoline fueled taxis with an age of more than 15 years old with hybrid taxis (replacement of about 3100 taxis)	125.9	2.9	2.7	-0.48%	0.11%	-5.19%	-1.33%	-0.07%
6	Increment of 3000 Euro 4 taxis	45	8.2	26.5	-7.39%	-6.36%	-8.73%	-2.31%	-3.17%
7	Replacement of 715 diesel buses with Euro 4 buses	84.7	1.6	4.2	0%	-0.35%	0%	0%	-3.67%
8	Replacement of 715 diesel buses with CNG fueled buses	102.5	9.8	4.2	0%	-0.35%	0%	0%	-3.67%
9	50% increase in urban bus numbers	54.1	11.2	48.2	-5.59%	-3.06%	-5.36%	-1.27%	10.65%
10	85% increase in urban bus numbers	91.9	18.9	81.8	-31.07%	-24.82%	-30.38%	-8.08%	10.43%
11	DPF installation on urban buses without a DPF (on about 452 buses)	2.3	0	6.2	0%	-0.46%	-0.01%	0.06%	-6.61%
12	Replacement of worn-out trucks without emission standard with Euro 4 trucks (replacement of about 22900 trucks)	2353.7	1.6	16.3	-0.03%	-1.22%	-0.09%	-0.06%	-8.37%
13	DPF installation on trucks without a DPF (on about 22900 trucks)	117.6	0	13.9	0%	-1.31%	-0.03%	0%	-9.4%
14	Replacement of carburetor motorcycles with fuel injection motorcycles (replacement of about 92000 motorcycles)	38.4	0.5	14.9	-2.48%	-2.28%	-5.2%	0%	-6.09%
15	Replacement of carburetor motorcycles with electric motorcycles (replacement of about 92000 motorcycles)	123.6	1.8	3	-2.34%	0.41%	-4.82%	2.66%	-1.54%
16	Construction of Tail Gas Treating Unit for the sulfur unit of the Tabriz Refinery	2.3	0	79.5	-10%	-1%	0%	-55%	0%

zens' public acceptance of the public transport system is increased and the effects, such as reducing the traffic of private cars and consequently reducing social costs, fuel consumption, etc. occur in practice.

Further modeling studies are required to show the dispersion of the emitted pollutants and consequently to predict future air quality and concentration of formed secondary pollutants. Moreover, the socio-political factors may cause considerable uncertainty on the projected emissions, which are beyond the scope of the current study. It is also important to note that treating fuels and vehicles as a joint system is critical and cleaner vehicle technology generally requires improved fuel quality and conversely.

Public awareness and participation in combating air pollution are the main pillars of mitigation strategies of air pollution. Road paving and regular road washing and cleaning for reducing non-exhaust emissions from vehicles and road dust (Bhanarkar et al., 2018), switching to non-motorized modes of transportation, by building pedestrian and bicycle paths or by encouraging cleaner alternatives such as electric vehicles, compliance with enforced vehicular norms, removal of encroachments on the roads, increasing the average vehicular speed by increasing the available roadway to avoid poor fuel efficiency, reducing congestion, reducing accidents, providing poorer areas with access to means of transportation (Heger and Sarraf, 2018), improvement of parking facilities, proper maintenance and inspection of old and in-use vehicles, and control of firecracker use could be considered as additional air pollution control strategies. Economic measures such as penalties for heavy emitters in the industrial, commercial, or transport sectors could also be considered (Majumdar et al., 2020).

4. Conclusion

Daily increment of urban population has led to increased urban activities and air pollution production, which has turned air pollution into a major problem in all crowded megacities. Urban air pollution has destructive environmental, health, and financial effects on urban areas and populations. Efficient management and control of urban air pollution require identifying air pollution sources and measuring the air pollution emission levels of these sources, in other words, compiling and developing an emission inventory. This inventory data is used to support decision-making on environmental protection issues in cities and countries. It is considered a good practice that countries update and improve the quality of national inventories (transparency, accuracy, completeness, comparability, and consistency) continuously. The development of an emission inventory requires the provision of extensive information that is not available completely in developing countries. Therefore, this study has been conducted to provide a comprehensive framework and methodology for developing comprehensive emission inventories in developing countries with restrictions in providing input data, by presenting a megacity case study, Tabriz, NW of Iran.

Under the scope of this study, primary sources of CO, NOx, VOCs, SOx, and PM emissions within the 35 km of the city have been considered for projection of the total emission through one year from April 2017 to April 2018. Nine main urban emission sources, mobile sources (covering PCs, taxis, pickups, urban and service buses, minibuses, light trucks, trucks, and motorcycles), residential, commercial, and public services, fuel stations, bus terminals, railway, airport, petrochemical complex and refinery, thermal power plant, and industries, have been considered.

Emission factors and activity data are the two major building blocks of every emission inventory. Emission factors required for all vehicles in mobile sources, and urban and service bus terminals were obtained using the IVE model while for other sources EPA emission factors were used. Activity data for each sector have been obtained by field studies, questionnaires, local databases, and self-declared reports.

Mobile and stationary sources of Tabriz emitted CO: 368,340, NOx: 44,580, VOC: 24,917, SOx: 13,340 and PM: 2428 tons annually, with the share of 98%, 90.9%, 61.8%, 1.5%, and 56.9% of mobile sources, respectively. Passenger cars (PCs) had the highest total emissions, followed by taxis, pickups, and motorcycles. Light-duty vehicles (PCs, taxis, and pickups) were the main source of CO, NOx, and VOCs. Although the trucks, minibuses, and light trucks make up only 9.1% of the total vehicle and about 3.5% of the total annual traveled distance, they are responsible for the emission of more than 70% of SOx and 32% of PM emissions. Urban buses, PCs, trucks, minibuses, and motorcycles were the main emitters of exhaust and non-exhaust PMs. PCs, minibuses, taxis, and urban buses have the highest non-exhaust PMs. Generally, running, start-up, non-exhaust, and evaporative modes contributed to 79.9%, 19.3%, 0.7%, and 0.1% of total emissions, respectively. The results show that the petrochemical company, refinery, and thermal powerplant constituted about 67% of the total emission from stationary sources, and the refinery was responsible for about 90% of total SOx emissions. The airport and bus terminals have the lowest emission amount.

The emission distribution maps within the urban area also were presented. As mobile sources were the main source of CO and VOCs, their dispersion have been scattered throughout the city. The southeastern, northern, and northwestern parts of the city and site of busy streets had higher emission concentrations. In the case of NOx pollutant, the map revealed a hotspot in the northwestern and western parts of the city and eastern and southeastern parts on the location of busy streets. Higher concentrations of SOx in the northwest and southwest parts of the city at the site of the airport, the railway, and some busy streets were observed. The high share of mobile and household (also commercial and public service) sources in the PM emission has increased its distribution throughout the city, and the emission hotspot is still seen in the northwestern and southeastern parts, as well as in some busy and centralized areas of the city.

A number of scenarios concerning mobile and stationary sources were proposed and their potential emission reduction and financial analyses (total cost, fuel-saving revenue, and reduced social damage of pollutants) were also performed. Scenario considering 85% increase in the number of urban buses has the highest emission reduction and the lowest cost compared to its reduction potency. It can be considered in the short-term mitigation programs and significant emission reduction could be achieved. Scenarios considering replacement of PCs and taxis with Euro 4 PCs and taxis, replacement of taxis with CNG fueled taxis, respectively 27% and 50% increment in the number of taxis and urban buses, and replacement of carburetor motorcycles with motorcycles equipped by fuel injection system, which had the emission reduction in the range of 0.7% and 8.5%, could be considered as medium-term air pollution mitigation programs. Given that stationary sources are the main source of SOx emissions and the refinery is the main cause of this share, the construction of Tail Gas Treating Unit for the sulfur unit of the refinery was considered and a 55% reduction in SOx emissions was predicted.

There are some strengths and weaknesses to this study. Proper and efficient management of urban air pollution and air quality requires a comprehensive emission inventory, consequently a large amount of basic data; however, in developing countries, this information is not in hand or difficult to obtain. In this study, a general and comprehensive framework has been developed for this reason; which has made this research unique and could be a puzzle piece in emission inventory studies and used by analogous megacities in the developing countries. Another strength of this article is the detailed definition of methodologies with sufficient detail separately by major emission sources are in megacities including mobile sources, residential, commercial, and public services, fuel stations, transport terminals, energy conversion section and also industries.

In addition to the strengths, this study has some limitations. The lack of an updated traffic model for Tabriz and local emission factors were the main drawbacks of the current study. The research team could not access some information such as fuel oil consumption in residential complexes and small-sized industries, also military flights, and runway vehicle information of the airport. Given these limitations, the authors suggest that these sources also be examined in future studies to improve the accuracy of the estimated emissions.

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Appendix A Supplementary data

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jes.2022.02.035.

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