Environ Monit Assess (2019) 191: 239
https://doi.org/10.1007/s10661-019-7364-9

Development of a road traffic emission inventory with high spatial–temporal resolution in the world's most densely populated region—Macau

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Received: 24 October 2018 / Accepted: 1 March 2019 / Published online: 22 March 2019

Abstract With rapid economic growth, road transport is contributing substantial adverse effects on urban air quality, especially in densely populated cities with high growth rate of GDP per capita, such as Macau. A high spatial–temporal resolution road traffic emission inventory is essential for assessment of environmental stresses imposed by local vehicle movements. To improve the accuracy and temporal–spatial resolution for emission inventory, through a bottom-up approach, link-based road traffic emission inventory with a spatial resolution of 0.1 km ∗ 0.1 km and a temporal resolution of 1 h for Macau in 2014 was developed by using a traffic model (VISUM), a road traffic emission model (TREM), the Geographic Information System (GIS), and the most up-to-date information available. Results show that the total annual emissions of CO, CO_2, PM, NO_X, and VOC in 2014 were 14,770, 413,099, 69, 1151, and 2945 tons, respectively. The estimated fuel consumption agreed well also with the statistical fuel consumption in Macau. Meanwhile, analysis of 3 scenarios on changes of road traffic emissions due to the operation of a light railway transit (LRT) system, variation on share of diesel, electric, and gasoline within the vehicle fleet, and replacement of vehicles with ones of Euro 5 and Euro 6 emission standards was carried out. This study provides a solid framework for developing high spatial–temporal resolution emission inventories for other densely populated cities of small area.

Keywords Emission reduction scenarios · Macau SAR · Road traffic model · Road transport emissions · Emission inventory · High resolution

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Introduction

Macau Special Administrative Region (SAR), a small city in the southern coast of the Pearl River Delta in China, is one of the world's most densely populated regions. It has an area of 30.3 km^2 and a population of 636,200 with a density of 20,500 people per square kilometer (until 2014). The economic condition of Macau heavily relies on the tourism and leisure industry. The cumulative visitor arrivals have reached 31.53 million by the end of 2014, a 90% growth from that in 2004 (DSEC 2014). However, high population density and fast economic growth result in the increasing number of vehicles and heavy road traffic (Lee 2012), which lead to the emission of abundant and various air pollutants. The number of registered vehicles in Macau increased about 50.0% from 2000 to 2013 and reached 239,795 in total by 2014 giving a very high 566 vehicles per kilometer of road figure (DSEC 2014). According to the monitoring data, the annual average concentrations of air pollutants, such as particulate matter (PM), nitrogen dioxide (NO_2), and carbon monoxide (CO), were the highest at roadside stations in comparison with other monitoring stations (DSPA 2015). Therefore, in Macau, the road transport sector is the biggest local air pollution source and the emission from the road transport is a main contributor to air pollution.

Although it is evident that air pollution from the transport sector is a main source in Macau, there is limited information focusing on the emissions of this sector. The Macau government publishes total emission for the road transport sector of the year without spatial–temporal distribution. However, the emission inventory with spatial–temporal distribution is an important input data for local-scale air quality model and a useful tool for evaluation on the effectiveness of potential measures through scenario analysis (e.g., usage of cleaner fuel, road traffic control, implementation of a new public transportation system), because it not only provides the amount of the air pollutant emitted within a specific period but also displays the spatial–temporal distribution of the pollutant sources by dividing the study area into a number of small grids (Liu et al. 2018). In addition, the studies about road traffic emission inventories of Macau are limited. Zhang et al. (2016) developed a link-based vehicle emission inventory with a spatial resolution of 0.5 × 0.5 km and temporal profile of 1 h by using a traffic model (TransCAD) and an emission factor model (EMBEV-Macau). However, the spatial resolution is not fine enough for a small city with a street width of less than 0.1 km. Secondly, they estimate annual emissions based on the daily emission without the consideration of the difference between emissions of different days. Thirdly, their emission study was only speed-dependent without considering terrain characteristics. Thereby, there is a need to develop a more refined emission inventory in Macau.

Emission inventories are usually estimated with two different approaches—(1) top-down approach and (2) bottom-up approach. For the national or regional level, the top-down approach, which does not require great amount of data, is commonly applied. Meanwhile, emission inventories developed for local and urban applications mostly compiled through bottom-up approaches (Guevara et al. 2016). Because of relying on different approaches, comparisons between national emission inventories with local emission inventories have pointed out significant discrepancies, especially in terms of allocation and total amount of PM residential biomass emissions (Pallavidino et al. 2014). Both top-down and bottom-up approaches require information concerning activity factors (e.g., total amount of fuel consumed) and emission factors per activity (e.g., amount of pollutant emitted per activity unit). Nevertheless, emissions compiled through a bottom-up approach are based on more specific information for each sector, such as housing units or number of vehicles per road link for domestic heating and traffic emissions, respectively (Dios et al. 2012). Alternately, top-down approaches are based on the disaggregation of variables defined at the regional or national level (e.g., fuel sold or consumed) in smaller areas based on auxiliary spatial surrogates that represent the activity (e.g., population density for wood burning emissions), thus achieving better spatial details (Dios et al. 2012). Bottom-up approaches allow higher spatial and temporal details, although they require a greater amount of data and, thus, more resources. Therefore, the bottom-up approach is more appropriate for application in smaller region, since it is easier to obtain the needed detailed data, and it provides finer resolution for analysis (López-Aparicio et al. 2017). Furthermore, the bottom-up approach also provides more accurate and reliable estimation on transportation emission as it allows the estimate of emission data with greater spatial and temporal details, and the improvement of resolution on vehicular emission inventory can substantially improve the accuracy for areas containing traffic-dense microenvironment (Jing et al. 2016; McDonald et al. 2014; Pallavidino et al. 2014).

The main objective of this study is to develop a high spatial–temporal resolution inventory of road traffic emissions in the urban area of Macau based on the year of 2014 through a bottom-up approach. The spatial resolution of this study is set at 0.1 × 0.1 km. In addition, hourly, daily, and monthly temporal profiles of traffic emissions will also be patterned. Results of this study will contribute to the knowledge on accurate distribution of road traffic emissions with high temporal–spatial resolution, which are important inputs for air quality model in order to better evaluate the air quality of Macau and to make further regulation plans.

Methodology and data

Road transport emissions

The framework of estimating the road traffic emissions consists of three steps, as shown in Fig. 1, which are as

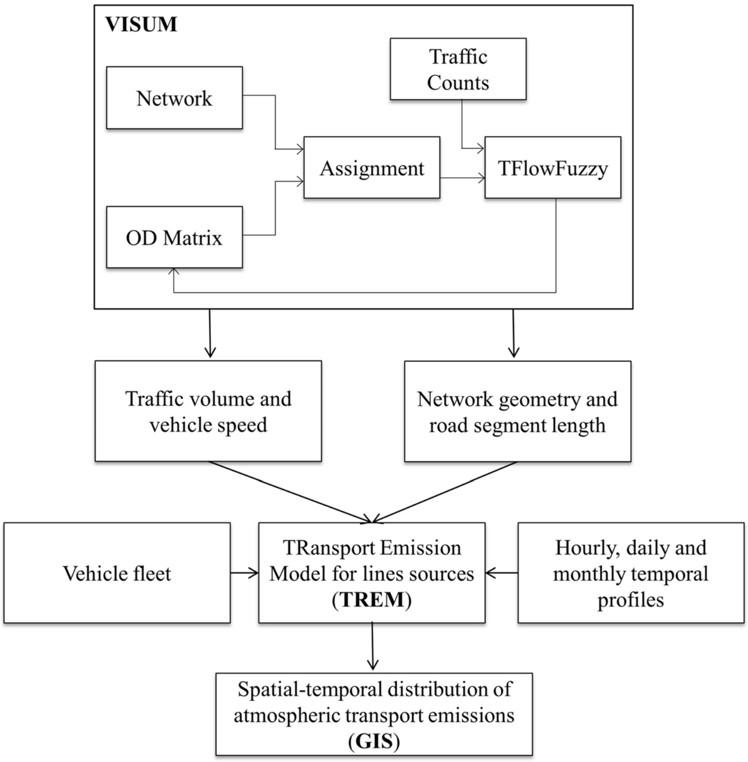

Fig. 1 Framework of high-resolution estimation for road transport emission

follows: (1) simulation of link-based vehicle volumes through the road traffic model (VISUM); (2) estimation of road transport emissions through the Transport Emission Model for line sources (TREM); and (3) display of spatial and temporal distribution of atmospheric transport emissions through the Geographic Information System (GIS) (ArcGIS).

VISUM has been developed by PTV AG in Germany, and it could be used for transportation planning, travel demand modeling, and network data management (PTV 2015). The model consists of a demand model, a network model, and several impact models. The demand model contains the origin destination (OD) matrix which is created with survey data. The network model consists of traffic zones, nodes, roads, public transport lines, and their timetables. The impact models used the data supplied by the demand and network models to analyze and evaluate the transport supply.

In VISUM, the origin–destination (OD) matrices developed by Wong and Yu (2011) were used as prior OD matrices in this study. The road transport network was created for Macau SAR, and it consists of 443 nodes and 1340 road segments (Fig. 2). The OD matrices were developed for private cars and motorcycles, and they are representative of a morning peak hour (between 8:00 and 9:00 a.m.) in the year 2009. To update the prior OD matrices without conducting a new OD survey which is expensive and time-consuming, the build-in function TFlowFuzzy of VISUM was applied. This procedure is useful to update prior OD matrices of the base year (2009) based on the observed traffic counts of the studied year (2014), i.e., to adjust a demand matrix so that assignment results for a supply actually match the real supply observed.

The input data for TFlowFuzzy in VISUM are observed traffic counts of private cars and motorcycles at 15 video camera locations of Macau SAR as shown in Fig. 2. More cameras are located in the Macau Peninsula as the population is significantly higher than other administrative divisions (Taipa, Cotai, and Coloane) (Zhang et al. 2016). The cameras' videos were provided by the Macau Transportation Bureau, and the traffic counts for private cars, motorcycles, taxis, trucks, and buses at morning peak period (between 8:00 and 9:00 a.m.) were performed. Based on the input data (traffic counts of private cars and motorcycles), the OD matrices could be updated by applying the TFlowFuzzy function. Then, the model would update the link choice proportions by solving the user-equilibrium traffic assignment problem. The final

Fig. 2 Road network used in VISUM and locations of video cameras and air quality monitoring stations

objective of the algorithm is to minimize the discrepancies between the traffic volumes of the observed links and the modeled values of the traffic volumes obtained by assigning the estimated OD matrix to the network with the updated link choice proportions. Finally, the updated OD matrices of private cars and motorcycles were assigned to the network with a multiclass equilibrium traffic assignment model in order to provide the traffic volume and vehicle speed for each road segment.

Since the road traffic simulation only provided the traffic volumes for private cars and motorcycles over the Macau SAR, the traffic volumes of taxis, trucks, and buses during the morning peak hour were calculated based on the traffic volumes of private cars. For each road segment, the near tool of ArcGIS was applied to find the nearest camera location. Then, the ratios of the private vehicle count to those of taxis, trucks, and buses could be derived from the camera videos, respectively. For example, the traffic volume of buses in a specified road segment was equal to the private cars' volume derived from the VISUM model multiplied by the ratio of bus counts to private car counts in the nearest camera location from the road segment. Consequently, the traffic volumes for different types of vehicles (private cars, motorcycles, taxis, trucks, and buses) and vehicle speed for each road segment were obtained.

The Transport Emission Model for line sources (TREM) is a traffic situation model. It was developed by the University of Aveiro to estimate emissions induced by road transport based on the MEET/COST methodology. The MEET/COST methodology has been carried out since 1999. Based on this methodology, several emission models have been developed. One of the widely used models is COPERT, which is a yearly emission estimation model on national level and was always used by the European Environment Agency. TREM was developed for estimation of road traffic emissions with high temporal and spatial resolution to be used in air quality modeling. It is recommended to be used for emission estimations on the urban level with hourly resolution and particularly designed for line sources. It calculates the hot road transport emissions (i.e., CO, CO_2, NO_X, VOC, and PM) as a function of average speed and road gradient. Vehicle speed is an important parameter affecting emission factors since vehicle exhaust emissions and fuel consumption are strongly dependent on speed (Gois et al. 2007). Road gradient is also a determining factor for accurate vehicle emission estimates (Wyatt et al. 2014). In addition, the vehicle category (e.g., gasoline passenger cars and diesel passenger cars), model year (e.g., Euro 1), and engine capacity (cc) are also distinguished to derive emission factors (Borrego et al. 2003, 2004). The vehicles were divided into 10 categories, which are gasoline passenger cars, diesel passenger cars, LPG passenger cars, gasoline light-duty vehicles, diesel light-duty vehicles, diesel heavy-duty vehicles, diesel urban buses, coaches, motorcycles, and new technology vehicles. The vehicle classes are distinguished by model year and engine capacity of individual vehicles and are totally divided into 350 vehicle classes. In general, the model year is identified by the emission standard compiled by the vehicle. However, Macau SAR does not have specific vehicle emission standards. Currently, Guangzhou, Shenzhen, and Hong Kong have legislation to use the European emission standards, and Macau, also, has the tendency to adopt the European emission standards for regulating car imports. Therefore, the model year was expressed through the European emission standards in this study. The European emission standards are regulated in a series of European Union directives staging the progressive introduction of increasingly stringent standards in regulating emission rates of vehicle engines. For example, the diesel passenger cars introduced in January of 2000 (i.e., Euro 3) should emit less than 0.50 g km^{-1} of NO_x, whereas a Euro 5, introduced in September 2009, should not emit more than 0.18 g km^{-1} of NO_x (Carslaw et al. 2011).

Based on these factors, the road transport emissions were estimated in TREM as in Eq. (1):

$$E_{p,h,r} = TV_{h,r} \times \sum\left\{FV_{cat.} \times \sum\left[FV_{cla.} \times EF_{cat.,cla.,p}\right]\right\} \times L \qquad (1)$$

where $E_{p,\,h,\,r}$ is the atmospheric emission of the pollutant p during hour h for the road segment r (kg h^{-1}); $TV_{h,\,r}$ is the total traffic volume of all vehicle categories (gasoline passenger cars, diesel heavy-duty vehicles, motorcycles, etc.) during the hour h for the road segment r (veh h^{-1}); $FV_{cat.}$ is the fraction of total traffic volume corresponding to a specific vehicle category (*cat.*); $FV_{cla.}$ is the fraction of vehicle class (*cla.*) classified by the model age (e.g., Euro 1, Euro 2, Euro 3, Euro 4) and the engine capacity (e.g., $CC < 1410\text{cm}^3$; $1410\text{cm}^3 < CC < 2010\text{cm}^3$; $\text{CC} > 2010\text{cm}^3$); $EF_{cat.\,,\,cla.\,,\,p}$ is the emission factor for the specified vehicle category, vehicle class, and pollutant which is a function of average speed and road gradient (kg veh^{-1} km^{-1}); and L is the road segment length (km).

For the input, the TREM required the following data: (1) traffic volume for each road segment, (2) vehicle speed for each road segment, (3) road segment length, (4) road gradient, and (5) fraction of vehicle category and class.

The road segment length, traffic volume, and vehicle speed were derived from the VISUM model.

The road gradient was calculated for each road segment using Eq. (2):

$$Grad(^\circ) = [(A_1 - A_2)/L] \times (180/\text{pi}) \qquad (2)$$

where A_1 and A_2 represent the altitude of the start and the end of each road segment, respectively. This input data was supplied by the Macau Cartography and Cadastre Bureau. The fraction of vehicle category and class were provided by the Macau Transport Bureau.

Since the VISUM model only provided traffic volumes between 8:00 and 9:00 a.m. on weekdays in October, temporal profiles (i.e., hourly, daily, and monthly coefficients) were needed in order to estimate the temporal variation of the traffic volumes and the subsequent emissions. In this study, the temporal profiles were developed by using the hourly variation of CO concentrations measured at roadside and ambient air quality monitoring stations of Macau SAR during the whole year of 2014. Figure 2 shows the locations of these stations. The CO concentrations were provided by the Macau Meteorological and Geophysical Bureau (SMG). According to Rozante et al. (2017), about 97.0% of CO concentrations originated from vehicle emissions, and there is a strong correlation between the CO concentration and the road traffic volume. In order to examine whether the CO concentration could be used as a surrogate of the traffic volume for deriving the temporal profile, CO concentrations measured at roadside air quality monitoring station of Macau SAR were compared with the traffic flow recorded in some road segments at hours 8:00–9:00 a.m., 15:00–

16:00 p.m., and 19:00–20:00 p.m. After that, the road transport emissions were calculated for the year 2014 using Eqs. (3), (4), and (5):

$$E_{p,h,dw,m,r} = \left\{\left[E_{p,9,dw,Oct.,r} \times H_{h,dw}\right]/H_{9,dw}\right\} \times D_{dw} \times \left[M_m/M_{\mathrm{Oct.}}\right] \quad (3)$$

if dw = weekday (wd.):

$$E_{p,9,dw,Oct.,r} = E_{p,9,wd.,Oct.,r} \quad (4)$$

if dw = weekend day (we.):

$$E_{p,9,dw,Oct.,r} = \left[E_{p,9,wd.,Oct.,r} \times H_{9,we.}\right]/H_{9,wd.} \quad (5)$$

where, $E_{p,\ h,\ dw,\ m,\ r}$ is the emission of pollutant p during the hour h on the day dw in month m for the road segment r (kg); $E_{p,\ 9,\ dw,\ Oct.\ ,\ r}$ is the emission of pollutant p during the hour 8:00–9:00 a.m. on the day dw in October (Oct.) for the road segment r; $H_{h,\ dw}$ is the hourly coefficients during hour h on the day dw; $H_{9,\ dw}$ is the hourly coefficients during hour 8:00–9:00 a.m. on the day dw; D_{dw} is the daily coefficients on the day dw; M_m is monthly coefficient in the month m; $M_{\mathrm{Oct.}}$ is monthly coefficient in October. In addition, $E_{p,\ 9,\ wd.\ ,\ Oct.\ ,\ r}$ is the emission of pollutant p during the hour 8:00–9:00 a.m. on weekday in October for the road segment r; $H_{9,\ we.}$ is the hourly coefficient during hour 8:00–9:00 a.m. on weekend day; and $H_{9,\ wd.}$ is the hourly coefficient during hour 8:00–9:00 a.m. on weekday.

Scenario analysis

In the next few years, the light railway transit (LRT) will be opened to the public, and the Macau government is considering some control strategies to reduce road transport emissions. In order to estimate the impact of these activities, three scenarios were proposed in this study. The reference year for these scenarios is 2014.

Scenario A—LRT: In order to reduce traffic congestion, the Macau LRT system started to be constructed in 2012 and is expected to start operation in 2019. According to the Macau transportation infrastructure office (GIT 2014), it was predicted that the private car trips would reduce by up to two thousand by the year 2020. The reduction factor of trips was applied to the OD matrix, and a new OD matrix was estimated in the VISUM model. Then, the TREM predicted the traffic emissions based on the new road traffic volumes.

Scenario B—Vehicle fuel variation: Due to engine technology development, diesel engines are more fuel-efficient nowadays. Therefore, it is not difficult to infer that there will be a tendency to replace existing gasoline vehicles with diesel ones in society. In order to estimate the effects brought by this trend, three sub-scenarios were tested in scenario B, including, scenario B1, in which 20.0% of gasoline passenger cars were replaced by diesel passenger cars and 20.0% of gasoline light-duty vehicles were replaced by diesel light-duty vehicles, scenario B2, in which 40.0% of gasoline passenger cars were replaced by diesel passenger cars and 40.0%of gasoline light-duty vehicles were replaced by diesel light-duty vehicles, and scenario B3, in which 60.0% of gasoline passenger cars were replaced by diesel passenger cars and 60.0% of gasoline light-duty vehicles were replaced by diesel light-duty vehicles.

In addition, with the increase of the traffic flow in Macau, the increase in traffic emissions is inevitable. Therefore, the vehicles with new energy technologies will be encouraged by the government. In the future, it will be a trend that many electric vehicles will circulate on the road (Ching 2010, 2011). So, another three sub-scenarios were constructed—scenario B4, in which 10.0% of gasoline passenger cars and 10.0% of diesel passenger cars were replaced by electric cars; scenario B5, in which 20.0% of gasoline passenger cars and 20.0% of diesel passenger cars were replaced by electric cars; and scenario B6, in which 50.0% of gasoline passenger cars and 50.0% of diesel passenger cars were replaced by electric cars.

Scenario C—Vehicle age: Without aggressive and sustained mitigation policies being implemented, road transport emissions could increase at a faster rate compared to emissions from other energy sectors. Recently, the Macau government encouraged people to replace old vehicles with new ones that meet the new European emission standards. The influence of the latest Euro standards on emissions was examined with the development of three sub-scenarios—scenario C1, in which 20.0% of pre-Euro vehicles were replaced by Euro 5 and Euro 6 standard vehicles; scenario C2, in which 20.0% of pre-Euro, Euro 1, and Euro 2 vehicles were replaced by Euro 5 and Euro 6 standard vehicles; and scenario C3, in which 20.0% of pre-Euro, Euro 1, Euro 2, and Euro 3 vehicles were replaced by Euro 5 and Euro 6 standard vehicles.

Results and discussion

VISUM—road traffic simulations

Based on the VISUM model, the traffic volumes for motorcycles and private cars between 8:00 and 9:00 a.m. on weekdays in October were simulated. In addition, the near tool of GIS was applied to obtain traffic volumes of buses, taxis, and trucks over the Macau SAR. The accuracy of estimated traffic volumes was evaluated through comparison with traffic counts from 15 video cameras over the main roads of Macau SAR (Fig. 3). The performance was indicated by computing the following statistical parameters: coefficient of determination (R^2) and relative root mean square error (rRMSE). Figure 3 shows the modeled traffic volumes of the motorcycles, private cars, buses, taxis, and trucks against actual traffic counts at 15 video camera locations.

For the private cars, VISUM revealed a good performance (low rRMSE and high R^2). As for the motorcycles, the rRMSE was relatively higher and the R^2 was relatively lower because the VISUM modeled null traffic volumes in some road segments. The null-modeled traffic volumes could be resulted from the error of the prior OD matrix. Nonetheless, the model showed a good accuracy for the majority of the road segments, because after removing the points with null traffic volumes, the rRMSE is 13% and R^2 is equal to 0.96. Since the road segments with null motorcycles modeled by VISUM ($<$ 10) were relatively few compared to the total 1340 road segments, the validation results of motorcycles are considered acceptable. Wong and Yu (2011) recorded a rRMSE of 34.4 and 38.4% for private cars and motorcycles, respectively. For the volumes of taxies, buses, and trucks, the results achieved from the near tool of GIS are acceptable compared with the results of Wong and Yu (2011). The rRMSE and R^2 range between 39.0–51.0% and 0.60–0.81, respectively. Given that the size of Macau is small, GIS is an appropriate methodology to estimate the volumes of the minor traffic modes (buses, trucks, and taxies).

Figure 4 shows the link-based flow pattern of private cars and motorcycles in Macau SAR. High road traffic volumes were recorded over the Macau Peninsula (especially near Praca Ponte Horta) and on the left/right bridges (Sai Van Bridge and Amizada Bridge). Null motorcycle and private car volume was recorded on the middle bridge (Governador Nobre de Carvalho Bridge) because it was reserved for public transport starting from 2007. Few motorcycles were recorded in Taipa, and most motorcycles were concentrated in the Macau Peninsula, because most people were not willing to cross the bridge with motorcycles. This phenomenon is consistent with Zhang et al. (2016). Road segments with null road traffic volumes were distributed over the Coloane, and this phenomenon could be caused by the error of the prior OD matrix. In addition, there is no camera distributed in Coloane, and, hence, the OD information associated with Coloane could not be improved through the TFlowFuzzy. According to Zhang et al. (2016), more than 80.0% of trip demands are concentrated in the Macau Peninsula. This means that the road traffic volumes over the Coloane are much smaller than those in the Macau Peninsula. However, it is still recommended to improve the OD matrix from the transportation survey or distributing more cameras over Coloane in the future study.

The detailed vehicle speed distribution over the main roads of Macau SAR during the morning peak hour (8:00 a.m.–9:00 a.m.) on weekdays in October 2009 is illustrated by the gray lines of different widths in Fig. 5. There are five categories of line widths, and each category corresponds to a specific range of vehicle speed. Vehicles in this network drove at an average speed of 35.0 km h^{-1} with a standard deviation of 7.10 km h^{-1}. In very congested streets, vehicles could only drive at a speed of 12.0 km h^{-1}. However, the maximum vehicle speed could reach up to 69.0 km h^{-1} in the unimpeded streets.

Road transport emissions—TREM

The vehicle fleet composition is a major factor affecting the road transport emissions (André et al. 2017). This is also a critical input in TREM apart from the link-based vehicle volume and speed. The vehicle fleet composition can be further classified into the vehicle category distribution and the vehicle age distribution. Figure 6 is

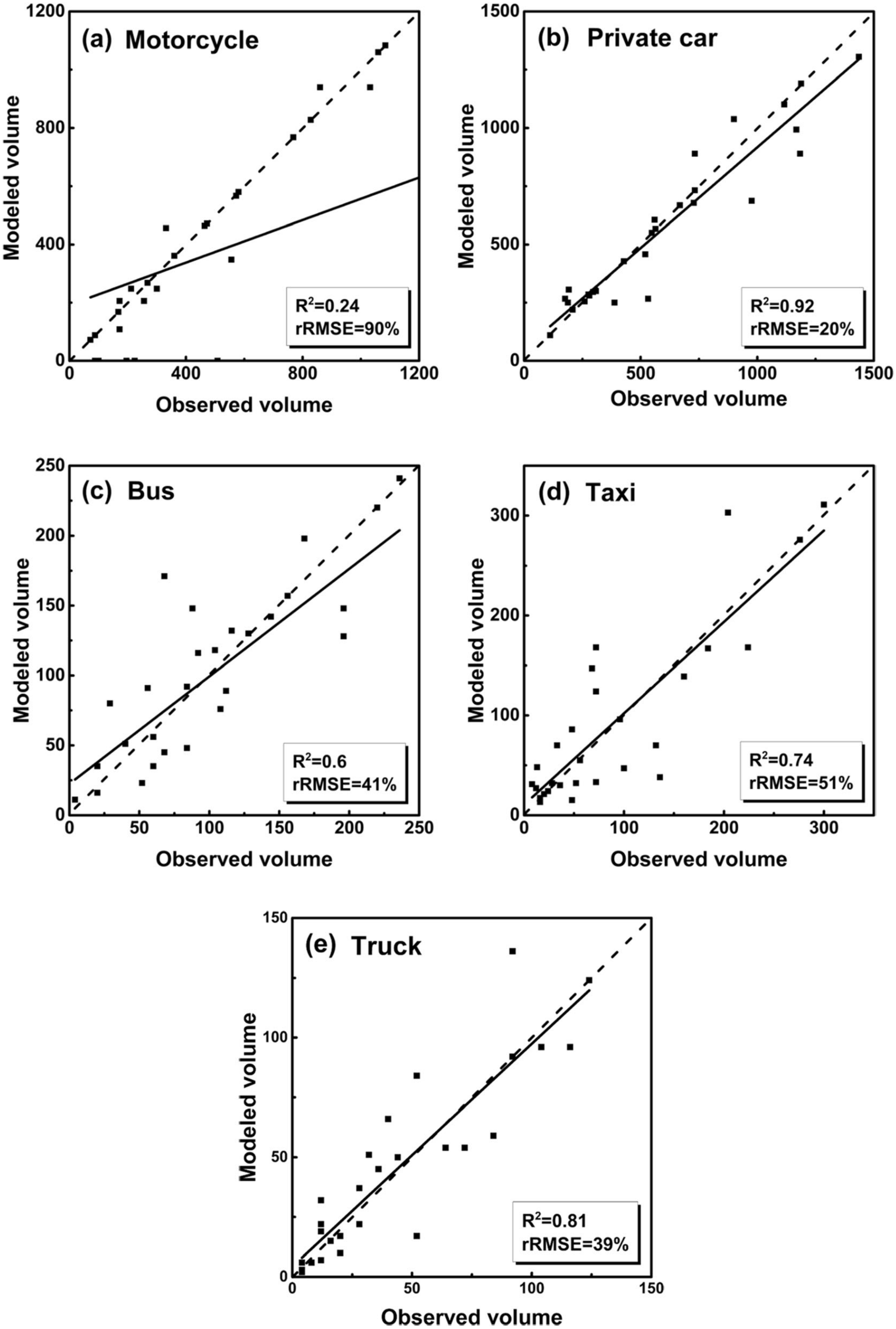

Fig. 3 Modeled traffic volumes of motorcycles, private cars, buses, taxis, and trucks by VISUM against measured traffic volumes

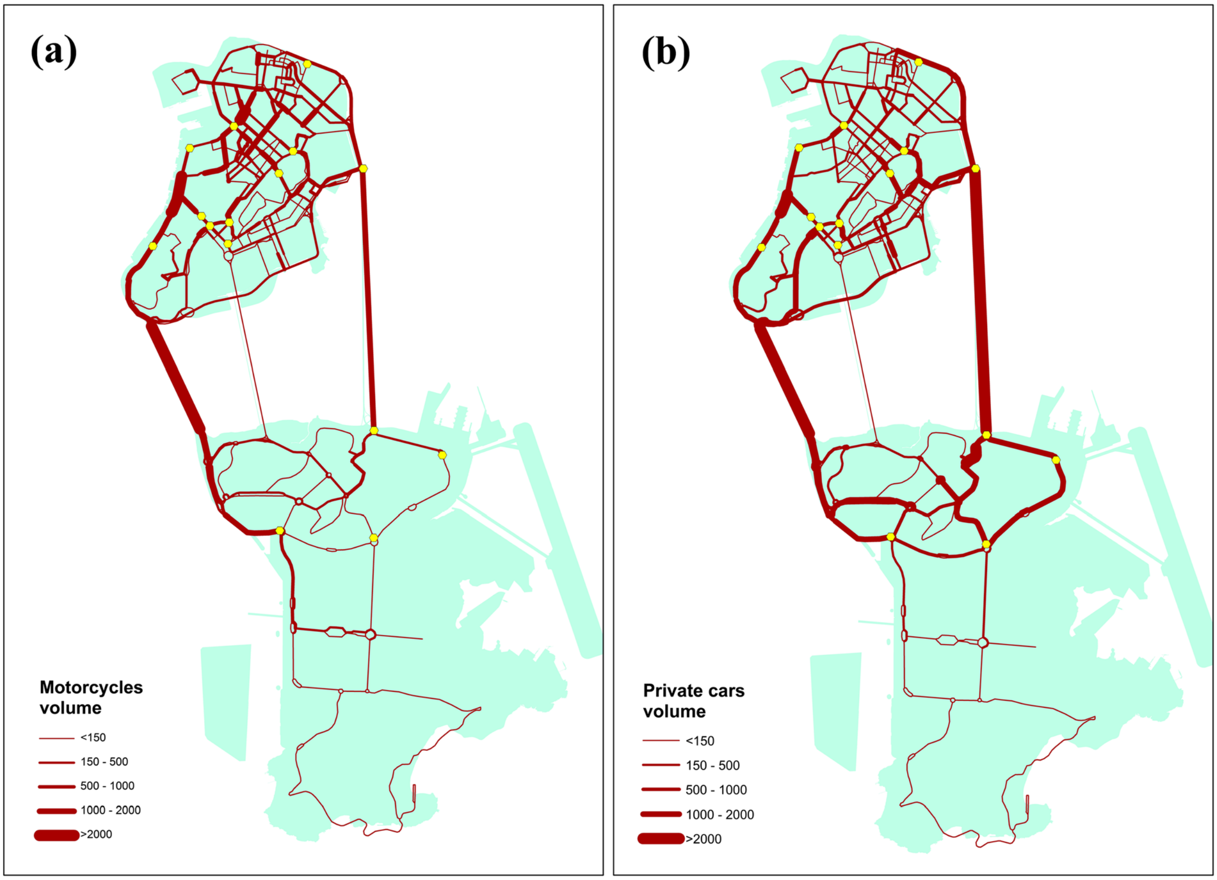

Fig. 4 Modeled traffic volumes over the Macau SAR for (**a**) motorcycles and (**b**) private cars

a pie chart classifying the vehicles of Macau SAR into 12 categories. Among these categories, MOTO_2 and MOTO_4 represent 2-stroke and 4-stroke motorcycles, respectively. P_G and P_D represent gasoline passenger car and diesel passenger car, respectively. LDV_G, LDV_D, and HDV_D represent the gasoline light-duty vehicles, diesel light-duty vehicles, and diesel heavy-duty vehicles, respectively. The gasoline passenger cars (~ 54.08%), 2&4-stroke motorcycles (~ 39.61%), and other categories (~ 6.32%) comprise the vehicle category distribution of Macau.

Table 1 shows the vehicle age distribution and the corresponding emission standard followed. It is noted that the majority (70%) of the gasoline passenger cars in Macau could only meet the old European emission standards (Euro 1, Euro 2, and Euro 3). Diesel passenger cars account for 0.95% of vehicles in Macau; among them, around 61% are conventional, and there is an increase in tendency of the number of diesel passenger cars in recent years. As for light-duty vehicles (diesel/gasoline), the majority of them could meet Euro 4 and Euro 5. However, most of the heavy-duty vehicles are also conventional. The motorcycles' age has much more average distribution.

As the link-based traffic volumes and speeds only represent the traffic conditions of the peak hour during the weekday, an indirect method was applied here to derive a temporal profile in order to extrapolate the conditions of the peak hour during the weekday to the rest of the weekday or the weekend. The temporal profile was derived by using the CO concentration as a surrogate of the traffic volume. Carbon monoxide is a typical pollutant from the vehicle emissions. Therefore, the street-level CO concentration should have positive correlation with the traffic volume. In order to verify the correlation between CO levels and road traffic volumes, the CO concentrations measured at the roadside air quality monitoring station located in Rua do Campo of the Macau Peninsula were compared with the traffic volumes of seven nearby road segments (i.e., C1, C4, C6, C7, C8, C14, and C15—see Fig. 2) during the

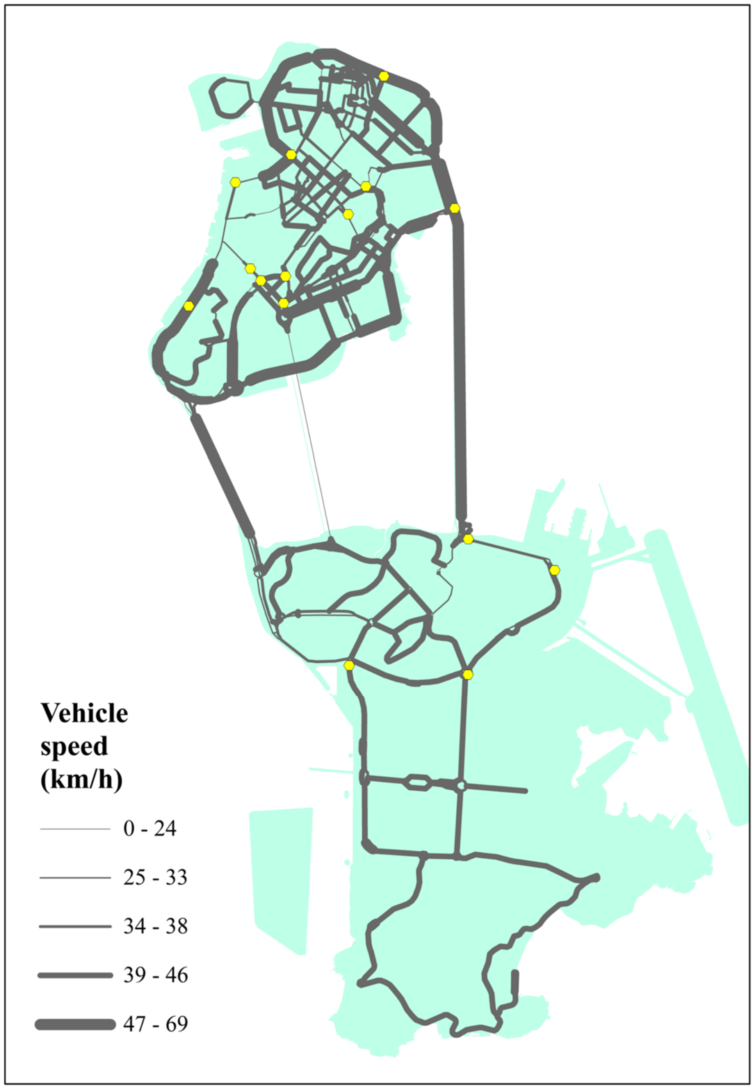

Fig. 5 Modeled vehicle speed for each road segment of the network in VISUM

periods 8:00–9:00 a.m., 15:00–16:00 p.m., and 19:00–20:00 p.m. Figure 7 presents the relationship between several camera counts and CO concentration recorded by the roadside air quality monitoring stations. Results showed a correlation coefficient larger than 0.9 which was recorded between CO concentrations and road traffic volumes, meaning that the temporal variation of CO concentration could be used as the surrogate of the traffic volume.

Figure 8 shows hourly, weekly, and monthly variation of CO concentration at roadside and ambient air quality monitoring stations.

In Fig. 8, the roadside air quality monitoring station recorded similar hourly temporal profiles of CO concentrations on weekdays and weekends. The main reason causing similar temporal profiles is that Macau is mainly dependent on the service industry. Therefore, large portion of Macau population also works on weekends. Two obvious peaks of CO concentrations were observed between 8:00–9:00 a.m. and 19:00–20:00 p.m., and this correlated well with the typical working period of Macau. As for the daily profile which describes the variation of daily averaged CO concentration within the week, it is noted that the CO level difference between weekdays and weekends is not significant. This is also related to the service industry feature in Macau. For the monthly profiles, highest monthly averaged CO concentration was recorded in January. In this month, large number of tourists came into Macau SAR for shopping from mainland China

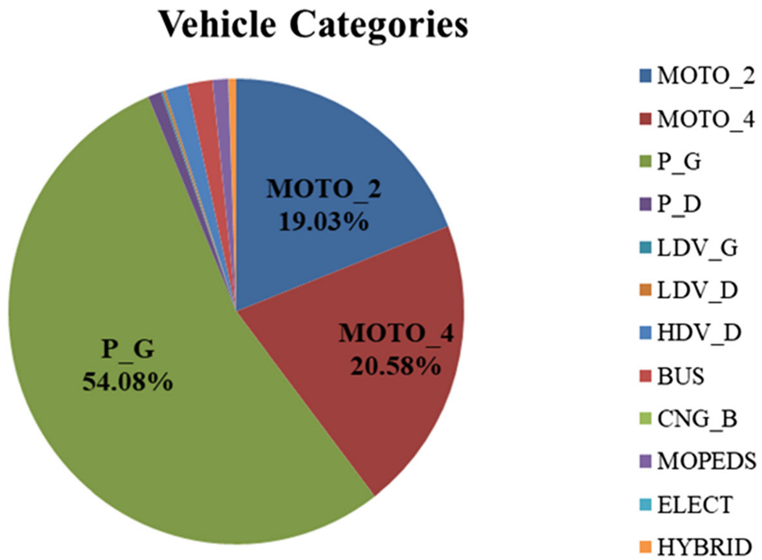

Fig. 6 Vehicle category distribution in Macau SAR (DSAT 2014)

before the spring festival. In addition, according to Lopes et al. (2016), except the ozone which is formed through photochemical reactions, the highest concentrations of the other pollutants (SO_2, PM, NO_2) in all PRD cities were also recorded in winter months (i.e., December, January, and February). This may be due to the smaller mixing height as well as the lower amount and frequency of rainfall during that period (Mok and Hoi 2005).

Figure 9 shows similar profiles of CO at the ambient air quality monitoring station. It is noted that the diurnal profile as well as the day of the week profile are almost flat, and it implies that this station is not influenced by the local traffic. As for the variation of the monthly CO profile, it may be also caused by the same meteorological factors as in the case of the roadside station. Therefore, the measured CO concentrations at this station could be adopted to represent the background concentrations of this pollutant in Macau. In this study, the difference between CO concentrations recorded by the roadside and ambient air quality monitoring stations was used to develop hourly, daily, and monthly temporal profiles for road traffic volume over the Macau SAR (Table 2). Low road traffic volumes were recorded at midnight. On weekend, traffic volumes were relatively lower than those on weekdays. It should be mentioned that the previous study of Zhang et al. (2016) in Macau also recorded similar temporal profiles of CO. These data could be used in future studies to calculate the hourly, daily, and monthly emissions.

Based on the derived road traffic volumes from the CO concentrations, monthly and daily link-based traffic emissions in Macau were estimated by TREM for the year 2014. Table 3 shows total monthly emissions of CO, CO_2, NO_x, VOC, PM, and fuel consumption in 2014 of the entire region. Highest road transport emissions occurred in January, and they were nearly 3 times higher than those in the lowest emission month (October). For the pollutants, there are large amounts of CO_2 emitted from road traffic, leading to greenhouse effect. According to the IPCC (2014), road transport activity is responsible for approximately 23.0% of total energy-related CO_2 emissions. Besides, there are also lots of CO and VOC emitted. Human exposure to these pollutants can lead to higher human health risk, such as impairing lung function, exacerbating asthma, increasing cardiovascular morbidity and mortality, aggravating adverse birth outcomes, and declining cognitive ability (Batterman et al. 2014; Du et al. 2012; Shekarrizfard et al. 2015; Tsai et al. 2010).

Figures 10, 11, 12, 13, 14 present the spatial allocation of CO, CO_2, PM, VOC, and NO_x emissions (tons) on Macau SAR's main street during 8:00 a.m. to 9:00 a.m. on weekdays in 2014. The resolution is 0.1 km × 0.1 km. Compared to the previous study (Zhang et al. 2016), the spatial resolution of this study is higher. In such refined resolution, the emission level in each street can be observed clearly. The improvement of resolution on vehicular emission inventory can

Table 1 Vehicle age distribution and corresponding emission standard[a]

Vehicle categories		…	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Gasoline pass. cars		Conv. (4.47%)		Euro 1 (22%)					Euro 2 (22.52%)				Euro 3 (22.17%)		
Diesel pass. cars and LPG		Conv. (60.92%)		Euro 1					Euro 2				Euro 3 (0.21%)		
Gasoline light-duty vehicles		Conv.				Euro 1				Euro 2				Euro 3 (1.53%)	
Diesel light-duty vehicles		Conv.				Euro 1				Euro 2 (1.09%)				Euro 3	
Diesel heavy-duty vehicles and bus		Conv. (76.39%)		Euro I					Euro II (0.01%)			Euro III (0.03%)			
Motorcycles	Moped	Conv. (78.73%)									Euro 1				Euro 2
	2-Stroke	Conv. (1.94%)									Euro 1 (30%)				
	4-Stroke	Conv. (2.14%)									Euro 1 (29.52%)				

Vehicle categories	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	…
Gasoline pass. cars	Euro 3 (22.17%)		Euro 4 (14.07%)					Euro 5 (13.4%)			Euro 6 (1.37%)	
Diesel pass. cars and LPG	Euro 3 (0.21%)		Euro 4 (12.87%)					Euro 5 (25.15%)			Euro 6 (0.85%)	
Gasoline light-duty vehicles	Euro 3 (1.53%)			Euro 4 (96.17%)				Euro 5 (1.53%)			Euro 6 (0.77%)	
Diesel light-duty vehicles	Euro 3			Euro 4 (73.1%)				Euro 5 (25.81%)			Euro 6	
Diesel heavy-duty vehicles and bus	Euro III (0.03%)		Euro IV (13.39%)			Euro V (9.87%)						
Motorcycles	Euro 2			Euro 3 (21.27%)								
	Euro 1 (30%)	Euro 2 (30.6%)		Euro 3 (37.47%)								
	Euro 1 (29.52%)	Euro 2 (30.00%)		Euro 3 (38.34%)								

[a] Value shown in the bracket is the percentage of the vehicles inside a particular vehicle category

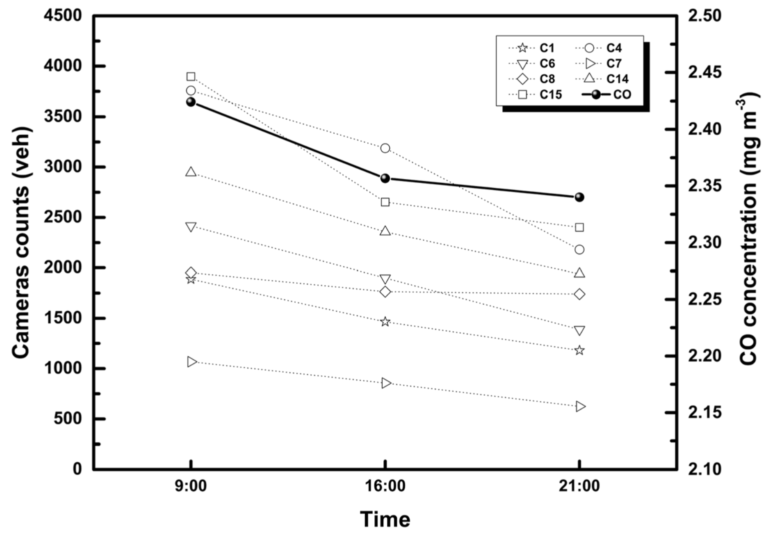

Fig. 7 Time variation of counts and CO concentrations at Macau roadside air quality monitoring station

substantially improve the accuracy for areas containing traffic-dense microenvironment. Furthermore, this provides a reliable input for further air quality simulation with higher resolution. For spatial allocation, emission peaks were located near the Praca Ponte Horta of the Macau Peninsula and on two bridges connecting Taipa and the Macau Peninsula. However, it is noted that there is no emission on the middle bridge (Ponte Governador Nobre de Carvalho) because the estimated traffic volume on this bridge is zero as explained before. Few emissions were estimated in Cotai and Coloane. This is consistent with Zhang et al. (2016)'s work. They observed that 80% of the vehicles were concentrated in the Macau Peninsula and the vehicle volume is the determining factor to the road transport emission spatial allocation. In addition, the emissions on weekdays and weekends in different months were also derived, and the total annual emission in 2014 was estimated by summing the daily emissions

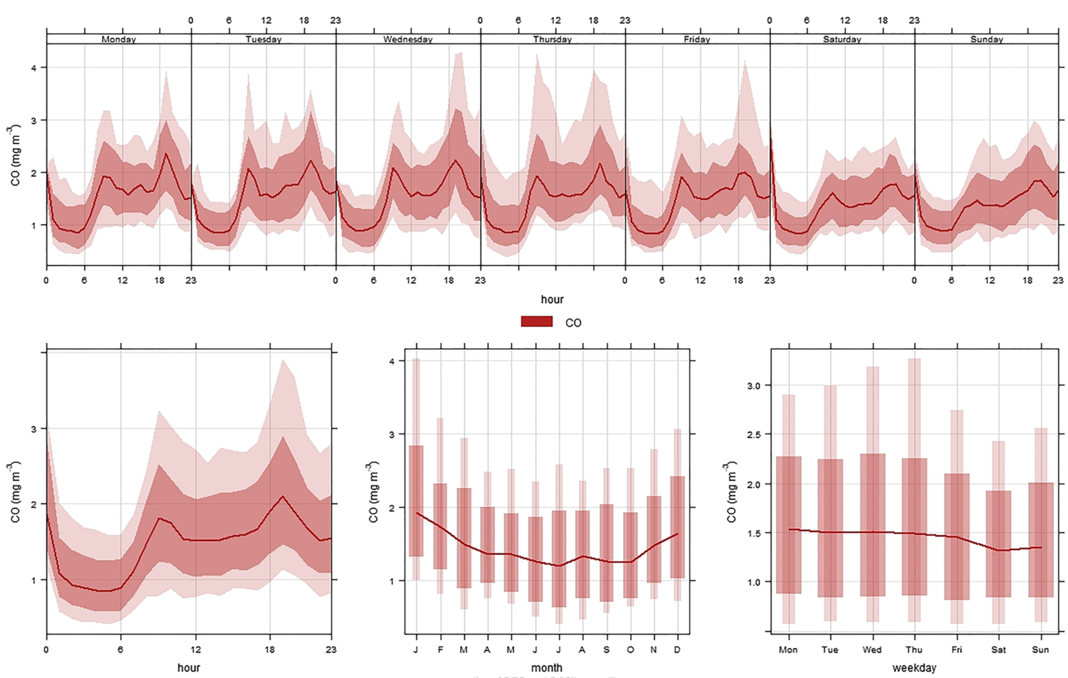

Fig. 8 Hourly, weekly, and monthly variation of CO concentrations at roadside station

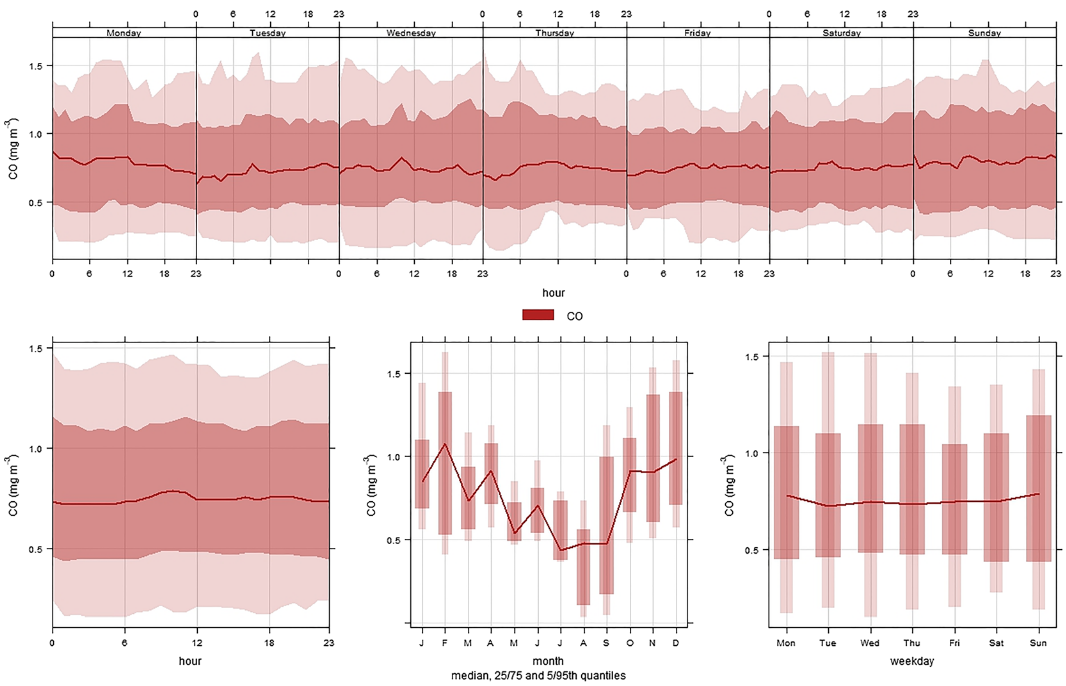

Fig. 9 Hourly, weekly, and monthly variation of CO concentrations at ambient station

Table 2 Hourly, daily, and monthly temporal profiles of derived traffic volumes from CO measurements

Hour	Weekdays	Weekends	Daily profiles		Monthly profile	
0:00–01:00	1.42	2.32	Weekdays	1.08	Jan.	1.61
01:00–02:00	0.53	0.64	Weekends	0.81	Feb.	1.00
02:00–03:00	0.34	0.37			Mar.	1.11
03:00–04:00	0.25	0.25			Apr.	0.74
04:00–05:00	0.21	0.21			May	1.10
05:00–06:00	0.20	0.51			Jun.	0.77
06:00–07:00	0.23	0.79			Jul.	1.03
07:00–08:00	0.51	0.99			Aug.	1.25
08:00–09:00	1.03	1.19			Sep.	1.08
09:00–10:00	1.56	1.06			Oct.	0.57
10:00–11:00	1.35	0.97			Nov.	0.81
11:00–12:00	1.11	1.03			Dec.	0.94
12:00–13:00	1.04	0.97				
13:00–14:00	1.05	1.03				
14:00–15:00	1.10	1.00				
15:00–16:00	1.19	1.12				
16:00–17:00	1.17	1.18				
17:00–18:00	1.28	1.32				
18:00–19:00	1.59	1.50				
19:00–20:00	1.92	1.69				
20:00–21:00	1.62	1.65				
21:00–22:00	1.22	1.37				
22:00–23:00	1.03	1.16				
23:00–00:00	1.08	1.30				

Table 3 Road transport emissions by month of year 2014

Months	CO (tons)	CO_2 (tons)	PM (tons)	NO_x (tons)	VOC (tons)	Fuel consumption (tons)
Jan.	2028	56,714	9.51	158	404	28,707
Feb.	1135	31,753	5.32	89	226	16,073
Mar.	1375	38,450	6.45	107	274	19,463
Apr.	902	25,238	4.23	70	180	12,775
May	1375	38,443	6.44	107	274	19,459
Jun.	929	25,975	4.35	72	185	13,148
Jul.	1297	36,286	6.08	101	259	18,367
Aug.	1545	43,196	7.24	120	308	21,865
Sep.	1316	36,816	6.17	103	263	18,636
Oct.	722	20,182	3.38	56	144	10,216
Nov.	966	27,026	4.53	75	193	13,680
Dec.	1181	33,020	5.54	92	235	16,714

Fig. 10 Spatial distribution of road transport emissions for CO over the Macau SAR

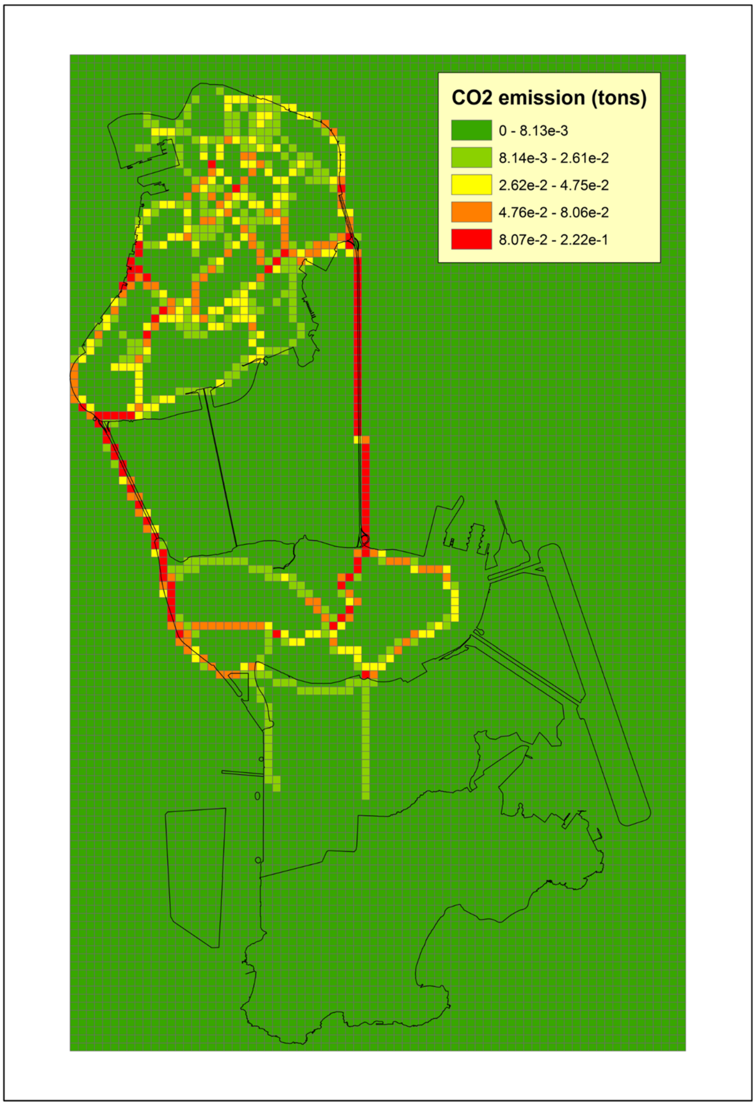

Fig. 11 Spatial distribution of road transport emissions for CO_2 over the Macau SAR

Validation of the results

The validation methods include inverse air quality modeling and mass-balance techniques. In this study, according to the data obtained, soft verification was done by comparing our results with the government report, and the bias analysis was discussed. Through the bottom-up approach, the estimated total emissions of CO, CO_2, PM, NO_x, and VOC during the year 2014 were 14,770, 413,099, 69, 1151, and 2945 tons, respectively. In the annual environmental report published by the DSPA, the total emissions of these pollutants were 15,493.6, 2824.3, and 5276.3 tons, respectively. The CO, NO_x, and VOC road transport emissions estimated in this study were 4.7, 59.2, and 44.2% lower than those reported by the Macau environment bureau (DSPA 2015). This bias may be due to the following reasons. First, the emissions estimated by the DSPA might be based on constant emission factors published in the guidebook. However, the emission factor should be a function of the vehicle speed and corresponds to different vehicle classification, and this was handled by TREM in the present study. Second, the large difference might be due to the different activity data (e.g., traffic volume) used. It was not clear what activity data DSPA used; however, in this research, the activity data (traffic volumes) were simulated using VISUM which was evaluated as reliable data before. In addition, the total

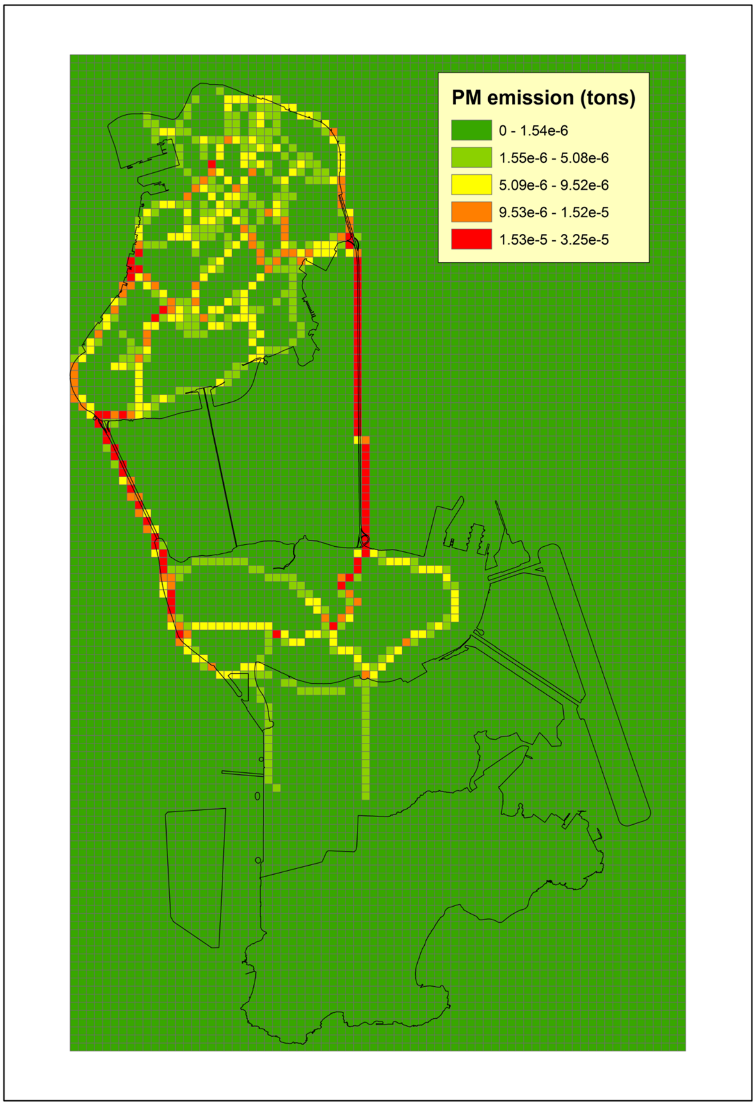

Fig. 12 Spatial distribution of road transport emissions for PM over the Macau SAR

annual vehicle fuel consumption estimated in this thesis was 209,103 tons in 2014, which is only about 10% lower than the statistical road transport fuel consumption of 230,000 tons published by the Macau statistical bureau. Thereby, it is reasonable to conclude that the estimation in this study is reliable. The 10% bias could be assigned to the following two reasons. First, the annual average temperature in Macau SAR is around 23 °C. The vehicle emissions were considered as hot exhaust emission only. Second, traffic volume on the Governador Nobre de Carvalho Bridge is due to the limitation of estimation of buses and taxis on that bridge, and some null traffic volume roads in Coloane is due to the limited camera distribution and OD matrix survey.

Scenario results

Finally, the estimated total traffic emissions of TREM were used as the baseline values and compared with the estimated emissions after implementation of each of the following three hypothetical scenarios. These scenarios include (A) implementation of the Macau LRT system, (B) vehicle fuel variation (dieselization and adoption of electric vehicles), and (C) replacement of old vehicles with higher European emission standards. Figure 15 shows the scenario results for road transport emissions of CO, NO_x, CO_2, PM, and VOC and fuel consumption. In scenario A, each pollutant emission

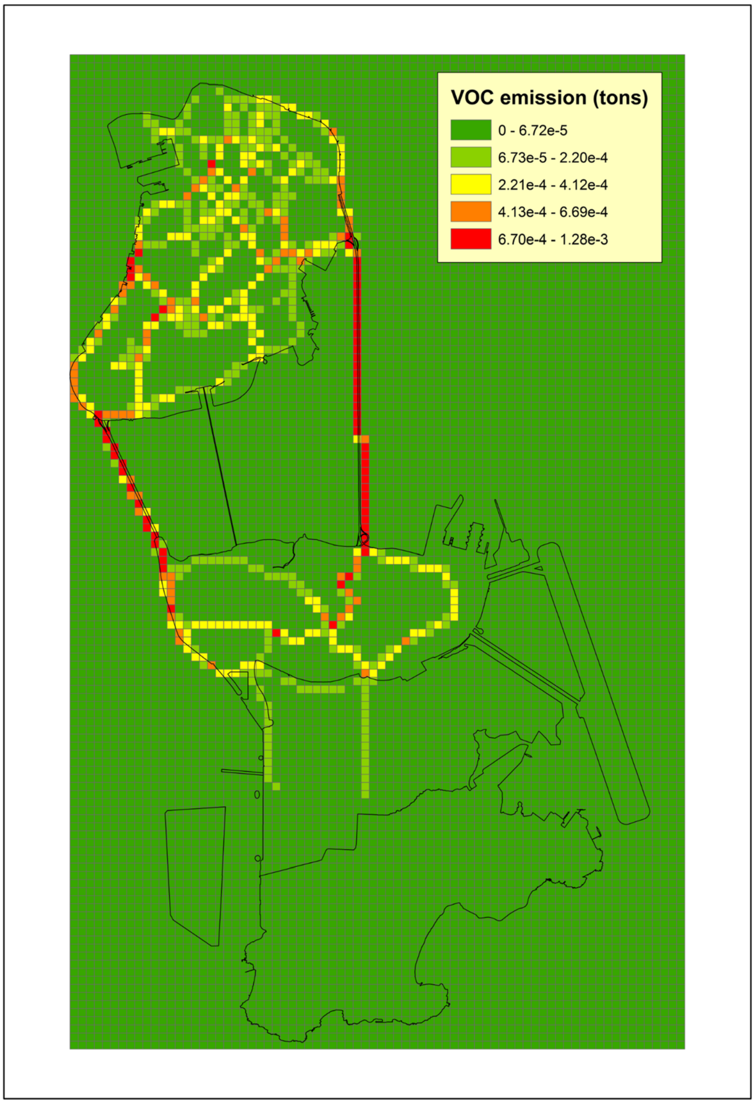

Fig. 13 Spatial distribution of road transport emissions for VOC over the Macau SAR

reduced around 2.0–3.0% compared to the reference year (Table 4). This reduction is meaningful for a public transport facility. Moreover, LRT brings people more convenience and can effectively reduce the road traffic congestion problem. In scenario B1, the PM and NO_x emissions increased 43.0 and 10.0%, respectively. However, PM and NO_x emissions sharply increased by 125.0 and 25.0% compared to the reference year when 60.0% (sub-scenario B3) gasoline passenger cars and light-duty vehicles were replaced by diesel ones. This indicates that the diesel vehicles have a high impact on PM and NO_x emissions from the road transport sector, especially for PM. This will adversely affect Macau SAR air quality and even will aggravate the tropical island effect. Therefore, it is not recommended to change the gasoline car to diesel one, except in the case where the diesel vehicles were installed an exhaust emission treatment device. In sub-scenario B6, the replacement of 50.0% of the traditional fuel vehicles (i.e., gasoline or diesel) by electric vehicles could reduce impact on CO (−3.0%), PM (−2.2%), and VOC (−0.7%) emissions (sub-scenario B6). However, CO_2 emissions reduced 4.1, 10.0, and 27.5% when 10.0% (sub-scenario B4), 20.0% (sub-scenario B5), and 50.0% (sub-scenario B6) of traditional fuel vehicles were replaced by electric vehicles, respectively. Concerning NO_x emissions, the maximum

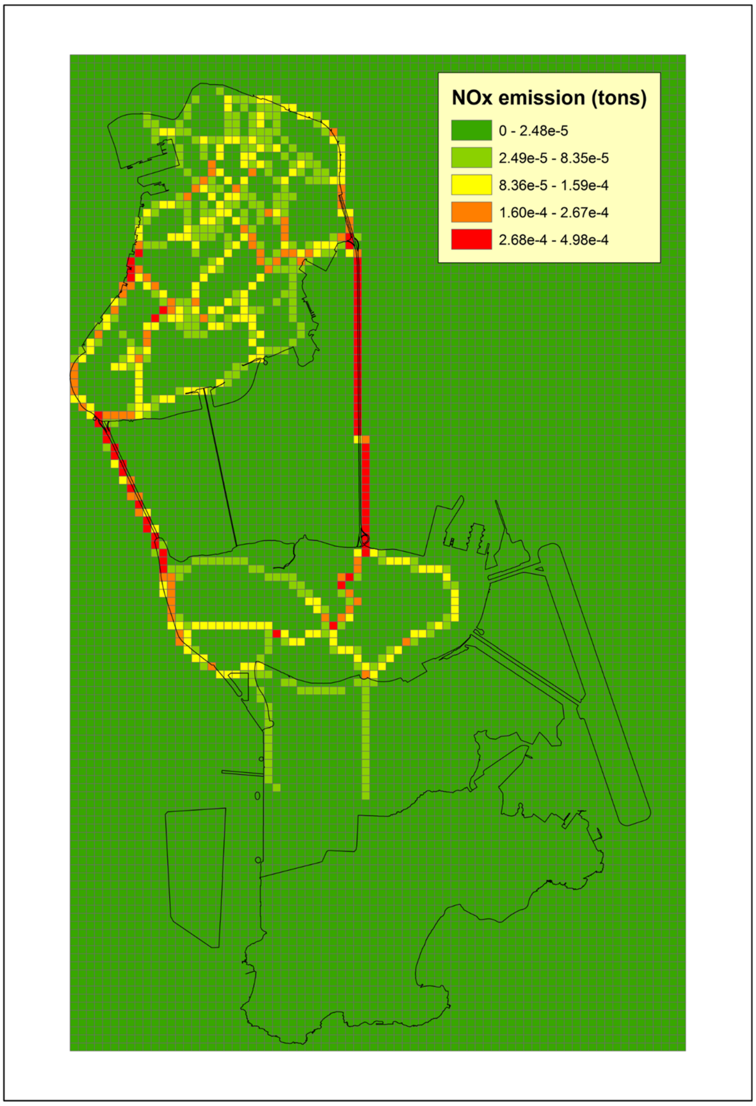

Fig. 14 Spatial distribution of road transport emissions for NO_x over the Macau SAR

reduction was 10.1%. Fuel consumption was obviously decreased. It was concluded that electric vehicles are the best option to reduce the emission of GHG. The substitution of 20.0% pre-Euro vehicles with latest Euro emission standards (i.e., Euro 5 and Euro 6) vehicles (sub-scenario C1) led to the reduction of CO, PM, NO_x, and VOC emissions by 0.4, 8.3, 6.0, and 1.7%, respectively. In the sub-scenario C2, the decrease in CO and VOC was sharper (− 5.6%, − 7.9%) compared with sub-scenario C1, while PM and NO_x decreased gently. The scenario C3 results in CO, VOC, PM, and NO_x decreased by 7.6, 9.8, 13.8, and 8.7%, respectively, based on the reference year. In such case, rigid emission standards were important for reducing pollutant emissions.

In this study, the basic three scenarios were developed and analyzed to evaluate the effectiveness of potential measures, which is the first scenario analysis about the Macau road transport emission inventory. We suggest further scenarios be developed if there are some new policies implemented. According to the analysis, further regulation plans could be made by the local government.

Conclusion

This study develops high spatial–temporal resolution emission inventory for Macau, which is an important

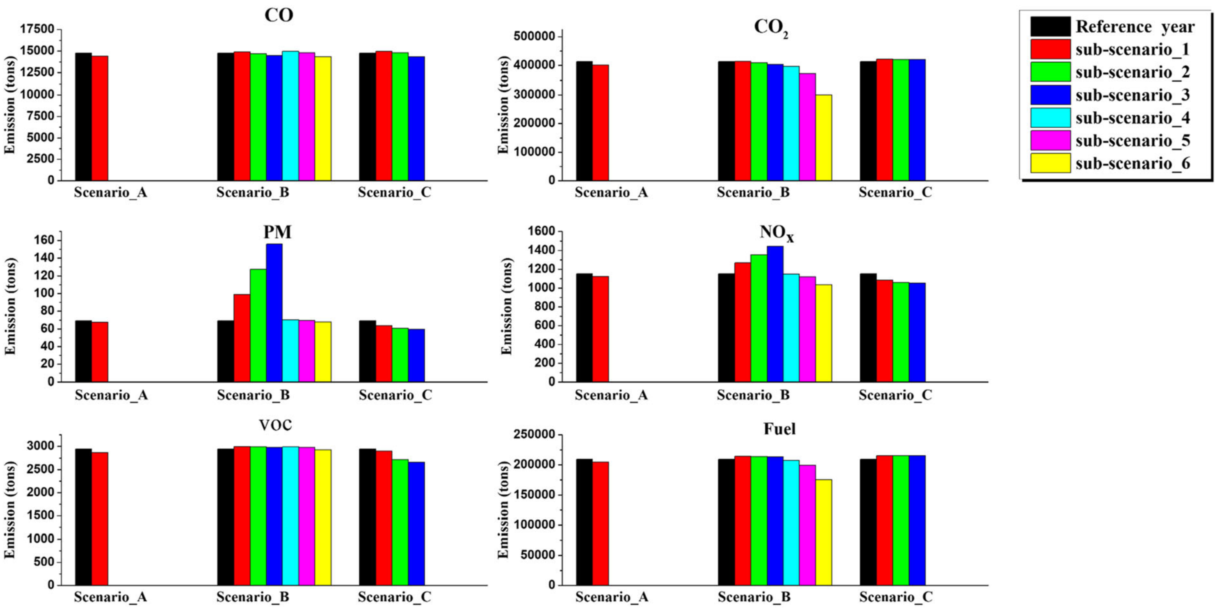

Fig. 15 Results of scenario analysis

input for local-scale air quality model and a useful tool for evaluating the effectiveness of potential measures through scenario analysis. The outcome of this study will contribute to the control of the air pollutant emission, making Macau a tourism center and, thus, develop its economy. In addition, this paper can provide a useful local case study and a solid framework for developing high-resolution environmental assessment tools for other vehicle-populated small cities in the world.

In this study, atmospheric emission inventory of road transport over the Macau SAR with high spatial and temporal resolution was developed by implementing a road traffic model (VISUM), a road transport emission model (TREM), and GIS. The VISUM model was applied for a morning peak hour (i.e., between 8:00 and 9:00 a.m.), and it revealed, in general, a good performance for private car and motorcycle traffic simulations. These results were comparable to other road traffic model applications over the study region. The VISUM

Table 4 Estimated annual traffic emissions of four hypothetical scenarios

Scenarios		Annual emissions					
		CO (kton)	CO_2 (kton)	PM (ton)	NO_x (kton)	VOC (kton)	Fuel consumption (kton)
Base year 2014		14.77	413.10	69.25	1.15	2.95	209.10
S_A		14.40	400.92	67.37	1.12	2.87	204.90
S_B	B_1	14.90	414.52	99.05	1.27	3.00	214.46
	B_2	14.69	408.88	127.42	1.36	2.99	213.98
	B_3	14.47	403.22	155.89	1.44	2.98	213.47
	B_4	14.95	396.03	70.08	1.15	2.99	207.10
	B_5	14.80	371.94	69.48	1.12	2.97	199.23
	B_6	14.33	299.64	67.76	1.03	2.93	175.62
S_C	C_1	14.71	421.06	63.53	1.08	2.90	215.28
	C_2	13.94	420.60	60.56	1.06	2.71	215.43
	C_3	13.65	420.44	59.70	1.05	2.66	215.52

outputs applying the near tool of GIS showed a good performance for buses, trucks, and taxis traffic simulations. It was recorded that the Macau Peninsula is the administrative division with the highest traffic congestion and the minimum speed could reach up to 12 km h^{-1}. The majority of vehicles in the Macau SAR are gasoline passenger cars and motorcycles with old European emission standards. It was verified that a correlation exists between the CO concentrations measured at roadside air quality monitoring station and the road traffic volume over the Macau SAR. The highest road transport emissions were observed over the Macau Peninsula. The total road transport emissions of CO, CO_2, PM, NO_x, and VOC estimated by TREM during the whole year of 2014 were 14,770, 413,099, 69, 1151, and 2945 tons, respectively. The fuel consumption was 209,103 tons. Within the year 2014, highest monthly emissions occurred in January, and these were 3 times higher than those in October (month with the lowest monthly emissions). As for the weekly variation, emissions on weekdays were around 25.0% more than those on weekend. For the diurnal variation, the road transport emissions were higher between 8:00–9:00 a.m. (start of the working day) and 19:00–20:00 p.m. (end of the working day). In this work, the annual CO, NO_x, and VOC road transport emissions were 4.7, 59.2, and 44.2% lower than those reported by the Macau Environment Protection Bureau. However, good agreement of the total annual vehicle fuel consumption estimated in the present study with that published by the Macau statistical bureau suggested that the present results represented the emissions better. Finally, the scenario analysis revealed some aspects to mitigate the road transport emissions; (1) although people are willing to have vehicles with diesel engine, it is not recommended since that will have highly adverse impact on NO_x and PM emissions; (2) it is recommended to continue encouraging citizens to use new energy automobiles (e.g., hybrid electric vehicles and battery electric vehicles) and to change vehicles from old Euro standard emissions to more stringent standard emissions; and (3) it is important to improve the public transport system in order to reduce the road traffic volume in the Macau SAR.

Acknowledgements This study is supported by the Science and Technology Development Fund of the Macau SAR government under grant no. 079/2013/A3, the research committee of the University of Macau under the multi-year research grant MYRG2014-00038-FST, as well as the university post-graduate studentship. The authors would like to thank Prof. K.P. Kou and Prof. K.I. Wong for supplying the transportation survey data in 2009. The authors would also like to thank the Macau Meteorological and Geophysical Bureau for supplying the data. This work was performed in part at the High-Performance Computing Cluster (HPCC) which is supported by the Information and Communication Technology Office (ICTO) of the University of Macau.

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