



# Estimating Road Transport Pollutant Emissions Under Traffic-Congested Conditions with an Integrated Modelling Tool—Emissions Reduction Scenarios Analysis

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## Abstract

This study aims to investigate, in microscale, the pollutant emissions due to road traffic under traffic-congested conditions at street level and the impacts on air quality of traffic emissions reduction scenarios by applying an Integrated Modelling Tool (IMT) for a main road axis in Thessaloniki, Greece. IMT links a real-world traffic model, a dynamic emissions model and a Lagrangian dispersion model coupled with a boundary layer flow module. Pollutant emissions from cars at edges with traffic lights were +30% higher than those estimated at other edges while NO<sub>x</sub> emissions were +22% higher at the edges with bus stops. A comparison of the IMT and COPERT Street Level emissions results showed that the IMT emissions were higher than the COPERT Street Level emissions for roads with traffic lights or bus stops, characterized by high variability in vehicle speed per second due to stopping and accelerating. This resulted in up to 2 times higher NO<sub>x</sub> emissions. IMT was applied to assess the impact on the atmospheric environment of the redesign of the road axis promoting sustainable urban transportation. A reduction by –20% of the cars and motorcycles traffic flows in combination with the increase by a factor of 2 of the frequency in the circulation of city buses replaced with battery electric vehicles will result in lower pollutant and CO<sub>2</sub> emissions ranging from –29 to –41%. Reductions of about –65% in the road traffic NO<sub>x</sub> maximum concentration levels were also estimated.

**Keywords** Road traffic emissions · Integrated Modelling Tool · COPERT Street Level · Traffic emissions reduction scenarios

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## 1 Introduction

Many research studies have reported that road transport deteriorates the air quality of urban centres, thus impacting human health [7, 49, 50]. The road transport sector has been identified as the major contributor of air pollutant emissions such as NO<sub>x</sub>, NMVOCs and particulate matter [13, 33, 38]; however, this fact is mostly associated with the increase in passenger and freight transport in urban centres [15]. Moreover, Fameli and Assimakopoulos [20] reported that around 66% of CO<sub>2</sub> emissions estimated over the greater area of Athens, Greece was attributed to emissions from passenger cars. Several studies have shown the impacts of mitigation strategies on road transport emissions and the environment [8, 12, 28] such as the use of more efficient vehicles, alternative fuels, electric vehicles, traffic signal coordination and improvements in public transportation systems [53].

To improve air quality simulation results, it is essential to have an accurate estimation of road traffic emissions. This will enable decision-makers to implement the most appropriate emissions mitigation measures. The scientific community has used different kinds of models to estimate road traffic emissions [48]. Static emission models, which are mainly based on the average speed of vehicles, are widely used for the European emission inventories on a national or regional level [29–31]. COPERT [15, 35] is a static modelling approach that is most often used to estimate vehicle exhaust emissions. However, on an urban microscale basis, this approach has the disadvantage of not accurately simulating the real traffic situation since it takes into account the average speed of vehicles, which most often leads to an underestimation of pollutant emissions [4]. It has been shown that different instantaneous speeds and acceleration levels influence the pollutant emissions [36]; therefore, in recent years there has been an increased interest in the use of dynamic emissions models integrated within microscopic traffic models. Traffic microsimulation models may offer a more accurate estimation in terms of the representation of driving behaviour taking into account the dynamics of driving cycles using vehicle speeds and accelerations at the highest resolution (usually 1 s) [51]. A series of dynamic emission models (PHEM [45], PHEMlight [22], VER-SIT + [47]) have been developed, coupled with microscopic traffic models (DRACULA [25], SUMO [27], AIMSUN [2], etc.). These models have been applied in several atmospheric pollution studies [13, 36, 40].

This study aims to analyse the air pollutant and CO<sub>2</sub> emissions due to road traffic under congested conditions at street level by applying an Integrated Modelling Tool (IMT) for a main road axis in Thessaloniki, Greece. IMT was developed to dynamically simulate the environmental impacts of road traffic at street level linking the following modules: the real-world traffic model “Simulation Of Urban Mobility” (SUMO [27]), the dynamic emissions model “Passenger Car and Heavy Duty Emission Model” (PHEMlight [22]) and the dispersion model “Pollutant dispersion in the atmosphere under variable wind conditions” (VADIS [5–7]). The study further analyses the spatial variability of the pollutant and CO<sub>2</sub> emissions under traffic-congested conditions (i.e. focusing on the traffic peak hour) in comparison to the main elements of the road network. Furthermore, the emissions results of the COPERT Street Level static model (EMISIA, 2015 [11]) were compared with IMT, highlighting the differences between the two different types of models. Finally, the research investigates the effectiveness of the measures used to reduce traffic congestion on the air quality improvement.

It is worth mentioning that the study, which investigates emissions at the local scale, provides additional knowledge on the determination of the environmental profile at street level considering that the smart cities concept is a

key component of street-level data. Under this view, the manuscript accounts for the measured traffic load, the specific road elements and characteristics (e.g. traffic lights, bus stops) in its methodological approach and results, while it also combines estimations and identifies the differences between outputs from a static and a dynamic emission model. Additionally, in the expected near future, the increased transport demand in the urban areas puts tremendous pressure on the urban atmospheric environment; thus, research on the reduced environmental impact of the urban transport systems is a current challenge not only for the scientific community but also for policymakers. However, the existing modelling tools are usually segregated; in contrast, the current study presents an integrated tool to perform the assessment of mobility scenarios. Thus, different traffic emissions reduction scenarios that reduce traffic congestion and emissions and their environmental effects are simulated and their impacts on air quality are compared. This holistic approach enables the scientific community and policymakers to make decisions about local and urban scale mitigation measures.

## 2 Methodology

In this section, the IMT is presented and its setup and application over a main road axis in Thessaloniki, Greece is described in detail. Thessaloniki is located in the northern part of Greece and it is the second largest city in the country with more than one million inhabitants [17]. The total number of vehicles being in operation in January 2018 has been estimated to be 756,596 in which 70% is passenger cars [18]. The studied road axis of Thessaloniki is located very close to Thermaikos Gulf connecting the city entrance from the airport with the city centre while it crosses urban areas with very important commercial activities being characterized also with high population density. The total length of the road axis is about 6.4 km (see Fig. 2).

IMT was applied considering the current traffic conditions of the road axis and those induced by the redesign of the road axis as a low carbon mobility solution (LCMS) to reduce traffic load. The LCMS can be associated with three different traffic scenarios related to reduced traffic flows of passenger cars and improvement of public transportation (e.g. use of “clean vehicles”).

### 2.1 Modelling System

The IMT is a modelling tool that was developed to simulate the environmental impacts of road traffic at street level and to assess the environmental performance of low carbon urban mobility solutions to reduce traffic congestion in terms of energy efficiency, air pollutant emissions,

air pollution dispersion and noise [26, 32, 39]. The IMT integrates many modules that have been linked including (Fig. 1):

1. Road traffic module based on the real-world traffic model “Simulation of Urban Mobility” (SUMO) [27] ([https://sumo.dlr.de/wiki/SUMO\\_User\\_Documentation](https://sumo.dlr.de/wiki/SUMO_User_Documentation)),
2. Traffic-related pollutant and CO<sub>2</sub> emissions, and energy consumption modules based on the dynamic model “Passenger Car and Heavy-Duty Emission Model (Light)” (PHEMLight) [22, 37] (coupled online with SUMO),
3. Traffic-related pollutants dispersion module based on the model “Pollutant dispersion in the atmosphere under variable wind conditions” (VADIS) [5–7],
4. Traffic-related noise module based on the methodology “Common Noise Assessment Methods in Europe” (CNOSSOS-EU) [24].

SUMO is an open-source, microscopic road traffic simulation package designed to simulate real-world traffic in large road networks. The main input data to simulate road traffic at street level with SUMO within IMT are related to the road axis and its traffic definition: the number of edges and lanes of the road, the coordinates of traffic lights, the bus stops or other sign, the specification of lanes (i.e. bus lanes), the slope of the road, the number of circulating vehicles per hour and vehicle type. It should be mentioned that the validity of the microsimulation traffic model SUMO used in the current study has been investigated in

the past through the comparison of the simulated vehicle speeds with measurement data [19, 34].

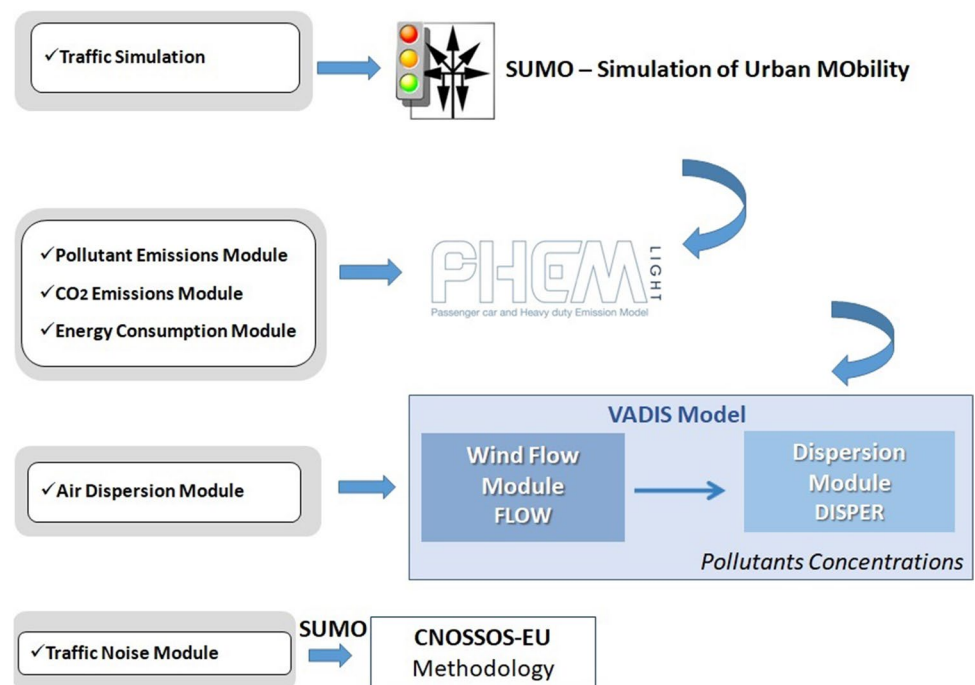
PHEMLight is a simplification of the “Passenger Car and Heavy-Duty Emission Model” (PHEM) [45]. PHEMLight has been evaluated through the comparison with PHEM results [44] while PHEM has been thoroughly validated with field data in the past [21, 22].

PHEMLight estimates fuel consumption, air pollutant emissions of carbon monoxide (CO), nitrogen oxides (NO<sub>x</sub>), hydrocarbons (HC) and particulate matter (PM<sub>x</sub>, comprise mostly particles with diameter less than 1 μm) and CO<sub>2</sub> emissions for different vehicle emission classes comprising information on the type, shape, weight of vehicles as well as engine-related properties of vehicles (i.e. rated power, fuel type, emission standard as Euro I, Euro II, etc.). PHEMLight estimates only hot exhaust emissions from vehicles (non-exhaust and cold-start emissions are not included in the model). CO emissions are not presented in the current study since they are not considered significant in terms of air quality; the upgrade of vehicle technologies in the last years (catalytic converters) has reduced these emissions substantially [16].

PHEMLight uses data files that include all the necessary vehicle parameters of the modelled emission classes. The main vehicle emission classes included in the PHEMLight emission database are listed below:

- Passenger cars (PC) (named cars in IMT),
- Light commercial vehicles of size class I (LCV I) (named motorcycles in IMT),

Fig. 1 Linking of IMT modules



- Light commercial vehicles of size class III (LCV III) (named delivery vehicles in IMT)
- Heavy-duty vehicles—city bus (HDV\_CB) (named buses in IMT),
- Heavy-duty vehicles—coach (HDV\_CO) (named coaches in IMT),
- Heavy-duty vehicles—rigid trucks (HDV\_RT) (named trucks in IMT),
- Heavy-duty vehicles—truck + trailer (HDV\_TT) (named trailers in IMT).

Furthermore, the vehicle emission classes are further defined for different technologies (i.e. gasoline engine (G), diesel engine (D), gasoline/diesel electric engines (parallel hybrid powertrain) (G\_HEV/D\_HEV), compressed natural gas engine (CNG) and battery electric vehicles (BEV)) and emission standards (EU0 to EU6c) for each vehicle type.

VADIS is a computational fluid dynamic (CFD) model coupling a boundary layer flow module (FLOW) which uses the numerical solution of the three-dimensional (3D) Reynolds averaged Navier–Stokes equations and the *k-ε* turbulence closure to calculate the wind, turbulent viscosity, pressure, turbulence and temperature 3D fields with a Lagrangian dispersion module (DISPER) [5–7]. VADIS does not take into account the chemical transformation of pollutants.

The main input data for the application of VADIS within IMT are the outputs of the pollutant and CO<sub>2</sub> emissions module, the meteorological data (air temperature, pressure, wind velocity and wind direction) as well as the geometry of the buildings located along the studied road axis. It should be noted that no background pollutant concentrations are taken into account signifying that only the dispersion of the pollutant emissions from the road traffic is simulated.

The traffic-related noise module is based on the methodology “Common Noise Assessment Methods in Europe” (CNOSSOS-EU) [24]. Noise emissions calculations are based on fleet of vehicles, road surface, ambient temperature and road gradient (slope of the road). It should be noted that the noise module uses as input the output data from the traffic module of IMT (i.e. SUMO).

An important feature of the IMT is the option for building mobility scenarios. The user can set and simulate his customized mobility scenarios. However, it is also possible to define mobility scenarios and examine their environmental impacts while selecting among eight different mobility interventions/solutions (or soft actions) already integrated in the IMT [43]. The mobility interventions/solutions are related with the (a) bus public transportation (e.g. addition of a bus lane, addition of one or more bus lines), (b) soft mobility (e.g. addition of a bike lane), (c) road elements (e.g. changes in the location and duration of traffic lights, removal or addition of a road lane), (d) traffic characterization (e.g.

changes in vehicle type distribution or traffic temporal pattern) and (e) freight logistics (e.g. changes in vehicle type or delivery hours).

For the application of the IMT, the user may proceed following the main steps below:

1. Insert the input data of the base case run (i.e. road network definition, traffic load and synthesis, buildings dimensions, meteorology),
2. Apply the selected module,
3. Get the output data as graphs and maps,
4. Build the mobility scenarios (soft actions) (optional),
5. Apply the selected module (for the selected soft action) (optional),
6. Get the mobility scenarios output data as graphs and maps (optional) for comparison with the base case.

It should be noted that health and cost modules have been developed to estimate the impact of mobility scenarios on citizens’ health and health-related costs. They are based on statistical modelling to relate air pollution and meteorology with health events (deaths, hospitalizations) and the latter ones with health costs [9]. These modules are not currently fully integrated in IMT, and for this reason are not presented in Fig. 1, but represent the IMT near-future final development.

The current study focuses on air quality and the atmospheric environment, and therefore on the application and results presentation from the traffic transport module (SUMO), the pollutant and CO<sub>2</sub> emissions modules (PHEM-light) and the pollutants dispersion module (VADIS); the results from the application of the other modules of IMT (noise, health and cost) are out of the scope of the current study and will be presented elsewhere.

## 2.2 IMT Application

The IMT was implemented for the traffic model and the air pollutant and CO<sub>2</sub> emissions for each hour of the day considering the following input traffic data of mid-September 2017.

The main input data required by the traffic model are related to the zone and traffic definition. In particular, the road network definition requires the following input data: the number of edges and lanes, coordinates of traffic lights, bus stops or other sign, specification of lanes (i.e. bus lanes) and the slope of the road. It should be noted that the road of the study area is generally flat and therefore the slope of the road was not taken into account. The traffic data are related to the number of vehicles per hour circulated in the road and vehicle types.

The road axis of Thessaloniki consists of 54 nodes (including 31 traffic lights, 18 bus stops and 5 other positions) and therefore of 53 edges (i.e. road segments). Only

the first 3 edges of the road axis include a two-way road. Most of the part of the road axis consists of 3 traffic lanes and one bus lane. The length of the edges of the studied road axis ranges from 25 to 300 m with an exception of edges 3 and 6 which have 500-m length.

Measurements of the traffic load were performed by the Hellenic Institute of Transport of the Centre for Research & Technology, Hellas (HIT-CERTH) at 5 sites along the studied road axis of Thessaloniki during the period 18 to 22 September 2017 [10]. Table 1 presents the main characteristics related to zone definition for five parts of the road axis (shown in Fig. 2) that will be studied in the current paper and which are characterized by different traffic load as measured by HIT-CERTH.

Figure 3 presents the spatial average of the hourly traffic load along the road axis per vehicle type on the basis of the HIT-CERTH measurements and previous related studies (trucks and trailers do not circulate in the road axis under study) as well as based on the data derived from the Organization of Urban Transportation of Thessaloniki (<http://oasth.gr>) for the circulation of public buses. The traffic conditions can be considered as typical for a day in mid-September 2017. The maximum traffic load is at 08:00–09:00 while on a daily basis, cars represent the 80% of the total traffic volume, followed by motorcycles (15%) and buses (3%). Delivery vehicles and coaches represent a very low share (~1%).

Regarding the public transportation (i.e. circulation of urban buses), further and more detailed traffic data (number of bus lines, bus stops for each bus line, average circulation frequencies) were derived from the Organization of Urban Transportation of Thessaloniki (<http://oasth.gr>). More specifically, nine bus lines travel through the road axis. The time of the buses wait at each bus stop is defined at 15 s.

The vehicle types defining the traffic load were further classified per technology and emission standard using respective information on a national scale (Greek annual database) from the COPERT Street Level model for the year 2017 (<https://www.emisia.com/utilities/copert-street-level/>). This information has been introduced in the model in order to define, for each vehicle type (i.e. cars, motorcycles, delivery, buses, coaches), the probability (0 to 1) of each emission class (e.g. PC\_G\_EU5 corresponds to a passenger car with

a gasoline engine and emission standard Euro5). Thus, each vehicle type is classified into technology types and emission standard as described in “Section 2.1”. In particular, 94% of cars, 69% of delivery vehicles and 100% of motorcycles are classified into gasoline engine while 100% of buses/coaches are classified into diesel engines.

The dispersion of traffic-related emission was simulated using IMT applied for the 19th September 2017 (selected due to meteorological conditions unfavourable for pollutant emissions dispersion) at the traffic peak hour (08:00–09:00) in a small part of the road axis (road part 4 in Table 1) to allow the dispersion module to run in high spatial resolution (~10 m) and simulate the street canyon effect. This part of the road axis has a length of about 400 m and was selected for the dispersion model simulation because it presented the highest traffic flows. The height of the buildings along the road was defined at about 20 m. The necessary meteorological parameters (temperature, pressure, and wind velocity and direction) were obtained using the Weather Research and Forecasting model (WRF) [46] in the greater area of Thessaloniki. WRF model has been applied for the period September–November of 2017 over the studied urban area of Thessaloniki. IMT was applied with temperature and pressure values of 24.42 °C and 1 bar, respectively. The wind was blowing from the southwest (240°) at 3 m s<sup>-1</sup> speed.

### 2.3 Evaluation of Traffic Model

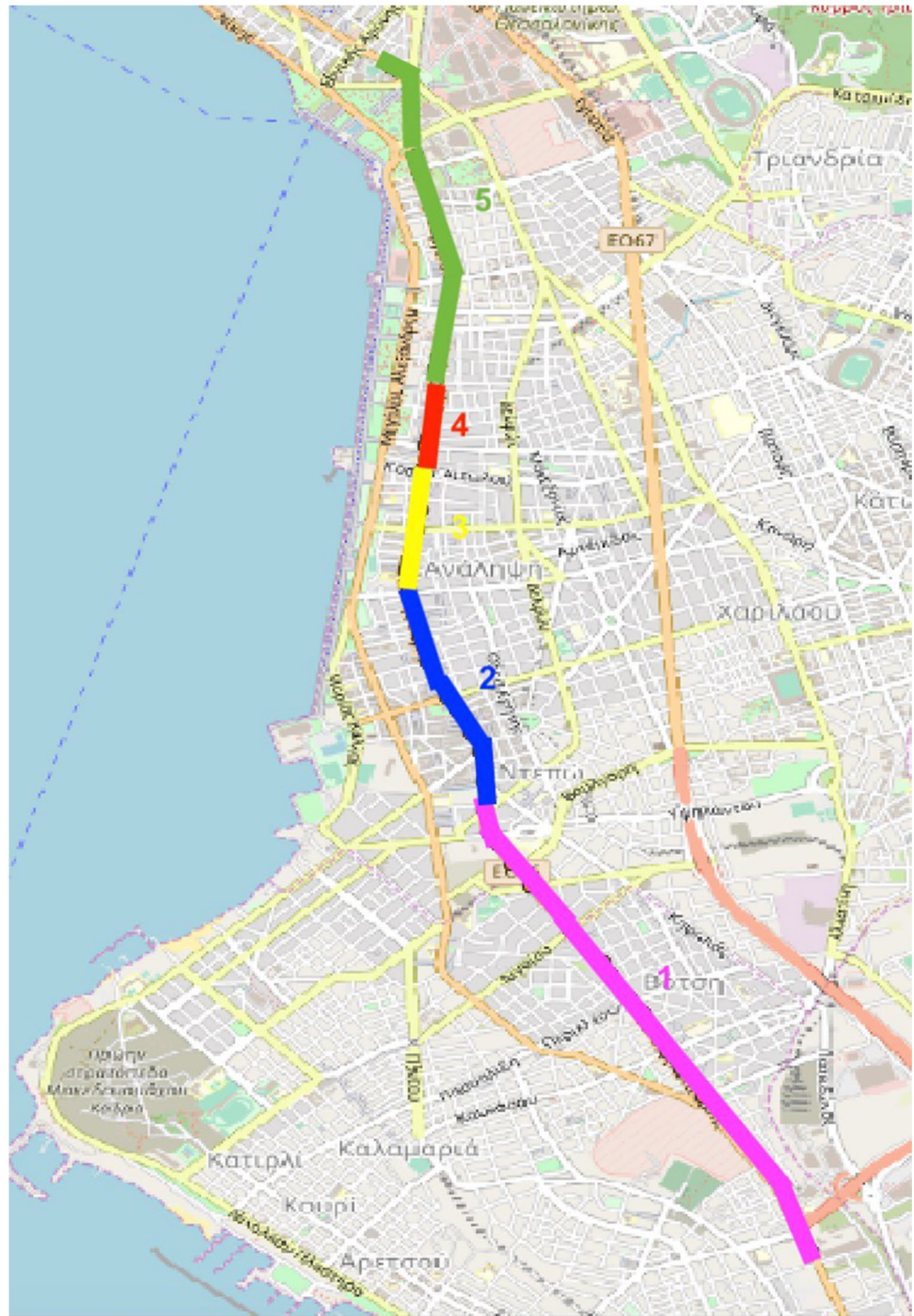
The traffic model integrated with IMT is evaluated through the comparison of the simulated mean speed of buses and passenger cars on a daily basis (i.e. for 24 h) with measurement data. Traffic measurements of buses have been derived from the Organization of Urban Transportation of Thessaloniki and concern hourly measurement data of mean speed of buses along the study road axis of Thessaloniki for the hours 04:00–23:00 when public transportation is in operation. Regarding the traffic measurement data of passenger cars, those concern the 24 hourly mean speed of taxis circulating along the study road axis in a typical weekday of September 2017.

Figure 4 depicts the comparison between the simulated (with IMT) and observed mean speed for passenger cars

**Table 1** Zone definition

Road part	Edges	Road length (km)	Bus stops	Traffic lights	Bus stops per km	Traffic lights per km
1	1–19	2.6	7	12	2.7	4.6
2	20–29	1.1	3	6	2.8	5.6
3	30–35	0.7	2	3	3.1	4.6
4	36–39	0.4	2	1	5.1	2.6
5	40–53	1.7	4	9	2.4	5.3

**Fig. 2** Thessaloniki road axis for modelling simulations (road parts 1 to 5 as described in Table 1)

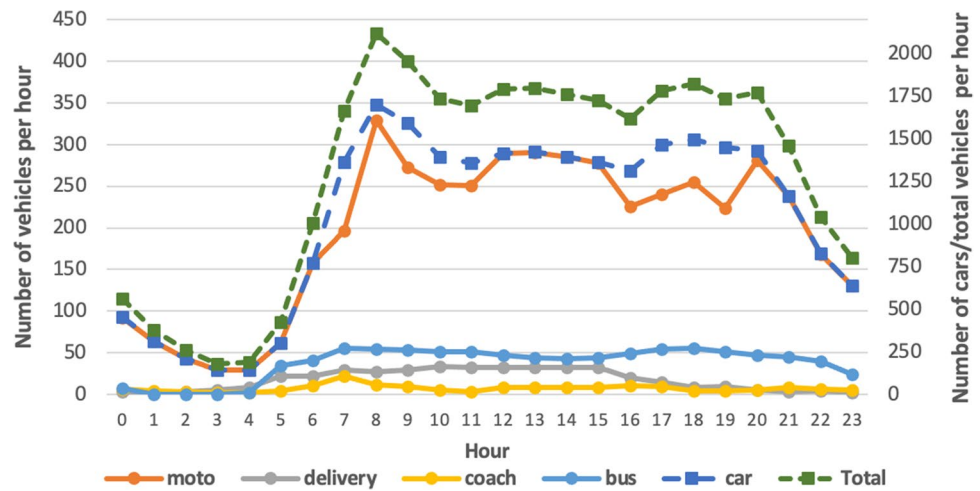


and buses. A good agreement is presented between simulated and observed data for both vehicle types on a daily basis with a correlation of 0.84 and 0.94 for passenger cars and buses, respectively. In the peak hour, it seems that the simulated mean speeds of both vehicle types agree very well with the measurement data.

## 2.4 Traffic Emissions Reduction Scenarios

Considering the policies towards competitive and resource-efficient transport systems and Sustainable Urban Mobility Plans which promote soft mobility (i.e. cycling and walking) and encourage the use of public transport systems [14], a low carbon mobility solution (LCMS) is

**Fig. 3** Hourly distribution of traffic load along the road axis by vehicle type



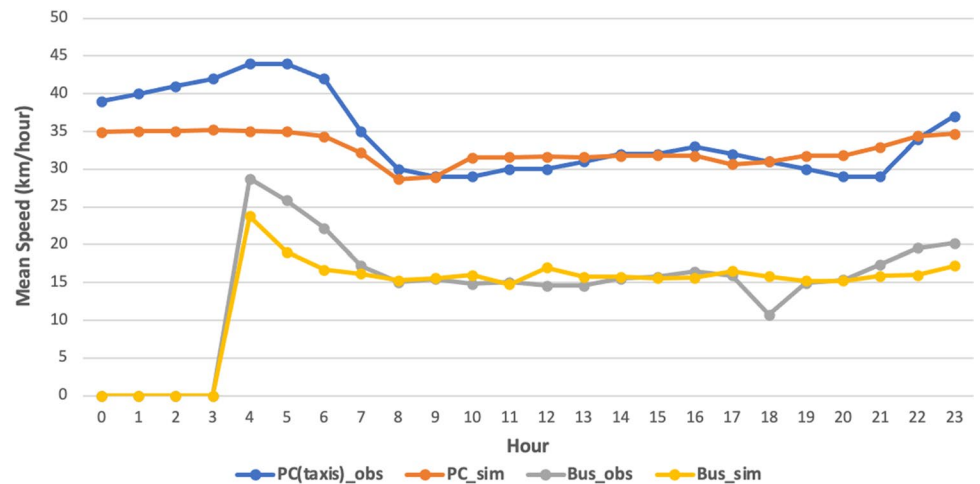
analysed for the studied road axis of Thessaloniki aiming to reduce road traffic and its negative environmental effects. The LCMS was selected after extensive participatory process and consultation, including local authorities, policymakers, traffic and environmental experts, other stakeholders (e.g. urban transportation service providers), and the public, in the framework of the INTERREG MED project REMEDIO [42] with a future possible option to be included in the Sustainable Urban Mobility Plan of the City of Thessaloniki being under development. The LCMS refers to the redesign of the road axis. More specifically, the traffic lanes will be reduced from 3 to 2 almost along the whole part of the axis, while the existing bus lane on the right-hand side of the road will be upgraded to a modern 2nd generation separated bus lane. Moreover, a bicycle lane on the road left-hand side will be constructed.

On the basis of the above, the LCMS can be associated with the following emissions reduction scenarios for the traffic conditions for which the IMT was applied at the traffic peak hour (08:00–09:00):

- 1st scenario (SCN10): The traffic volume of passenger cars and motorcycles is reduced by 10% with respect to the base case [1, 41],
- 2nd scenario (SCN20): The traffic volume of passenger cars and motorcycles is reduced by 20% and the average frequency of the public bus lines through the road axis increases by a factor of 2 with respect to the base case (e.g. 1 bus every 20 min becomes 2 buses every 20 min) [1, 41],
- 3rd scenario (SCN20\_BEV): SCN20 applies taking into account that all public buses circulating in the road axis of Thessaloniki are replaced with battery electric vehicles (BEV) which produce zero pollutant and CO<sub>2</sub> emissions along the road.

It should be mentioned that the traffic emissions reduction scenarios have been designed in order to satisfy the current demand of transportation along the road axis considering though the improved modes of transportation

**Fig. 4** Comparison of simulated mean speed of passenger cars and buses with measurement data along the road axis of Thessaloniki on a daily basis



(public transportation, walking, cycling) and new means of transportation (i.e. subway).

### 3 Results and Discussion

The results of the dynamic model IMT are presented in this section, focusing on the different characteristics of the traffic and elements of the road to the determination of pollutants emissions. In addition, the differences in dynamic versus static road traffic emissions modelling are identified that should be taken into account in the simulation of real-world driving conditions in microscale. Finally, the environmental impacts of sustainable urban mobility are quantified with IMT to allow also prioritization of policymakers' decisions.

#### 3.1 Pollutant and CO<sub>2</sub> Emissions Results for the Base Case

The diurnal variation of the total air pollutant and CO<sub>2</sub> emissions is configured by the diurnal pattern of the traffic load (Fig. 3). For all the pollutants, the emissions values are higher the hours 7:00 to 10:00, presenting a peak at 08:00–09:00 when the traffic load is maximum.

In the following, further analysis of air pollutant and CO<sub>2</sub> emissions focusing mainly on the traffic peak hour (08:00–09:00) is made. Cars are the major emission source for all the pollutants (Figure S1, in the supplement) due to their traffic load being higher than that of all the other vehicle types (see Fig. 3). Motorcycles are the second contributor to CO<sub>2</sub>, PM<sub>x</sub> and HC emissions followed by buses, while coaches and delivery vehicles have a lower share to the emissions. Buses are the second in the rank source of

NO<sub>x</sub>, emitting amounts comparable to those emitted from cars despite the much lower share in traffic flows that they represent. This happens mainly due to the fact that, according to the emissions factors of PHEMlight, those related to gasoline vehicles are by a factor of 10 smaller than those of diesel-powered vehicles [22]. Similar is the case for coaches which also represent a quite important share of NO<sub>x</sub> emissions, followed by motorcycles and delivery vehicles (Figure S1, in the supplement). The total and per vehicle type pollutant and CO<sub>2</sub> emissions over the road axis present the same ranking of vehicle emissions sources on a daily basis, too (i.e. for 24 h).

Table 2 presents the average number of vehicles per type that circulate in the five road parts of the road axis (described in Table 1) along with the corresponding simulated mean speed (i.e. range of values per edge and mean value over all edges) per vehicle type at the traffic peak hour. Road part 4 is the part with the highest traffic flow of cars which is the major emission source. However, the lowest vehicle speeds were simulated in the 2nd road part because it has the highest number of traffic lights per road length (Table 1). Similar is the case for the 5th road part which presents comparable mean vehicle speeds with the 2nd one. The number of buses circulated in the road axis is highest at the road parts 3 to 5 while the lowest simulated mean speed of buses has been estimated for the 4th road part (~35% lower compared to road parts 3 and 5) where the highest ratio of the number of bus stops per km is presented (Table 1). It has been shown that stopping and accelerating at traffic lights is an important contributor to vehicular emissions in urban environments [3]. For this reason, following in the current study, the road traffic emissions are further analysed accounting for the vehicle speeds as well as the

**Table 2** Average number of vehicles and IMT simulated mean speed (in km/hour) per vehicle type in the parts of the road axis at traffic peak hour

Road part (edges)	Car		Motorcycle		Delivery		Coach		Bus	
	No. <sup>1</sup>	Mean speed range <sup>2</sup> (mean <sup>3</sup> )	No	Mean speed range (mean)	No	Mean speed range (mean)	No	Mean speed range (mean)	No	Mean speed range (mean)
1 (1–19)	1194	7.9–45.2 (27.3)	135	6.8–43.7 (25.9)	27	7.5–46 (30.9)	17	7.4–46 (31.5)	19	4.6–44 (19.0)
2 (20–29)	1728	3.9–44.1 (14.3)	195	4.7–42.8 (15.1)	14	3.5–44.8 (19.0)	3	4.3–44.9 (23.3)	31	8.4–42 (20.0)
3 (30–35)	1613	13.6–44.6 (29.0)	257	13–42.6 (28.3)	26	12.5–45.2 (31.3)	6	10.8–47.4 (35.2)	39	15–43 (24.3)
4 (36–39)	2370	6.4–47.2 (26.8)	722	6–44.6 (25.0)	41	11.1–47.2 (30.4)	14	7.7–47.4 (33.1)	39	3.1–35.5 (13.8)
5 (40–53)	1596	6.3–47.0 (25.1)	336	5.8–44.5 (24.2)	29	9.8–47.4 (28.4)	21	13–47.7 (28.8)	39	3.5–48 (18.7)

<sup>1</sup>Number of vehicles circulated in each edge of the road part

<sup>2</sup>Minimum and maximum value of mean speed per edge of the road part

<sup>3</sup>Mean speed over all edges of the road part



operation of traffic lights in the different road parts of the road axis under study. Furthermore, the spatial variability of emissions from buses is investigated in comparison with their stopping at bus stops.

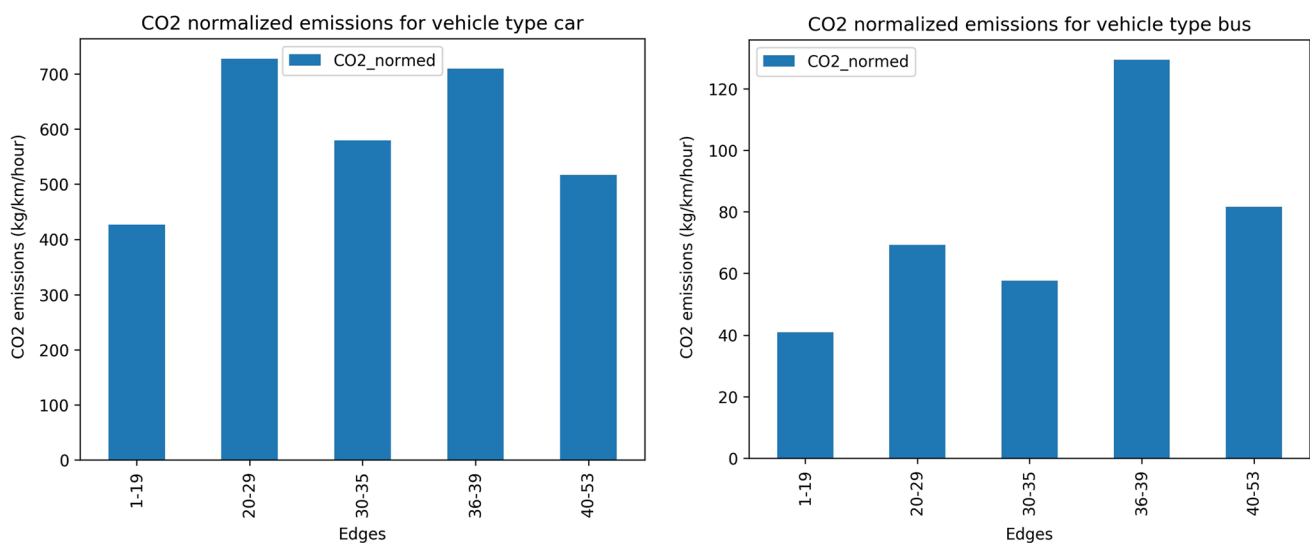
Figure 5 illustrates the average normalized CO<sub>2</sub> emissions for cars and buses for each of the five road parts of the road axis at the traffic peak hour. Other pollutants present also similar spatial distribution and therefore are not shown. The normalized values are defined as the pollutant emissions during the specific interval normed by time and edge length. As far as cars are concerned, although the number of cars circulating in the 2nd road part is 27% lower than the highest number circulating in the 4th part, the corresponding average normalized pollutant emissions of the 2nd part of the road are the highest (comparable in most cases though with those in the 4th part). This is due to the highest number of traffic lights (see Table 1) operating in the 2nd road part leading to 40% lower speed for cars with respect to the 4th road part as well as to higher accelerations inducing increased emissions, in addition to the fact that the number of traffic lights per road length is minimum at the 4th part of the road axis. The lowest normalized emissions from cars, for all pollutants, are presented in the 1st part of the road axis where the traffic flow is significantly lower in comparison with the other road parts. Emissions from buses are more dependent on the number of bus stops rather than on the number of traffic lights; the highest normalized emissions are estimated at the 4th road part being by around 60% higher for most pollutants than those in the 5th part where the traffic flow of buses is the same. The 4th road part of the road axis presents the highest ratio of bus stops (almost double) per road length while the corresponding ratio of traffic

lights per km is the lowest. Also, the spatial distribution of the normalized CO<sub>2</sub> emissions for cars and buses along the whole road axis of Thessaloniki at the traffic peak hour highlights the high variability of normalized emissions per edge because of the existence of traffic lights and bus stops (Figure S2, in the supplement).

Finally, it should be referred that on a daily basis (i.e. for 24 h) lower average normalized pollutant emissions are estimated by around 40% and 20% for cars and buses, respectively, while a similar pattern of normalized pollutant emissions (Fig. 5, Fig. S2) has been identified and therefore not presented here.

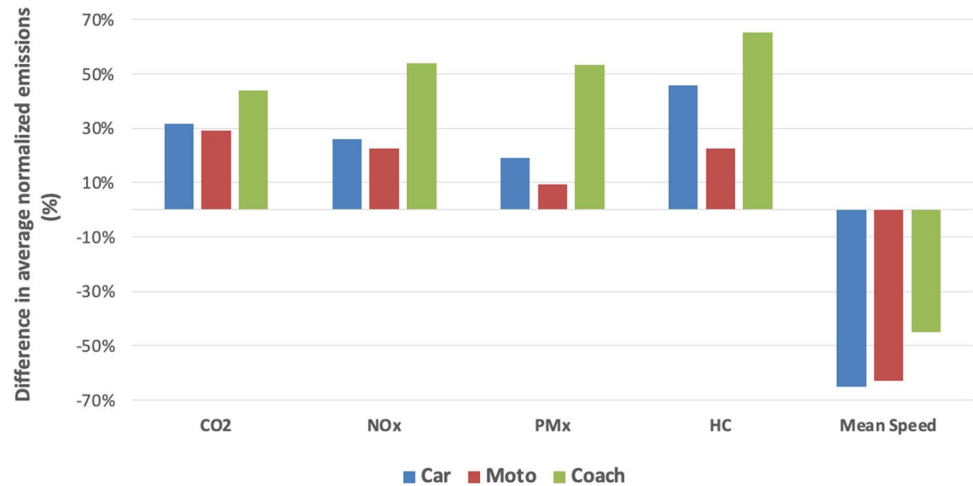
In the following, further analysis is made to estimate the percentage differences in average normalized pollutant emissions per vehicle type (cars, motorcycles, coaches) between edges with traffic lights and edges without traffic lights having the same traffic flow for the traffic peak hour as well as on a daily basis (i.e. for 24 h). Emissions of delivery vehicles are not studied since they represent a very low share for all pollutants (Fig. S1, in the supplement). For buses, the corresponding analysis is made for edges with bus stops and edges without bus stops. To identify the impact of traffic lights and bus stops on pollutant emissions, it was necessary to eliminate other factors that may influence pollutant emissions such as the structure of the road and therefore only road parts with the same number of traffic lanes were selected (i.e. 4 traffic lanes including one bus lane).

Figure 6 shows the percentage differences in average normalized pollutant emissions between the edges with traffic lights (with TL) and edges with no traffic lights (without TL) along the selected parts of the road axis of Thessaloniki for cars, motorcycles and coaches for the



**Fig. 5** Average normalized CO<sub>2</sub> emissions (in kg/(hour×km)) for cars (left) and buses (right) in road parts 1 (edges 1–19), 2 (edges 20–29), 3 (edges 30–35), 4 (edges 36–39) and 5 (40–53) at the traffic peak hour

**Fig. 6** Percentage differences in average normalized pollutant emissions ( $\text{CO}_2$ ,  $\text{NO}_x$ ,  $\text{PM}_x$ , HC) and mean speeds of vehicles between edges with traffic lights and edges without traffic lights having the same traffic flow and traffic lanes at the traffic peak hour



traffic peak hour as well as on a daily basis. The percentage differences are defined as follows:

$$\% \text{Difference} = \frac{(\text{with TL} - \text{without TL})}{\text{without TL}} \% \quad (1)$$

For the traffic peak hour (Fig. 6), normalized pollutant emissions for cars and motorcycles are around 30% and 20%, respectively, higher in edges with traffic lights while the highest dependence on stopping and accelerating at traffic lights is shown for HC and the lowest for  $\text{PM}_x$ . For coaches, a much higher impact of traffic lights on road traffic emissions has been estimated (~50% higher emissions in edges with traffic lights for  $\text{CO}_2$ ,  $\text{NO}_x$  and  $\text{PM}_x$  and 68% higher for HC) indicating that emissions from heavy-duty vehicles are more sensitive at stopping and accelerating at traffic lights compared to other vehicles. Regarding the differences in mean speeds, light vehicles (i.e. cars and motorcycles) mean speed is by up to –65% lower at edges with traffic lights than at those without, while for heavy-duty vehicles (i.e. coaches) the mean speed values are by –45% lower in edges with TL.

For 24 h, smaller increases in average normalized pollutant emissions and mean speeds in edges with traffic lights are presented on a daily basis for most cases compared to those at the traffic peak hour (Figure S3, in the supplement) highlighting the higher influence of traffic lights on pollutant emissions under traffic-congested conditions.

The percentage differences in average normalized pollutants emissions from buses between the edges with bus stops (with BS) and edges without bus stops (without BS) along the selected parts of the road axis of Thessaloniki have been also estimated for the traffic peak hour as well as for 24 h (Table S1, in the supplement). It has to be noted that edges with no bus stops are mainly edges with traffic lights. The percentage differences are defined as follows:

$$\% \text{Difference} = \frac{(\text{with BS} - \text{without BS})}{\text{without BS}} \% \quad (2)$$

The highest percentage differences in average normalized emissions are presented for the traffic peak hour as following: +12%, +22%, +30% and +93% for  $\text{CO}_2$ ,  $\text{NO}_x$ ,  $\text{PM}_x$  and HC, respectively. The corresponding mean speed values of buses are by –41% lower in edges with bus stops compared to the other ones at the traffic peak hour. Smaller differences are presented on a daily basis.

To summarize, the analysis of the emissions results indicated that pollutant emissions from traffic are influenced by the different elements of the road (i.e. traffic lights, bus stops) leading in some cases to higher emissions in edges with traffic lights even though these edges are characterized by lower traffic flows compared to other ones. Bus stops have also an impact on pollutant emissions due to stopping and accelerating of buses leading to considerable differences in pollutant emissions between edges with bus stops and edges without bus stops.

### 3.2 Comparison of Dynamic and Static Emission Models Results

The emissions results of IMT presented in “Section 3.1” for cars and buses at the traffic peak hour are compared with those estimated by the emission model COPERT Street Level (EMISIA [11]) applied for the road axis of Thessaloniki. The comparison is made only for the specific vehicle types since as shown in “Section 3.1”, they are the most important contributors to  $\text{NO}_x$ ,  $\text{CO}_2$  and  $\text{PM}_x$  emissions, considered the most important pollutants of road transport.

COPERT SL is a static emission model which is widely used on a European level for the estimation of road transport emissions on a single street or a full city street network on an hourly basis requiring the following input data: coordinates of nodes, length of edges, the average speed of vehicles per

**Table 3** Comparison between IMT and COPERT SL emissions (in kg/km/hour) from cars at the peak hour of traffic data for CO<sub>2</sub>, NO<sub>x</sub> and PM<sub>x</sub> for each road part (1–4)

Road part	CO <sub>2</sub> (kg/km/hour)		NO <sub>x</sub> (kg/km/hour)		PM <sub>x</sub> (kg/km/hour)	
	IMT	COPERT SL	IMT	COPERT SL	IMT	COPERT SL
1	330.10	273.28	0.44	0.31	0.024	0.004
2	832.12	604.61	1.10	0.51	0.061	0.007
3	543.32	367.96	0.71	0.42	0.047	0.006
4	670.62	616.47	0.86	0.63	0.051	0.009

edge, number of vehicles per edge and vehicle type distribution according to technology and emission standard.

COPERT SL can be used for the estimation of emissions for the pollutants CO, NO<sub>x</sub>, CO<sub>2</sub>, PM (as PM<sub>2.5</sub> comprises mainly PM<sub>1</sub>) and volatile organic compounds (VOC). In COPERT SL, vehicles are classified in the following vehicle types: passenger cars, light commercial vehicles, heavy-duty trucks, buses, motorcycles and mopeds. The vehicle types are further classified based on technology and emission standards similarly to IMT classification. It should be mentioned that COPERT SL, similarly to PHEMlight, estimates only hot exhaust emissions (non-exhaust and cold-start are not included). Also, VOC emissions include methane (CH<sub>4</sub>) emissions, similarly to PHEMlight (for HC emissions).

COPERT SL was applied to estimate emissions from cars and buses using the same input data as for the IMT application, while for the average speed per edge of each vehicle type, the values simulated by IMT were used. On an average level along the whole road axis, IMT results of the hourly CO<sub>2</sub>, NO<sub>x</sub> and HC/VOC emissions from cars differ by +25%, +50% and –20%, respectively, in comparison with COPERT SL. The difference between IMT and COPERT SL in PM<sub>x</sub> emissions results for cars is larger than those of the other pollutants; IMT estimated much higher PM<sub>x</sub> values compared to COPERT SL. Concerning buses, the corresponding differences between IMT and COPERT SL for the hourly CO<sub>2</sub>, NO<sub>x</sub>, PM<sub>x</sub> and HC/VOC emissions are +45%, +40%, +25% and –30%, respectively.

Previous studies have shown that there are expected differences in the results of static and dynamic traffic emissions models with dynamic models to usually give higher emissions values [4]. Wismans et al. [52] found absolute differences in NO<sub>x</sub> emissions between static and dynamic models

that could be up to 45%, with the differences being larger for CO<sub>2</sub>. Borge et al. [4] estimated a +20% difference in NO<sub>x</sub> emissions estimated with the COPERTv8.1 and HBEFAv3.1 (Handbook Emission Factors for Road Transport [23]) emissions models, representative of the “average-speed” and “traffic situation” model types, respectively. Concerning the HC and VOC emissions estimated by IMT and COPERT SL, respectively, it should be noted that although the emission results between the models are generally comparable, the effort for direct comparison is difficult because of the possible different chemical speciation of organic compounds in the two models.

In Tables 3 and 4, the comparison between the IMT and COPERT SL pollutant and CO<sub>2</sub> emissions from cars and buses for the 5 road parts of the road axis of Thessaloniki including only edges with 3 traffic lanes and one bus lane (similarly to the approach described in “Section 3.1”) is presented for the traffic peak hour (08:00–09:00). HC emissions are not presented due to the high uncertainties in comparison as described previously. It is apparent that for all pollutants, the highest differences between IMT and COPERT SL emission results for cars are found in the 2nd road part of the road axis where the lowest car speeds are presented (Table 2) and a high number of traffic lights exist (Table 1). In particular, in the selected edges of the 2nd road part, the simulated speed of cars per second is highly differentiated due to the stopping and accelerating at traffic lights leading to mean speeds ranging from 4 to 8 km/h resulting in +40% higher CO<sub>2</sub> emissions compared to COPERT SL which cannot take into account the real traffic conditions and therefore the high variability of vehicle speeds per second due to stopping and accelerating. Also, NO<sub>x</sub> emissions produced by IMT are 2 times higher than those of COPERT SL. In the

**Table 4** Comparison between IMT and COPERT SL emissions (in kg/km/hour) from buses at the peak hour of traffic data for CO<sub>2</sub>, NO<sub>x</sub> and PM<sub>x</sub> for each road part (1–4)

Road part	CO <sub>2</sub> (kg/km/hour)		NO <sub>x</sub> (kg/km/hour)		PM <sub>x</sub> (kg/km/hour)	
	IMT	COPERT SL	IMT	COPERT SL	IMT	COPERT SL
1	29.16	22.82	0.28	0.23	0.009	0.008
2	73.86	42.88	0.73	0.42	0.023	0.014
3	61.61	54.73	0.60	0.55	0.018	0.019
4	119.22	54.75	1.17	0.53	0.036	0.018

4th road part where the lowest number of traffic lights per km is presented, the corresponding differences in the average emissions results are about +8% and +35% for CO<sub>2</sub> and NO<sub>x</sub>, respectively.

According to Table 4, for buses, the highest differences between IMT and COPERT SL emissions results are identified in the 4th road part of the road axis where the highest number of bus stops per km are located (Table 1) and the mean speed of buses in the edges with bus stops is ~3 km/h; IMT emissions are more than doubled compared to those of COPERT SL. High differences in pollutant emissions (~+65%) between IMT and COPERT SL are presented also in the 2nd part of the road and particularly in edges where the bus speed is low (~8 km/h) since buses stop and accelerating at traffic lights. In the rest road parts, pollutants emissions are comparable.

The above comparison highlights the fact that dynamic models take into account the large variability of vehicle speeds per second in traffic conditions characterized by congestion or in general in traffic conditions that are highly characterized by vehicles stopping and accelerating (e.g. in the presence of traffic lights or bus stops) producing larger emissions than those estimated with static models such as COPERT SL which calculate emissions on a smaller temporal resolution (i.e. 1 h) taking into account only the mean speed of vehicles. Quaassdorff et al. [40] also showed that the modelling system VISSIM-VERSIT + micro produced higher PM<sub>10</sub> and NO<sub>x</sub> emissions in a congested road compared to the static model COPERT.

### 3.3 Traffic Emissions Reduction Scenarios Analysis Results

The IMT atmospheric pollutant and CO<sub>2</sub> emissions module was applied over the road axis under study for the traffic peak hour (08:00–09:00 as in the base case) considering the traffic scenarios associated with the LCMS described in “Section 2.4”. It should be mentioned that the following results for the traffic emissions reduction scenarios have been estimated without considering any evolution of vehicle fleet (i.e. fuel-efficient and less polluting fleet renewal) with an exception for the public transportation in SCN20\_BEV.

Following, the comparison between the IMT results for the base and traffic scenarios is discussed. The differences are defined as follows:

$$\% \text{Difference} = \frac{\text{Scenario-Base Case}}{\text{Base Case}} \%$$

Table 5 presents the percentage differences in mean speed per vehicle type between the base case and traffic scenarios (SCN10, SCN20) at traffic peak hour along the road axis. Increases in mean speeds up to around 7%, 6% and 6% are presented for cars, motorcycles and delivery

**Table 5** Differences (%) in mean speed per vehicle type between the base case and traffic scenarios for the road axis of Thessaloniki at traffic peak hour

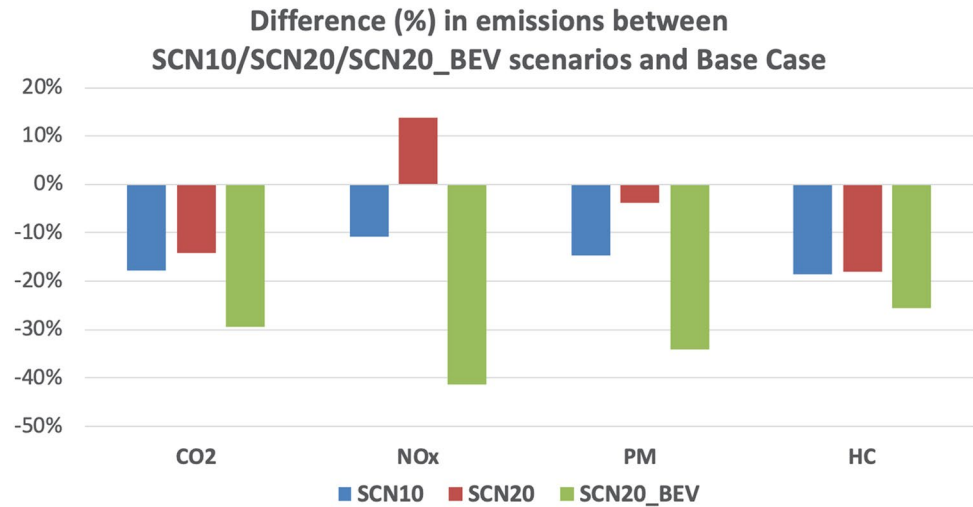
Scenario	Car	Motorcycle	Delivery	Coach	Bus
SCN10	+6.9%	+5.7%	+6.0%	+11.7%	+0.04%
SCN20	+10.6%	+9.6%	+9.7%	+13.4%	-1.75%

vehicles in SCN10 while higher corresponding increases (around +10%) are shown for SCN20. The mean speed of buses remains almost unchanged in traffic scenario SCN10 in comparison with the base case, since the buses circulate along the bus lane and their circulation frequency is not changed by the redesign of the road in the case of SCN10. A small speed decrease is shown for SCN20 due to the increase of buses flow. The traffic scenarios mean speed of coaches presents an increase up to 13% with respect to the base case.

In Fig. 7, the percentage differences in total hourly pollutant and CO<sub>2</sub> emissions between the base case and traffic scenarios SCN10, SCN20 and SCN20\_BEV are presented. More particularly, decreases in all base case pollutant and CO<sub>2</sub> emissions have been estimated due to SCN10, ranging from –10 to –20% approximately. SCN20 results in smaller decreases in the base case PM<sub>x</sub>, HC and CO<sub>2</sub> emissions, comparing to SCN10, while NO<sub>x</sub> emissions increase by around +14%. These results are due to the increase of the diesel-fuelled buses flows for public transportation. It is worth to mention that PM<sub>x</sub> present a very small decrease (–4%). PM<sub>x</sub> emissions are produced mainly by cars and motorcycles while buses are third in the rank (Fig. S1, in the supplement). Thus, the decrease in traffic flows of cars and motorcycles in combination with the increase of buses leads to smaller decreases in PM<sub>x</sub> emissions comparing to other pollutants (except for NO<sub>x</sub>). Significant are the decreases in all pollutant and CO<sub>2</sub> emissions in the case of SCN20\_BEV ranging from –26 to –41%. The highest decrease is presented for NO<sub>x</sub> emissions for which diesel-fuelled public buses are one of the major sources.

The changes in pollutant emissions because of the traffic scenarios described above are expected to impact the atmospheric dispersion of pollutants. The IMT dispersion module was applied over a part of the road axis (see also “Section 2.2”) for the base case and the traffic scenarios SCN10, SCN20 and SCN20\_BEV to identify the impacts of the traffic scenarios on the determination of pollutant atmospheric concentrations related to road traffic (especially for NO<sub>x</sub> and PM<sub>x</sub> concentration levels). In the case of SCN10, the NO<sub>x</sub> and PM<sub>x</sub> maximum concentration levels are reduced by –9% and –12%, respectively, compared to the base case. In the case of SCN20, the NO<sub>x</sub> and PM<sub>x</sub> maximum concentration levels increase by around +23% and +9%, respectively, compared to the base case indicating the necessity of the use

**Fig. 7** Differences (%) in total hourly pollutant and CO<sub>2</sub> emissions between the base case and traffic scenarios for the road axis of Thessaloniki at traffic peak hour



of “clean vehicles” for public transportation (as in SCN20\_BEV). Finally, regarding SCN20\_BEV, significant decreases in maximum pollutants atmospheric concentrations related to road traffic are estimated reaching up to  $-65\%$  for NO<sub>x</sub> levels and  $-48\%$  for PM<sub>x</sub> levels. The reduction of the circulation of private vehicles by  $-20\%$  in combination with the use of battery electric vehicles for public transportation in the redesigned road axis will result in better improvement of the atmospheric environment in the study area.

## 4 Conclusions

The current study analyses in microscale the air pollutant and CO<sub>2</sub> emissions from the road traffic under traffic-congested conditions (i.e. at traffic peak hour) on a main road axis of the city of Thessaloniki (Greece), as well as the impacts of three traffic emissions reduction scenarios on pollutants emissions and related concentrations over the study area. The study is based on the application of the IMT integrating the real-world microsimulation traffic model SUMO, the dynamic emission model PHEMlight and the dispersion model VADIS.

Air pollutant and CO<sub>2</sub> emissions from cars are the highest while buses are the second contributor to NO<sub>x</sub> emissions. The analysis of the spatial variability of pollutant and CO<sub>2</sub> emissions on a daily basis as well as at the traffic peak hour was investigated focusing on the different elements of the road in order to study the impact of pollutant emissions on stopping and high accelerations at traffic lights and bus stops. The analysis indicated that at the traffic peak hour, CO<sub>2</sub> and NO<sub>x</sub> emissions from cars are  $+26\%$  and  $+32\%$ , respectively, higher in edges with traffic lights while the corresponding reductions in the mean speed of cars were  $-58\%$ . NO<sub>x</sub> emissions from buses were by  $+22\%$  higher in edges with bus stops while relatively small increases presented for

CO<sub>2</sub> ( $\sim +12\%$ ). Smaller increases estimated on a daily basis compared to the traffic peak hour.

The comparison of IMT emissions results with the static emission model COPERT SL showed that IMT pollutant and CO<sub>2</sub> emissions are higher compared to those of COPERT SL; CO<sub>2</sub>, and NO<sub>x</sub> emissions from cars differ by  $+25\%$  and  $+50\%$ , respectively, in comparison with COPERT SL while the corresponding differences for buses are  $+45\%$  and  $+40\%$ . The comparison of the spatial variability of pollutant emissions from cars between the two models showed that the highest differences were identified in the road part of the road axis where the highest number of traffic lights per km was presented (up to 2 times higher NO<sub>x</sub> emissions compared to COPERT SL) while the corresponding comparison for buses indicated that the IMT produced almost double emissions in the road part where the highest ratio “bus stops/km” was presented. Under this view, accounting for the specific road elements and characteristics and for the real-world traffic conditions that differentiate vehicle speeds and accelerations, it is expected to have an impact on the local and urban scale measures to reduce traffic congestion and its environmental effects. Sustainable Urban Mobility Plans to reduce traffic congestion, to enhance public transportation and soft mobility are beneficial for the atmospheric environment. The most effective traffic emissions reduction scenario studied at street level in terms of atmospheric environment improvements is related both with the reduction of cars and motorcycles flows by  $-20\%$ , as a result also of the increase in the frequency of public buses circulation, and the public buses replacement from diesel-fuelled vehicles to modern battery electric ones producing locally zero emissions. In terms of emissions, this scenario results in lower pollutant and CO<sub>2</sub> emissions ranging from  $-29$  to  $-41\%$ . In terms of road traffic pollutants dispersion, significant can be the reductions in NO<sub>x</sub> and PM<sub>x</sub> maximum concentrations (about  $-65\%$  and  $-48\%$ , respectively).

Finally, concerning limitations of the methodology implemented, it should be considered that the social impact of the sustainable urban mobility (i.e. associated health impact and costs) has temporal and spatial scales which are more extended and not always the same with those of the traffic impact and environmental impact. To this direction, the future upgrade of IMT is necessary for the harmonization of temporal and spatial references of all impacts of sustainable urban mobility.

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**Author Contribution** Natalia Liora: Methodology—data gathering, analysis and interpretation of data.

Anastasia Poupkou: Methodology—critical revision.

Kontos Serafim: Methodology.

Charikleia Meleti: Methodology—critical revision.

Katerina Chrysostomou: Experiment.

Georgia Aifadopoulou: Experiment.

Stella Zountsa: Experiment.

Chrisostomos Kalogirou: Experiment.

Ricardo Chacartegui: Methodology.

Francesca Liguori: Methodology.

Massimo Bressan: Methodology.

Susana Marta Almeida: Methodology.

Dimitrios Melas: Methodology—critical revision.

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**Data availability** Data and material are available after communication with the corresponding author.

**Code availability** The code of IMT is not available. The IMT is available to users as an online model under licence terms.

#### Declarations

The authors declare that they have no competing interests.

## References

- Aifadopoulou, G., Morfoulaki, M., Chrysostomou, K., Porfiri, K., Petrou, A.: Deliverable 3. Evaluation of the final proposal for the upgrade of the pilot road axis. Project: REMEDIO “REgenerating mixed - use MED urban communities congested by traffic through Innovative low carbon mobility sOolutions”. Centre for Research and Technology Hellas - Hellenic Institute of Transport (CERTH/HIT) delivered to Major Development Agency Thessaloniki S.A (MDAT) (2018)
- AIMSUN Version 8.2 User’s Manual TSS – Transport Simulation Systems (2017)
- Blokpoel, R., Hausberger, S., Krajzewicz, D., Vreeswijk, J.: Emission optimized control for isolated intersections. 22nd ITS World Congress, Bordeaux, France. Paper Number ITS-2109 (2015)
- Borge, R., de Miguel, I., de la Paz, D., Lumbreras, J., Perez, J., Rodriguez, E.: Comparison of road traffic emission models in Madrid (Spain). *Atmos. Environ.* **62**, 461–471 (2012). <https://doi.org/10.1016/j.atmosenv.2012.08.073>
- Borrego, C., Tchepel, O., Barros, N., Miranda, A.I.: Impact of road traffic emissions on air quality of the Lisbon region. *Atmos. Environ.* **34**, 4683–4690 (2000)
- Borrego, C., Tchepel, O., Costa, A.M., Amorim, J.H., Miranda, A.I.: Emission and dispersion modelling of Lisbon air quality at local scale. *Atmos. Environ.* **37**(37), 5197–5205 (2003)
- Borrego, C., Tchepel, O., Costa, A.M., Martins, H., Ferreira, J., Miranda, A.I.: Traffic-related particulate air pollution exposure in urban areas. *Atmos. Environ.* **40**, 7205–7214 (2006). <https://doi.org/10.1016/j.atmosenv.2006.06.020>
- Brand, C., Goodman, A., Ogilvie, D.: Evaluating the impacts of new walking and cycling infrastructure on carbon dioxide emissions from motorized travel: a controlled longitudinal study. *Appl. Energy* **128**, 284–295 (2014)
- Chiusolo, M., Cadum, E., Stafoggia, M., Galassi, C., Berti, G., Faustini, A., Bisanti, L., et al.: Short-term effects of nitrogen dioxide on mortality and susceptibility factors in 10 Italian cities: the EpiAir study. *Environ. Health Perspect.* **119**(9), 1233–1238 (2011). <https://doi.org/10.1289/ehp.1002904>
- Chrysostomou, K., Petrou, A., Aifadopoulou, G., Morfoulaki, M.: Microsimulation modelling of the impacts of double-parking along an urban axis. In: Nathanail E., Karakikes I. (eds) *Data Analytics: Paving the Way to Sustainable Urban Mobility*. CSUM 2018. *Advances in Intelligent Systems and Computing*, vol 879. Cham: Springer (2019)
- COPERT Street Level user’s manual v2.2.53. Emisia Mission for Environment ([www.emisia.com](http://www.emisia.com))
- De Coensel, B., Can, A., Degraeuwe, B., De Vlieger, I., Botteldooren, D.: Effects of traffic signal coordination on noise and air pollutant emissions. *Environ. Model. Softw.* **35**, 74–83 (2012)
- Degraeuwe, B., Thunis, P., Clappier, A., Weiss, M., Lefebvre, W., Janssen, S., Vranckx, S.: Impact of passenger car NO<sub>x</sub> emissions on urban NO<sub>2</sub> pollution – scenario analysis for 8 European cities. *Atmos. Environ.* **171**, 330–337 (2017). <https://doi.org/10.1016/j.atmosenv.2017.10.040>
- EC: White Paper. Roadmap to a Single European Transport Area – Towards a Competitive and Resource Efficient Transport System. European Commission, COM(2011) 144 final (2011)
- EEA: EMEP/EEA Air Pollutant Emission Inventory Guidebook 2016. 1.A.3.b.i, 1.A.3.b.ii, 1.A.3.b.iii, 1.A.3.b.iv Passenger Cars, Light Commercial Trucks, Heavy-duty Vehicles Including Buses and Motor Cycles. – Update Jul. 2018 (2018)
- EEA Report: Air Quality in Europe – 2018 Report. European Environment Agency. ISSN 1977–8449 (2018)
- EL.STAT: Demographic Characteristics 2011 Census (2011)
- EL. STAT: Motor vehicles in operation, by category and use per Greek prefecture. January 2018. <https://www.statistics.gr/en/statistics/-/publication/SME18/> (2018)
- Erdmann, J., Rummel, J., Wagner, P.: SUMO and the German Handbook for the Dimensioning of Highways (HBS). *Towards Simulation for Autonomous Mobility Lecture Notes in Mobility*. Springer (2017)
- Fameli, K.M., Assimakopoulos, V.D.: Development of a road transport emission inventory for Greece and the Greater Athens Area: effects of important parameters. *Sci. Total Environ.* **505**(2015), 770–786 (2015)
- Hausberger, S., Zallinger, M., Luz, M.: Emission Factors from the Model PHEM for the HBEFA Version 3. Report Nr. I-20/2009 Haus-Em 33/08/679 from 07.12.2009. Graz University of Technology (2009)

22. Hausberger, S. & Krajzewicz, D.: COLOMBO: Deliverable 4.2 - Extended Simulation Tool PHEM Coupled to SUMO with User Guide (2014)
23. HBEFA: Handbuch Emissionsfaktoren des Strassenverkehrs 3.1 — Dokumentation. Infrac, UBA, Berlin. BUWAL, Bern/UBA, Wien. Available from: [www.hbefa.net](http://www.hbefa.net) (2010)
24. Kephelopoulos, S., Paviotti, M., Anfosso-Lédée, F.: Common noise assessment methods in Europe (CNOSSOS-EU) (2012). <https://doi.org/10.2788/31776>
25. Liu, R., van Vliet, D., Watling, D.: Microsimulation models incorporating both demand and supply dynamics. *Transp Res* **40A**(2):125–50 (2006)
26. López, E., Palomo, F., Liora, N., Kontos, S., Almedia-Silva, M., Baptista, P., Liguori, F., Lorenzet, K., Fernandez, R., Ortiz, C., Poupkou, A., Meleti, Ch., Melas, D., Patti, S., Faria, M.V., Ferreira, J. and Lanera C.: Integrated modelling tool for the analysis of traffic-congested roads in urban centers. In: Proceedings of the 14th International Conference on Meteorology, Climatology and Atmospheric Physics (COMECAP 2018), 15–17 October 2018, Alexandroupolis, pp. 852–857 (2018)
27. Lopez, P.A., Behrisch, M., Bieker-Walz, L., Erdmann, J., Flötteröd, Y.-P., Hilbrich, R., Lücken, L., Rummel, J., Wagner, P., and Wießner, E.: Microscopic traffic simulation using SUMO. *IEEE Intelligent Transportation Systems Conference (ITSC)*, 2018. The 21st IEEE International Conference on Intelligent Transportation Systems, 4.-7. Nov. 2018, Maui (2018)
28. Madireddy, M., De Coensel, B., Can, A., Degraeuwe, B., Beusen, B., De Vlioger, I., Botteldooren, D.: Assessment of the impact of speed limit reduction and traffic signal coordination on vehicle emissions using an integrated approach. *Transp. Res. D-Tr E*. **16**, 504–508 (2011). <https://doi.org/10.1016/j.trd.2011.06.001>
29. Markakis, K., Poupkou, A., Melas, D., Tzoumaka, P., Petrakakis, M.: A computational approach based on GIS technology for the development of an anthropogenic emission inventory of gaseous pollutants in Greece. *Water Air Soil Pollut.* **207**, 157–180 (2010a)
30. Markakis, K., Poupkou, A., Melas, D., Zerefos, C.: A GIS based anthropogenic PM10 emission inventory for Greece. *Atmos. Pollut. Res.* **1**:71–81 (2010b)
31. Markakis, K., Katragkou, E., Poupkou, A., Melas, D.: MOSESS: a new emission model for the compilation of model-ready emission inventories. Application in a coal mining area in Northern Greece. *Environ. Model. Assess.* **18**, 509–521 (2013)
32. Melas, D., Liora, N., Poupkou, A., Kontos, S., Meleti, Ch., Liguori, F., Patti, S., Baptista, P., Ferreira, J., Almedia-Silva, M., Chacartegui, R., López, E., Ortiz, C., Faria, A.M., Lanera, C., Zounza, S., Chrysostomou, K., Kelessis, A., Yiannakou, A., Tzoumaka, P., Aifadopoulou, G., Kalogirou, C.: Environmental analysis in traffic-congested roads using an integrated modelling tool. 1st Scientific Conference PANACEA September 23–24, 2019 Crete (2019)
33. Moussiopoulos, N., Vlachokostas, Ch., Tsilingiridis, G., Douros, I., Hourdakakis, E., Naneris, C., Sidiropoulos, C.: Air quality status in Greater Thessaloniki Area and the emission reductions needed for attaining the EU air quality legislation. *Sci. Total Environ.* **407**(2009), 1268–1285 (2009). <https://doi.org/10.1016/j.scitotenv.2008.10.034>
34. Neumann, T. Heinrichs, M., Behrisch, M., Erdmann, J., Sauerländer-Biebl, A.: Quantitative analysis of future scenarios of urban mobility using agent-based simulation - a case study. *Transportation Research Procedia*, 41, Seiten 295–308. Elsevier (2019). <https://doi.org/10.1016/j.trpro.2019.09.050> ISSN 2352–1457
35. Ntziachristos, L., Gkatzoflias, D., Kouridis, C., Samaras, Z.: COPERT: a European road transport emission inventory model. Athanasiadis, I.N., Rizzoli, A.E., Mitkas, P.A., Gómez, J.M. (eds) *Information Technologies in Environmental Engineering. Environmental Science and Engineering*. Berlin: Springer (2009)
36. Panis, L.I., Broekx, S., Liu, R.: Modelling instantaneous traffic emission and the influence of traffic speed limits. *The Science of the total environment* **371**(1–3), 270–285 (2006)
37. PHEMLight User Guide Version 1. Passenger Car and Heavy Duty Emission Model. Technische Universität Graz. Erzherzog-Johann-Universität INSTITUT FÜR VERBRENNUNGSKRAFT -MASCHINEN UND THERMODYNAMIK
38. Poupkou, A., Symeonidis, P., Ziomas, I., Melas, D., Markakis, K.: A spatially and temporally disaggregated anthropogenic emission inventory in the southern Balkan Region. *Water Air Soil Pollut.* **185**, 335–348 (2007)
39. Poupkou, A., Zountsa, S., Chrysostomou, K., Kelessis, A., Yiannakou, A., Liora, N., Kontos, S., Rizos, K., Dimopoulos, S., Giannaros, C., Tzoumaka, P., Aifadopoulou, G., Kalogirou, C., Meleti, Ch. and Melas, D.: Environmental assessment of low carbon mobility solutions with the use of an integrated modeling tool. 14th International Conference on Meteorology, Climatology and Atmospheric Physics (COMECAP 2018), 15–17 October 2018, Alexandroupolis (2018)
40. Quaassdorff, C., Borge, R., Pérez, J., Lumberras, J., de la Paz, D., de Andrés, J.M.: Microscale traffic simulation and emission estimation in a heavily trafficked roundabout in Madrid (Spain). *Sci. Total Environ.* **566–567**(2016), 416–427 (2016). <https://doi.org/10.1016/j.scitotenv.2016.05.051>
41. REMEDIO: Assessment report (Deliverable 3.5.1), integrated tool and low carbon mobility solutions assessment (Activity 3.5), October 2019 (<https://remedio.interreg-med.eu/>) (2019a)
42. REMEDIO: Methodological path of governance arrangements under REMEDIO Project (Deliverable 4.2.2), participatory governance for urban mobility solutions (Activity 4.2), October 2019. (<https://remedio.interreg-med.eu/>) (2019b).
43. REMEDIO: Transferability Plan of REMEDIO Project (Deliverable 4.3.2), October 2019 (2019c)
44. Rexeis, M., Dippold, M., Luz, R., Hausberger, S., Haberl, M., Krajzewicz, D., Wagner, P., Wölki, M., Blokpoel, R., Stützel, T., Dubois-Lacoste, J.: COLOMBO: Deliverable 4.3 Pollutant Emission Models and Optimisation (2014)
45. Rodler, S.J., Sturm, P., Rexeis, M.: Emission factors for heavy-duty vehicles and validation by tunnel measurements. *Atmos. Environ.* **37**(37), 5237–5245 (2003). <https://doi.org/10.1016/j.atmosenv.2003.05.002>
46. Skamarock, W.C., Klemp, J.B., Dudhia, J., Gill, D.O., Barker, D.M., Duda, M.G., Huang, X.Y., Wang, W., Powers, J.G.: A description of the advanced research WRF version 3. NCAR Technical Note (NCAR/TN – 475 + STR), Boulder (2008)
47. Smit, R., Smokers, R., Rabe, E.: A new modelling approach for road traffic emissions: VERSIT+. *Transp Res Part D: Transp Environ* **12**(6), 414–422 (2007). <https://doi.org/10.1016/j.trd.2007.05.001>
48. Sun, D., Zhang, Y., Xue, R., Zhang, Y.: Modeling carbon emissions from urban traffic system using mobile monitoring. *Sci. Total Environ.* **599–600**, 944–951 (2017)
49. Sun, Zhang: Influence of avenue trees on traffic pollutant dispersion in asymmetric street canyons: numerical modeling with empirical analysis. *Transp. Res. D: Transp. Environ.* **65**, 784–795 (2018)
50. Uherek, E., Halenka, T., Borken-Kleefeld, J., Balkanski, Y., Bernsten, T., Borrego, C., Gauss, M., Hoor, P., Juda-Rezler, K., Lelieveld, J., Melas, D., Rypdal, K., Schmid, S.: Transport impacts on atmosphere and climate: land transport. *Atmos. Environ.* **44**(2010): 4772e4816 (2010). <https://doi.org/10.1016/j.atmosenv.2010.01.002>

51. Wang, Y., Szeto, W.Y., Han, K., Friesz, T.L.: Dynamic traffic assignment: a review of the methodological advances for environmentally sustainable road transportation applications. *Transp. Res. B Methodol.* **111**, 370–394 (2018). <https://doi.org/10.1016/j.trb.2018.03.011>
52. Wismans, L., van den Brink, M., Brederode, L., Zantema, K., van Berkum, E.: Comparison of estimation of emissions based on static and dynamic traffic assignment models. Proceedings of 92th Annual Meeting of the Transportation Board, 13–17 January 2013, Washington DC (2013)
53. Zhang, R., Fujimori, S. and Hanaoka, T.: The contribution of transport policies to the mitigation potential and cost of 2 °C and 1.5 °C goals. *Environ. Res. Lett.* **13**:054008 (2018)

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