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Short Communication

Applying GIS to Control Transportation Air Pollutants

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Abstract

Air pollution caused by motor vehicles is one of the most serious problems of civilized society. The aim of this paper is to develop a decision support system that can be used by authorities to reduce air pollution from road transport. The essence of this system consists of mathematical sub-models based on the computer program methodology for calculating emissions from road transport, (COPERT IV) and (CALINE3) – a versatile dispersion model for predicting air pollution levels near highways and arterial streets, in order to simulate the models of air pollutant emission and dispersion in the area along the Belgrade-Niš highway. These sub-models were integrated into a geographic information system (GIS), which was used for selecting critical areas where air pollution levels were above limits.

The results showed the simulation of pollutant dispersion in two scenarios. In the first scenario, in the worst weather conditions, the concentrations of particulate matter (PM) and sulphur oxides (SO_2) are the highest in more grids than in the case of two other pollutants, but the concentrations of carbon monoxide (CO) and nitrogen oxides (NO_x) are more widespread. Moreover, the overall pollutant concentration is the highest in the area of Požarevac-V.Plana. In the second scenario, the concentration of all four parameters is the highest in the summer due to NW wind direction, and in autumn due to SE wind direction. It can be concluded that meteorological parameters and transportation characteristics have a significant influence on emission and dispersion of air pollutants.

Keywords: motor vehicles, COPERT IV methodology, CALINE3 model, air pollutants, geographic information system (GIS)

Introduction

Air quality monitoring (AQM) is still new in Eastern European countries [1], where traffic represents one of the largest sources of primary air pollutants in urban areas [2]. Motor vehicle emissions are a major source of air pollution in the world [3]. Air pollution from road traffic consists of a number of harmful substances [4]. Transport is necessary in modern society, but its increasing intensity brings certain unwanted effects. The significance of motor vehicle use is increasing in many areas through rising traffic volumes, despite vehicle emission controls and/or stabilizing or declining industrial emissions [5]. Road traffic involves numerous potential sources of metals pollution, e.g. combustion products from fuel and oil; wear products from tyres, brake linings, bearings, and clutches; corrosion products of vehicle components and road construction materials; and resuspension of soil and road dust. The significant reduction in the permissible lead concentration in petrol has led to a considerable decrease in exhaust lead emissions within the last two decades [6]. Traffic jams in cities and around main traffic arteries endanger the environment, and the increased fuel consumption reduces transport system efficiency because it influences the cost-effectiveness

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reduction. The negative influence of transport, regarding the environment, is air pollution. It is well known that the main pollutants from combustion of fossil fuels are: NO_x, CO, SO_x, VOCs (volatile organic compounds), and PM [7]. Vehicles are an important source of air pollution and they contribute high ambient pollutant concentrations in urban areas. The use of different types of fuels adds different concentrations of toxic pollutants to the environment. Based on the significant emissions of the fuel components, several vehicle fuels such as diesel, gasoline, compressed natural gas (CNG), gas-to-liquid (GTL), rapeseed oil methyl ester (RME), and dimethyl ether (DME) are the subject of new focus studies. Airborne PM, due to the increasing fuel demand for rapidly growing global population growth, also is of main concern [8].

NO_x ($NO+NO_2$) is a primary pollutant, emitted by all the combustion sources, and thus by motor vehicles, which are the main emission sources in most urban areas [9]. Every liter of fuel consumption during combustion makes 100 g of CO, 20 g of VOC, 30 g of NO_x, 2.5 g of CO_2, and a lot of other harmful, poisonous substances like compounds of lead, sulfur, and heavy particles. All these compounds cause air pollution, either by direct influence on human health, or globally, by increasing the effect of greenhouse gas (GHG) emissions [10].

The air quality in many countries has not been improved as dramatically, probably due to the fact that the maintenance of the catalytic SI engines are still not strict enough [11]. Various previous studies have already shown that a small number of petrol-engine cars, usually exhibiting abnormal operation or fitted with very old engines, are to be blamed for the bulk of emitted pollutants, e.g. 10% of the circulating cars emit approximately 50% of the carbon monoxide (CO) [12].

More than two thousand kilometres (2,150 km) of the main road network in Serbia is part of the international E-road network [13]. The part of European route E75 in Serbia spans approximately 600 km. It crosses the country from north to south, starting at the Horgoš border crossing with Hungary and ending with the Preševo border crossing with FYROM. Belonging to Pan-European Corridor X and interconnecting Serbian's biggest cities, it is a vital highway for the Serbian infrastructure, and that is why significant reconstruction work is being carried out there. The highway consists of three major sections, one of which is Belgrade-Niš, which is 237 kilometers long [14]. Generally, total heavy metal cotents in roadside soils were found to be strongly dependant on traffic density and showed and exponantial decrease with distance from the road, reaching background levels of 10-100 m [15].

Therefore, there is a need for better and comprehensive understanding of the environmental impact of roads, forecasting its effects and counteracting them. The application of modeling the impact of roads on the basis of GIS software gives new opportunities [16]. Air pollution was the reason for creating and implementing GIS in order to control the total emission of air pollutants in road transport. The GIS model will be made for the area around the Belgrade-Niš highway. This model will be created by integrating a transport model, an emission model, and a dispersion model. The characteristics of transport (vehicle type and technology, transport density on 20 sections of Belgrade-Niš highway and type of fuel) will be used for calculating emission, and the results of emission will be inputs for the dispersion model [17]. Dispersion data will be used for completing the GIS database, and the query analysis of GIS will enable the selection of critical areas or grids where air pollution is above limits, on a previously created map, with nodes and sections as separate layers. The results of such an integrated system will provide the decision-makers with the necessary information on the emission of pollutants and the additional visualization and analysis. The final results will also be necessary for taking adequate measures in the purpose of minimizing the air pollution in those areas.

Methods and Material

Model Description

The transport model that is investigated for the purpose of this paper is based on traffic characteristics of the Belgrade-Niš highway, which has two functions:

- The primary function: acting as the big capacity traffic artery of Serbia with high levels of transportation service for satisfying the expected traffic flows.
- The secondary function: acting as a direct stimulus for economic development and traffic connection in the highway influence zone.

The inputs for the emission model are: traffic flow on sections of Belgrade-Niš highway, number of vehicles by technology, emission factors and mathematical operations of COPERT IV methodology, fuel consumption and meteorological parameters from the Republic Hydrometeorological Service. All these data about vehicles are also presented in the project of the Institute of Faculty of Traffic and Transport Engineering, University of Belgrade [10].

To make the data concerning the vehicles useful for COPERT 4 model, it was necessary to adapt the existing categorization of vehicles to the vehicle classification in COPERT IV model (passenger cars, light trucks, heavy duty vehicles, buses, mopeds, and motorcycles). The vehicles also had to be classified by type of fuel consumption (leaded gasoline, unleaded petrol, diesel, LPG, hybrid, and CNG), which also was required for entry in the database. After that, vehicles were grouped according to engine capacity.

In order to calculate pollutant emissions using the COPERT IV model, on the Belgrade-Niš highway, the data about vehicle flow in 20 sections of the highway were taken from the electronic publication published by the public enterprise Roads of Serbia. The COPERT IV model, based on the above-mentioned data and the data about meteorological conditions, provided the results of fuel consumption and total emission of pollutants.

In order to determine the most frequent sections on the Belgrade-Niš highway, the participation of vehicles by category was expressed as a percentage and then the highway sections were ranked based on total traffic flow. All these data are interconnected in the GIS database. Fig. 1 shows the traffic flow by sections of Belgrade-Niš highway, which are marked by the intensity of vehicles per hour for 2009.

The data used for calculating pollutant emission are also in GIS the database. The results of fuel consumption are represented in Table 1 and Fig. 2.

In Serbia, motor vehicles on gasoline and diesel are most commonly used. The vehicles for personal transport, such as motorcycles and passenger cars, mostly run on gasoline, while vehicles for public transport, such as buses, trucks, and other light and heavy truck vehicles, mostly run on diesel [18]. Table 1 shows the highest consumption of diesel, then gasoline and at last LPG on the Belgrade-Niš highway. If we look at the fuel consumption per sections, it can be concluded that the highest consumption of gasoline and LPG was on the Belgrade-Transped section, while diesel consumption was the highest on the Požarevac-V.Plana section (Fig. 2).

COPERT IV methodology enables calculation of emissions by combining technical characteristics of vehicle manufacturers and data about activities. Total emission of air pollutants is calculated as the total amount of hot and cold emissions. However, only mathematical operation for hot emission was used for emission calculation on the Belgrade-Niš highway, because cold emission is rarely present on highways. The formula for hot emission is:

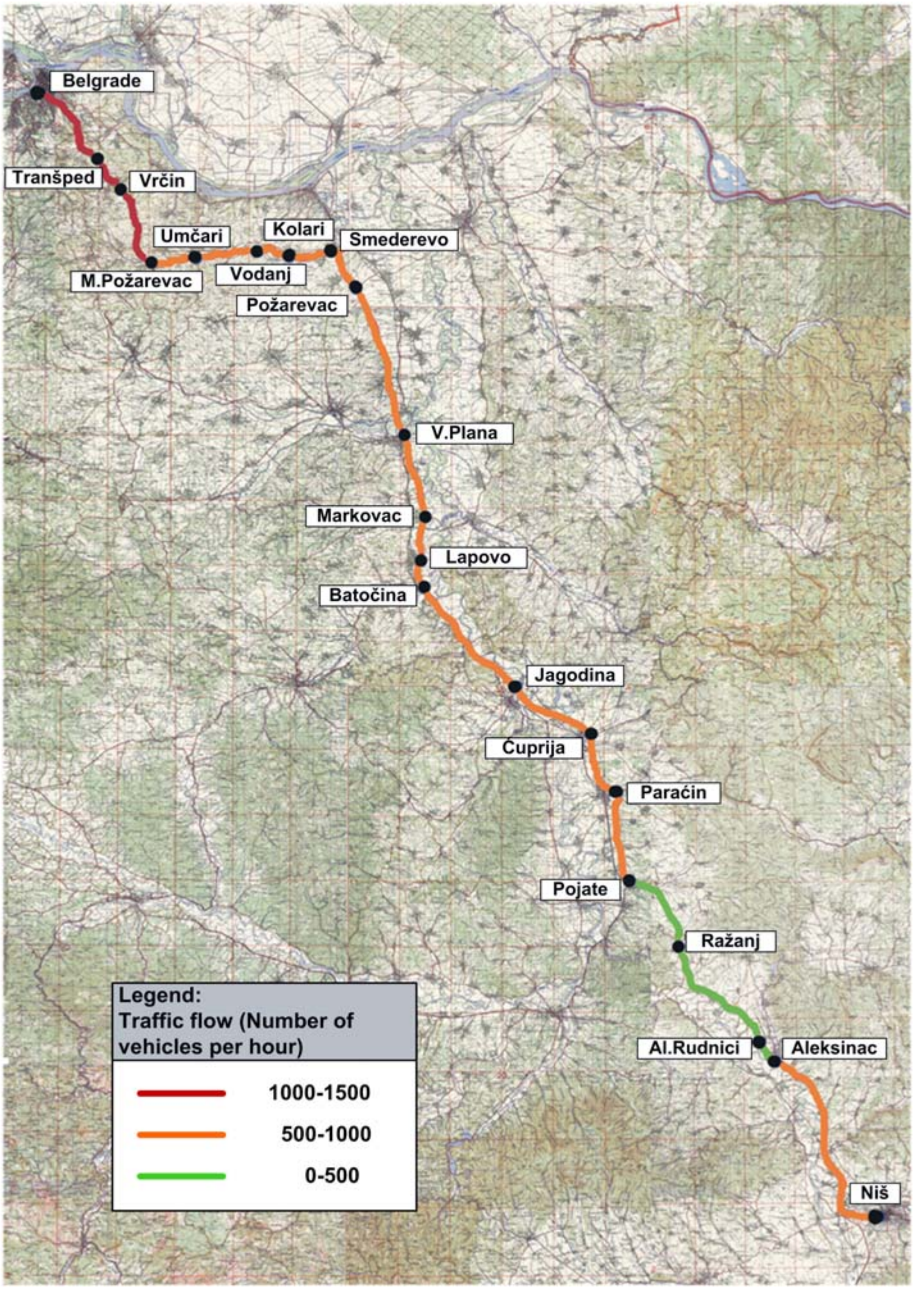

Fig. 1. Traffic flow on sections of the Belgrade-Niš highway.

Table 1. Total fuel consumption by sections of the Belgrade-Niš highway (2009).

Sections	Type of fuel			Total fuel (t):
	Gasoline (t)	Diesel (t)	LPG (t)	
Belgrade-Tranšped	5763.30	6714.97	273.78	12752.05
Tranšped-Vrčin	1724.82	2013.47	79.51	3817.80
Vrčin-M.Požarevac	5023.14	6192.27	236.85	11452.26
M.Požarevac-Umčari	1615.49	2248.18	76.14	3939.81
Umčari-Vodanj	682.90	957.24	32.18	1672.32
Vodanj-Kolari	714.68	1030.35	33.68	1778.71
Kolari-Smederevo	2685.82	3913.13	126.64	6725.59
Smederevo-Požarevac	1440.43	2214.65	67.88	3722.96
Požarevac-V.Plana	5638.68	9129.90	265.71	15034.29
V.Plana-Markovac	2403.56	4049.38	113.24	6566.18
Markovac-Lapovo	1331.45	2200.30	62.73	3594.48
Lapovo-Batočina	771.89	1285.88	36.37	2094.14
Batočina-Jagodina	3838.29	6660.27	180.81	10679.37
Jagodina-Ćuprija	2075.22	3654.48	97.76	5827.46
Ćuprija-Paraćin	1733.60	3045.77	81.66	4861.03
Paraćin-Pojate	1849.95	3248.60	87.16	5185.71
Pojate-Ražanj	1866.22	3590.90	87.94	5545.06
Ražanj-Al.Rudnici	2243.22	4382.58	105.71	6731.51
Al.Rudnici-Aleksinac	465.48	887.76	21.93	1375.17
Aleksinac-Niš	3335.78	6009.21	157.22	9502.21
Total fuel (t):	47203.92	73429.29	2224.90	122858.11

$$E_{hot;i,k,r} = N_k \times M_{k,r} \times e_{hot;i,k,r} \tag{1}$$

...where $E_{hot;i,k,r}$ is hot emission of air pollutats i (g), category of vehicles k, in specific period of time (hourly based for 2009) on road type r; N_k is the number of vehicles of technology k; $M_{k,r}$ is traveled road by vehicle (km/vehicle) for the vehicles of technology k, on road type r; $e_{hot;i,k,r}$ is emission factor (g/km) of air pollutants i, for the vehicle of chategory k, on road type r.

The emission of air pollutants is calculated by applying the previously described formula which is used in GIS query analysis. Fig. 3 shows the total emissions of CO, NO_x, PM, and SO_2. The biggest emission is on the Požarevac-V. Plana section and the area surrounding this section is the most polluted.

The inputs for a dispersion model are the results of emission and meteorological parameters. This model is based on the CALINE3 model, which is used for predicting levels of air pollution near highways [19]. The algorithms of the CALINE3 model are used for calculating air pollutants' dispersion. These algorithms are used in GIS query analysis. Table 2 shows limitations of air pollutants in Serbia. For the purpose of this study we used the limitations for 24h and 1h time sampling in uninhabited areas.

Results

Several planning and policy scenarios can be developed, and so-called hot-spots of traffic-originated air pollution can be identified and visualized within a GIS framework [21]. In this study, the simulation of dispersion is done for two scenarios. The first scenario deals with the worst meteorological conditions, where the wind speed is ≥ 1 m/s, stability class, according to Pasqual is set to 4, and all wind directions are taken into consideration. The calculation is made considering daily sampling in uninhabited areas, because the Belgrade-Niš highway does not pass through populated areas. This scenario is used for calculating dispersion of CO, NO_x, PM, and SO_2, and it is represented in Fig. 4. The results of the first scenario (the worst meteorological conditions), after applying the above-mentioned parameters for calculation, have shown that the concentrations of PM and SO_2 are

Table 2. Limits of air pollutants in Serbia [20].

Air pollutant (mg/m^3)	Time of sampling in uninhabited areas			Time of sampling in populated areas		
	24 h	1 h	annually	24 h	1 h	annually
CO	3	5	3	5	10	3
NO_x	0.07	0.085	0.05	0.085	0.15	0.06
PM	0.04	/	0.03	0.05	0.15	0.05
SO_2	0.1	0.15	0.03	0.15	0.35	0.05

highest in more grids than in the case of the other two pollutants, but the concentrations of CO and NO_x are more widespread. The concentration of all investigated pollutants is highest in the area of the Požarevac-V. Plana section, which is also presented in Fig. 3.

The second scenario involved the defined variables shown in Table 3, and the calculation was made for hourly sampling in uninhabited areas. The receptors were set at 1.5 m above ground. This scenario was used for calculating dispersion of CO, NO_x, PM, and SO_2, and it is represented in Figs. 5-8.

The results shown in Figs. 5-8 represent the concentrations of CO, NO_x, PM, and SO_2, which are worse in summer than in spring season, considering the NW wind direction. But, it is evident that they are worse in autumn than in winter, considering the SE wind direction.

The concentrations of CO, presented in Fig. 5, are the highest in the immediate surroundings of the Batočina-Jagodina section in spring and summer, but in autumn and winter they are the highest in the immediate surroundings of sections: Belgrade-Tranšped, Tranšped-Vrčin, and Požarevac-V. Plana.

The concentrations of NO_x and PM presented in Figs. 6 and 7 are the highest in the immediate surroundings of Batočina-Jagodina section, in spring and summer, but in autumn and winter they are the highest in the immediate surroundings of sections: Belgrade-Tranšped, Tranšped-Vrčin, Požarevac-V. Plana, and Batočina-Jagodina.

The concentrations of SO_2 presented in Fig. 8 are the highest in the immediate surroundings of Smederevo-Požarevac, and Aleksinac-Niš sections in spring. In summer the concentration is the highest in the immediate surroundings of Ražanj-Al.Rudnici and Aleksinac-Niš sections. In autumn it is the highest in the immediate surroundings of the Požarevac-V. Plana section and in winter, in the immediate surroundings of the Vrčin-M. Požarevac section.

Discussion

Route E-75, from Belgrade to Niš, which was also investigated by Pivić et al. [15], was the focus of our study. In order to control air pollutants originating from transport,

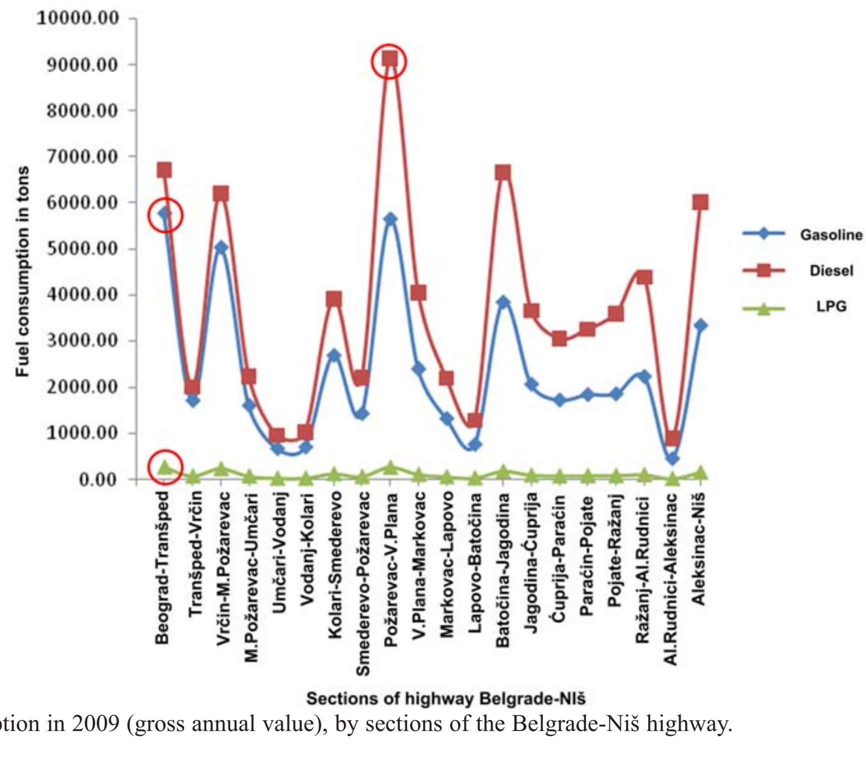

Fig. 2. Fuel consumption in 2009 (gross annual value), by sections of the Belgrade-Niš highway.

Table 3. Experimental measurements for each variable.

Variables	Measurements			
	Spring	Summer	Autumn	Winter
Wind direction (degrees)	NW (202)	NW (202)	SE (112)	SE (112)
Air temperature (ºC)	14.53	23.07	12.4	2.46
Wind speed (m/s)	2.3	1.9	2.45	2.63
Pasqual stability class	4	4	4	4

we have decided to develop a GIS-based application. According to Gajos and Sierka [22], GIS provides a wide range of possibilities for using numerous methods for describing, identifying, and monitoring complicated processes in order to achieve a higher level of environmental protection. As in the study of Lin and Lin [23], we have used sub models that are integrated in GIS in order to utilize spatial information and describe the distribution of the pollutants in the atmosphere. The integrated model consists of emission estimates, dispersion model and databases, which are all introduced into a GIS framework.

As Ma et al. [24] stated, the COPERT model is one of several well-known aggregate models that are normally applied to estimate traffic emission quantity at the network level by considering traffic flow properties such as vehicle fleet composition, average flow speed, and vehicle travel distance as inputs. This indicates that different data sources can be applied, not only for average vehicle emissions but also for air quality information, and considered as a function (dispersion process) of aggregate traffic emission in reality, which was confirmed by our study's results.

CALINE3 can be used to estimate the concentrations of nonreactive pollutants from highway traffic. This steady-state Gaussian model can be applied to determine air pollution concentrations at receptor locations downwind of "at-grade," "fill," "bridge," and "cut section" highways located

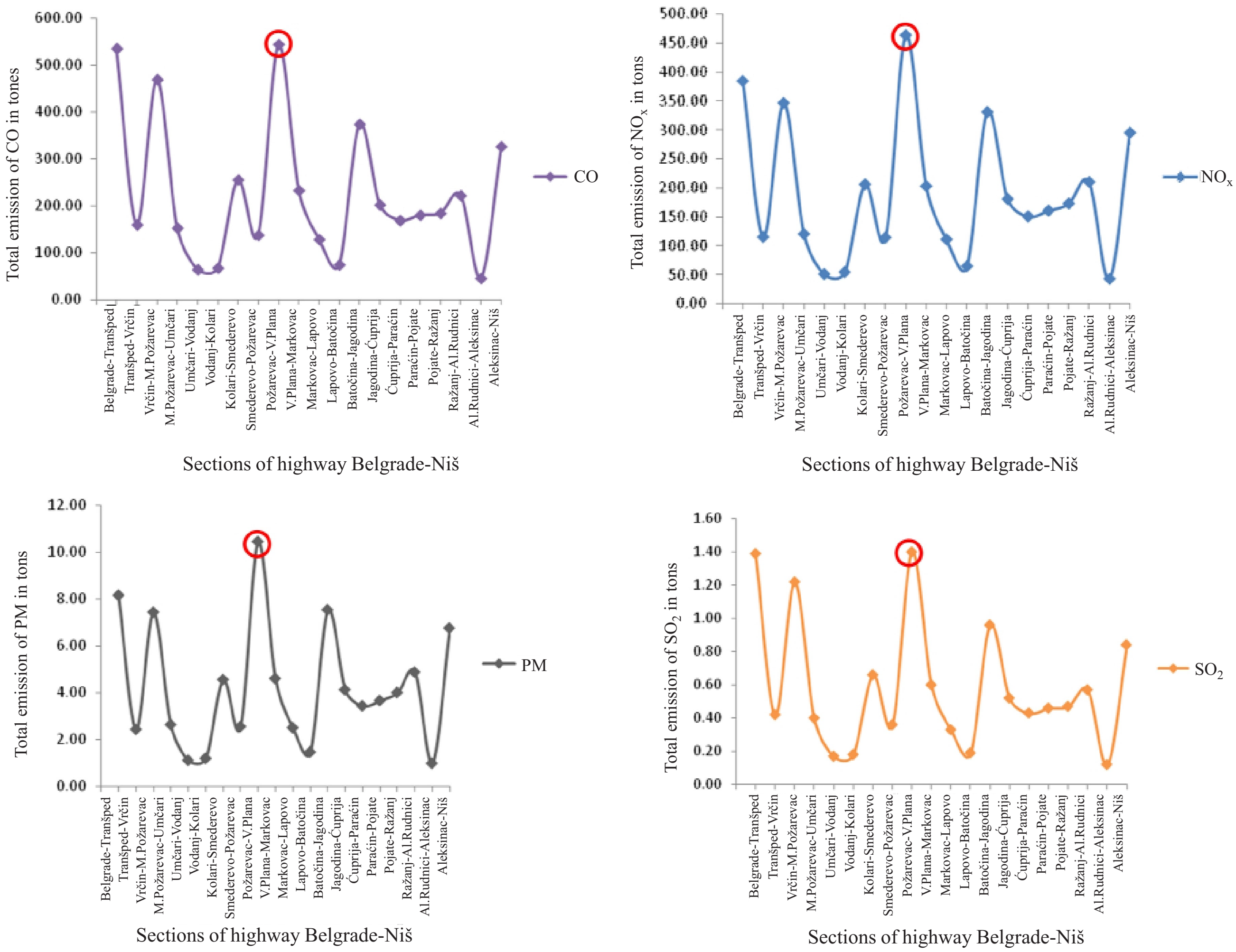

Fig. 3. Emissions of CO, NO_x, PM, and SO_2 in 2009 (gross annual value), by sections of the Belgrade-Niš highway.

in relatively uncomplicated terrain. The model is applicable for any wind direction, highway orientation, and receptor location. Model CALINE3 allows modeling of up to 20 links and 20 receptors within the XY plane [19], which was applicable to our study.

As Kecman et al. [25] discussed, our results also show that emissions of air pollutants originating from mobile sources are primarily determined by vehicle technology, fuel consumption, intensity and density, and meteorological conditions. The results represented in Pivić et al. [15] and our study showed that air pollutants from motor vehicles influence the area surrounding the investigated highway section. The results obtained by Lin and Lin [23], as well as the results of this study, have shown that the visualization and analytical features of GIS do provide more information and convenience to users.

Conclusions

The GIS-based model for controlling air pollutant total emissions in road transport is set up. The results of GIS show that emissions of motor vehicles influence air quality; it mostly depends on fuel consumption, vehicle technology, and meteorological parameters. Also, the results revealed that the integrated system can provide decision-makers with up-to-date emission information and give additional visualization and analysis possibilities. In order to over-

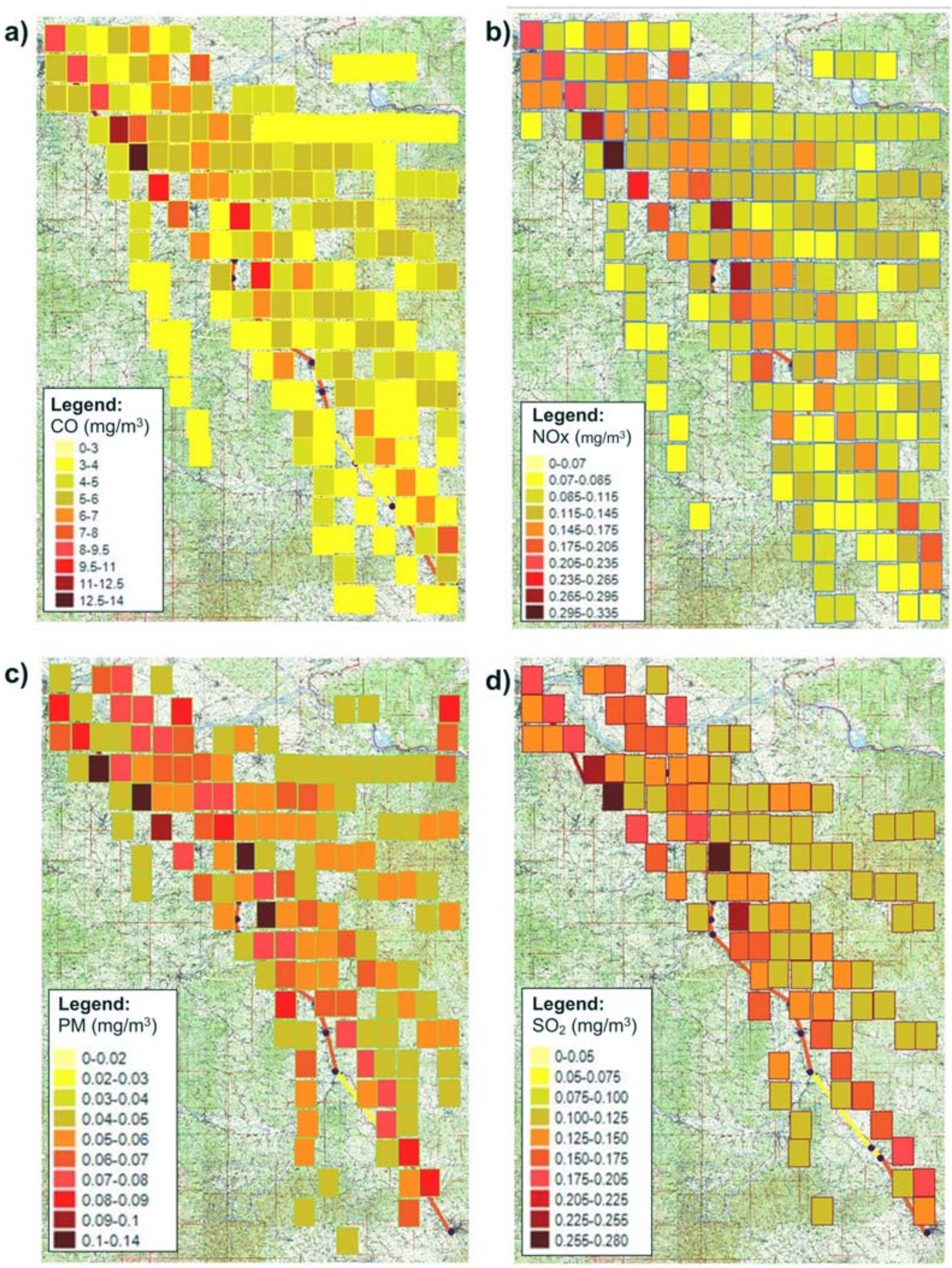

Fig. 4. Concentrations in the worst case scenario (24 h sampling): (a) CO, (b) NO_x, (c) PM, and (d) SO_2.

come or reduce air pollution problems, the authorities have to inform customers about fuel quality, coordinate Serbian standards with EU standards, introduce better regulations concerning air quality, introduce the best control for proper maintenance and functioning of vehicles, lead investigations about emission factors of vehicles and form a database of unique vehicle characteristics and emission factors, as well as of traffic flow along all important arteries.

The aim of the GIS model is the use of entered data into the GIS database, before and after processing, which can always be adjusted and changed, as well as a graphical display (on layers) of entities, or objects that are the subject of research and analysis. Also, the basic function of the GIS model is to present the results obtained on the basis of query analysis. Unlike other models, GIS displays data on the map, marking a critical area, which enables the respective authorities to react faster and apply adequate measures in order to protect the environment. Thus, the application of GIS can improve the process of controlling total pollutant emissions from road transport.

Research for determining the control strategy for total pollutant emissions from road transport is not complete for the entire territory of the Republic of Serbia. There is only partial, limited research that only provides information about pollutant emissions. Therefore, the application of GIS models in the control strategy for total pollutant emissions from road transport is important. Control of the total emissions of pollution sources using GIS is much more efficient.

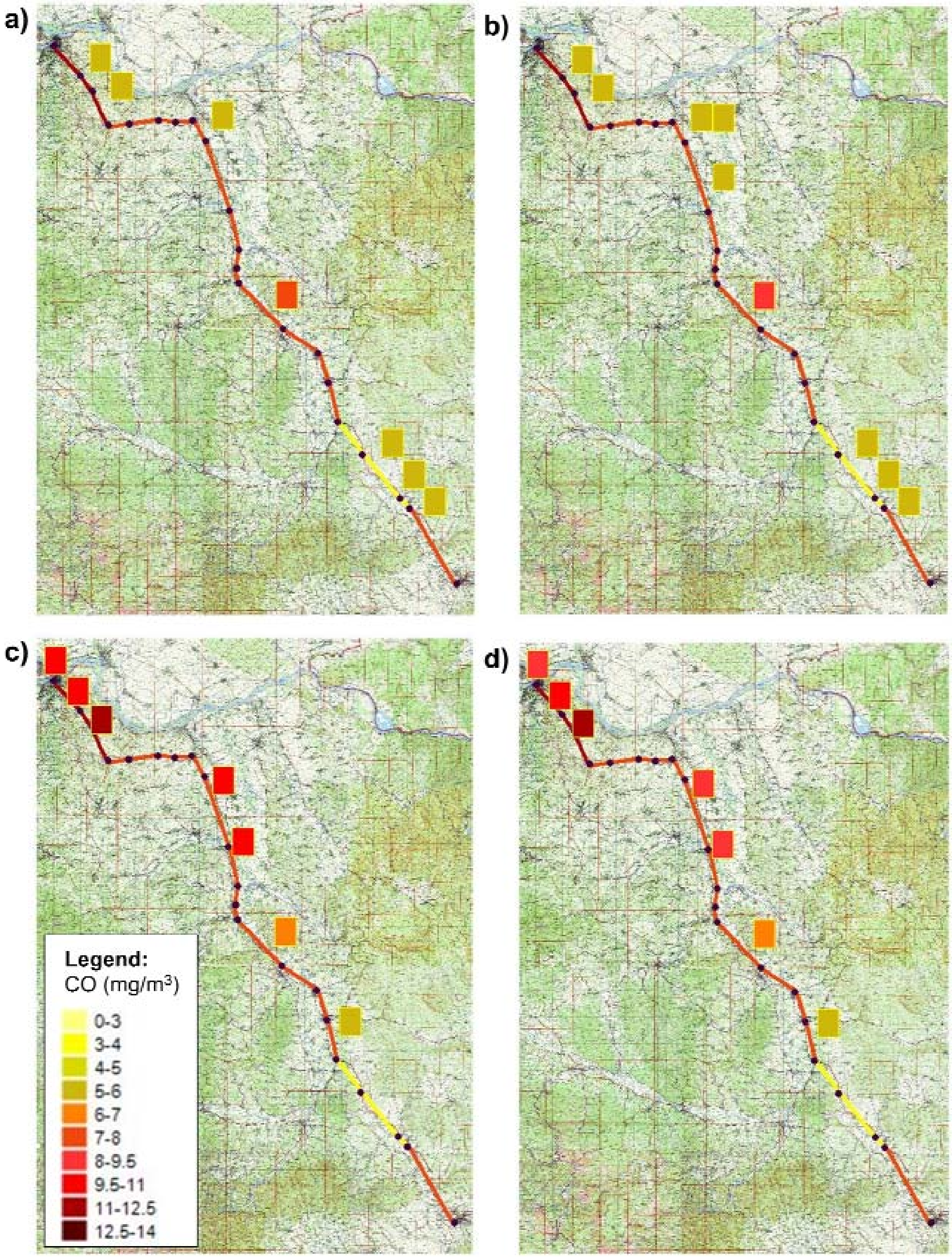

Fig. 5. CO concentrations in the second case scenario (1h sampling): (a) spring, (b) summer, (c) autumn, and (d) winter.

The use of GIS provides tangible results, presented graphically on a map, so that we can react faster in order to solve recorded problems.

Thus, further research will be related to the application of this model in controlling emissions of pollutants in urban areas that have problems with traffic jams. Also, this model, with some modifications, can be used for controlling the emissions of pollutants along all main and regional roads in the Republic of Serbia.

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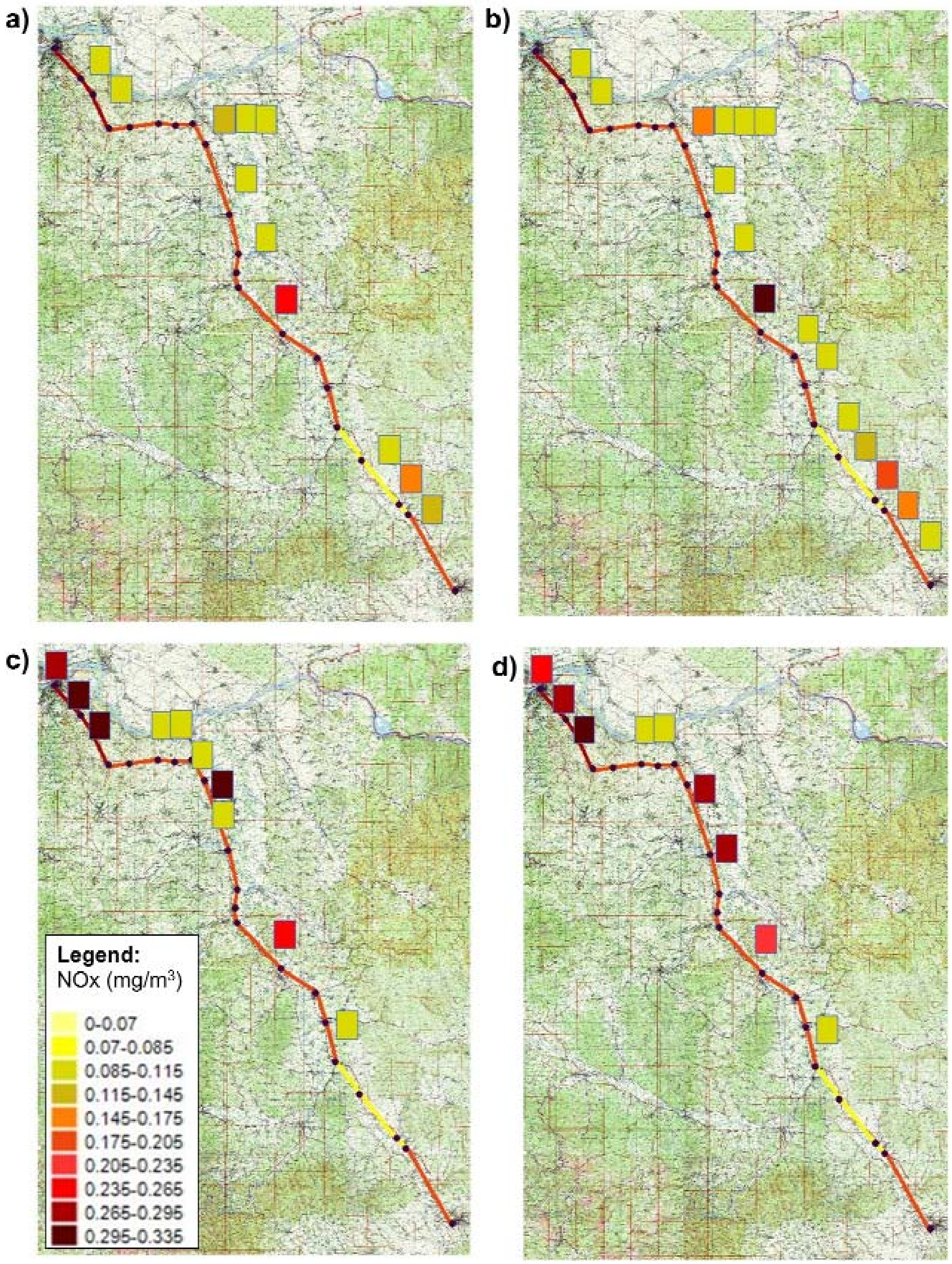

Fig. 6. NO_x concentrations in the second case scenario (1 h sampling): (a) spring, (b) summer, (c) autumn, and (d) winter.

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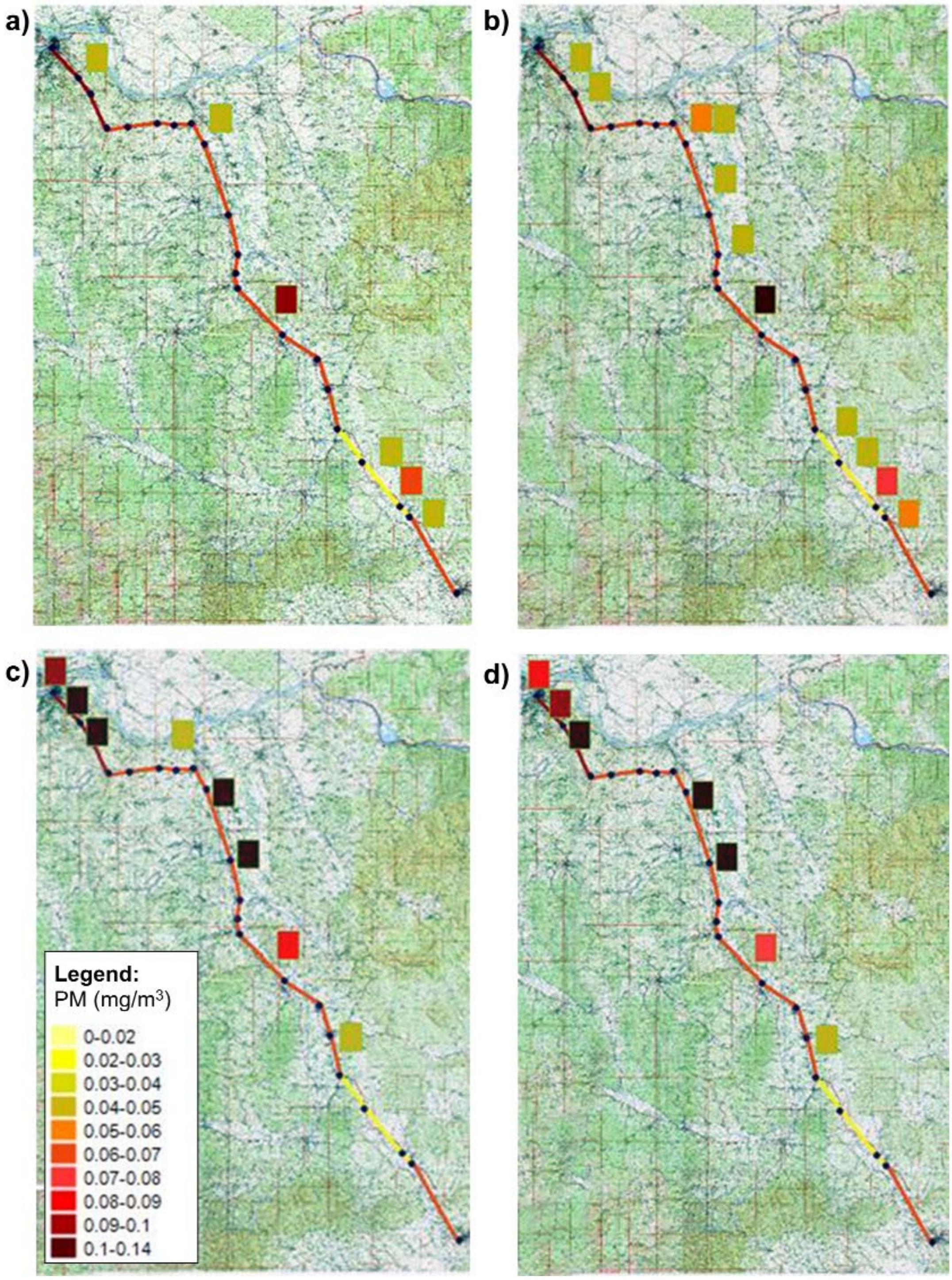

Fig. 7. PM concentrations in the second case scenario (1 h sampling): (a) spring, (b) summer, (c) autumn, and (d) winter.

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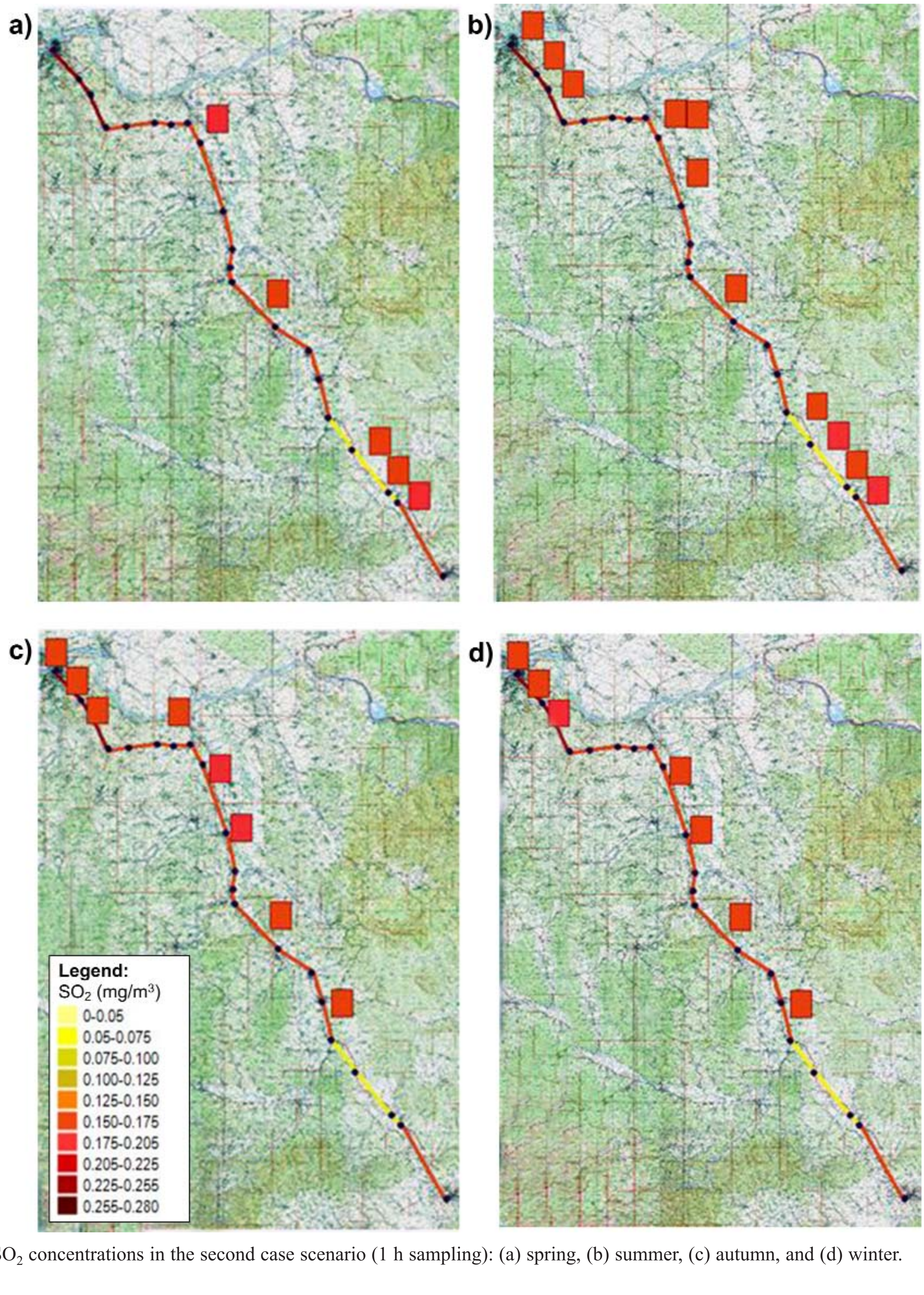

Fig. 8. SO_2 concentrations in the second case scenario (1 h sampling): (a) spring, (b) summer, (c) autumn, and (d) winter.

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