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Air Pollution Concentration near Sensitive Urban Locations: A Missing Factor to Consider in the Grade Separation Projects

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Abstract

The high vehicle congestion is the main contributing factor to air pollution originated from the engine's combustion in many urban areas. Grade separation projects have been used to solve this problem and have resulted in overall air pollution reduction in many cases. Many grade separation projects are constructed near sensitive urban locations accommodating susceptible individuals. This research argues that in such cases in addition to the overall air pollution reduction, air pollution concentration near sensitive locations is an influential factor for deciding the appropriate scenario. This research proposes a complementary simulation-based method for assessing the resulting pollution concentration of the new grade separation projects near sensitive locations. In this method, traffic congestion and air pollution of the different available project scenarios were simulated and compared. The recommended scenario was selected as a trade-off between the resulting traffic congestion, the amount of air pollution, and air pollution concentration near sensitive locations.

The proposed method was applied to an actual grade separation project in Dezful, Iran using VISSIM and EnViVer traffic and air pollution simulation software packages. It was shown that air pollution concentration near sensitive locations could be reduced by up to 40% with no significant change to the overall air pollution and the average vehicle speed. The achieved results in the case study uphold the pollution concentration near sensitive locations as a possible influential factor in the grade separation projects. The proposed method targets a new aspect of the grade separation projects assessment. As a result of the proposed method implementation, unintentional adverse impacts of air pollution can be avoided on the susceptible groups of citizens. The similar method proposed for the grade separation projects in this project can be adapted for other types of urban transportation projects.

Keywords: Grade separation; Air pollution; Simulation; Construction management; Traffic congestion

1. Introduction

Increased air pollution is an unfavorable environmental effect of the traffic and one of the critical factors in reducing the citizens' satisfaction in metropolitan areas (Wang et al., 2009; Alvanchi and Moghaddam, 2018; Han et al., 2018). The pollutants generated by combustion of fuel in the vehicle engines are the most important causes of air pollution in many large cities (Forehead et al., 2018). For example, in Tehran, Iran, it was estimated that 90% of air pollution is due to the fuel combustion in the vehicle engines (Bayat et al., 2012). The primary air pollutants from motor vehicles are CO, NO_x, PM, and HC (Brugge et al., 2007; Twigg, 2011). These pollutants have destructive effects on human health and the surrounding environment (Miri et al. 2016; Jakubiak-Lasocka et al. 2015; Cao et al. 2016), resulting in seven million casualties in 2012 (WHO, 2014).

It was estimated that road transportation is responsible for 30% of the particulate matter (PM) and the significant contribution of NO_2 in urban areas (Krzyżanowski et al., 2005). Short-term exposure to these PMs can intensify cardiovascular and respiratory symptoms (Gupta et al., 2007; Siddique et al., 2010; Balakrishnan et al., 2013). Long-term exposure to PMs, however, can even lead to premature mortality (Ostro, 2004; Cohen, 2005; Beelen et al., 2014). It was predicted that premature mortality is going to double by 2050 with the current incremental trend of air pollution, (Lelieveld et al. 2015). Air pollution is a more crucial issue in large cities in the developing countries than that of the developed countries due to the use of old diesel vehicles and inadequate public transportation systems (WHO 2018). In 2010, it was estimated that in China more than 1.2 million premature deaths have been caused by airborne contaminants (Yang et al., 2013; Xie et al., 2016). New Delhi in India (Kumar et al., 2018), Cairo in Egypt (Mahmoud et al., 2008), and Tehran in Iran (Bayat et al. 2012) are other examples of highly polluted cities in developing countries. Furthermore, air pollution analysis showed that a 2% increase in the air pollutants in 2017 compared to 2016 (Roshani et al., 2017).

The high unfavorable impacts of urban air pollution on people's lives and the integral role of road transportation systems on air pollution have encouraged researchers to investigate mitigation strategies. Expanding public transportation (Bel et al., 2018), improving vehicle engines (Haghighat et al., 2018), enhancing quality of fossil fuels (Jacobson et al., 2005), turning to environmental friendly and green energies (Chisti, 2008), and upgrading transportation infrastructures (Thambiran and Diab, 2011) are among the investigated mitigation strategies. Improving transportation infrastructures is a solution pursued in reducing traffic congestion and air pollution in many developing countries (Thambiran and Diab, 2011). Grade separations are among the most established infrastructures used for facilitating traffic congestion (El-fadel 2002). The simulation-based study conducted by El-fadel (2002) represented that construction of the grade separation infrastructure in the studied intersection could reduce the vehicles delays by 90% during the peak hours. Reduced vehicle traffic congestion and, pollution were also identified as results of the grade separation construction. Goyal et al. (2009) conducted a case study in Nagpur, India that flyover bridges resulted in a 60-70% reduction in the traveling time compared to the signalized intersections. In another case study in Thailand, Salatoom et al. (2015) found a time delay on the signal is reduced by 30% by constructing a two direction flyover on the signalized intersections.

Previous studies affirm new grade separation projects can reduce traffic congestion and the resulting pollution (Chowdhury et al., 2016, He et al., 2016, Islam, 2018). Grade separation projects cost citizens millions of dollars. The main incentive for constructing new grade separation projects is to improve the citizen's quality of life. Therefore, any unintended damage should be avoided for enhancing the citizens' quality of life. Following the widespread globalization perspective to human activities, past efforts have discussed global impacts of air pollution. The local impacts of new grade separation projects have not been assessed. New grade separation projects change the geometry of the projects' neighborhood. The global reduction of air pollution in the new grade separation projects does not necessarily result in pollution concentration reduction in all nearby locations. A spectrum of pollution concentration can be created. In many cases, new grade separations are built close to the highly populated and sensitive urban facilities such as hospitals, schools, and recreation centers, where susceptible groups of individuals commute. This research benefits from the recent improvement of information technology to address this gap in analyzing the local impacts of new grade separation projects with an emphasis on the pollution concentration near sensitive locations.

This research seeks to improve the sustainability of new grade separation projects. Reducing the pollution concentration near sensitive city locations, where susceptible groups of citizens commute, is the main objective followed in this research as a new perspective to urban development. This investigation proposes an original simulation-based approach to assess the traffic and air pollution concentration impacts of different grade separation scenarios in the adjacent sensitive locations. It determines the associated air pollution of different valid scenarios in the two sensitive points and introduces the best scenario based on the maximum air pollution reduction. First, different parts of the proposed simulation-based method are explained. Then, the capability of the proposed method is verified in a case study of an intra-city bridge project in Dezful, Iran. Finally, the research is concluded.

2. Proposed Method

Air pollution assessment method proposed in this research complements the technical assessment efforts performed during the feasibility studies and planning stages of new grade separation projects. In this method, first, different aspects of the project specifications, including traffic volume, emission pattern of different types of vehicles in the region, and the scope of the project are recognized. In the second step, various available grade separation scenarios are identified. Detailed geometrical properties of different valid scenarios and the volume of the expected traffic input/output in different directions are determined in each adopted scenario. Then, in the third step, the number and group type of individuals visiting or residing in neighboring locations are surveyed, and highly susceptible locations to the air pollution are determined. Locations such as hospitals, schools, playgrounds and various types of business centers can be marked as susceptible locations to the pollution concentration. Next, an air pollution simulation software, capable of microsimulation of pollution concentration from traffic flow, is used for modeling and simulating different adopted scenarios in the fourth step. In microsimulation or microscopic simulation, every single traffic element is modeled. Therefore, the simulation model becomes capable of capturing impacts of individual traffic elements such as cases and roads (for further information about microsimulation methods please refer to Charypar et al. 2007). Finally, achieved simulation results are analyzed and concluded in the fifth step. The resulting volume of air pollution and its concentration near identified sensitive locations are two main factors to consider in analyzing and prioritizing different scenarios. This conclusion works as an input to the grade separation project decision-making process. It complements other decision-making factors such as traffic congestion results, financial assessment, and construction method assessment. Figure 1 summarizes the steps of the proposed method.

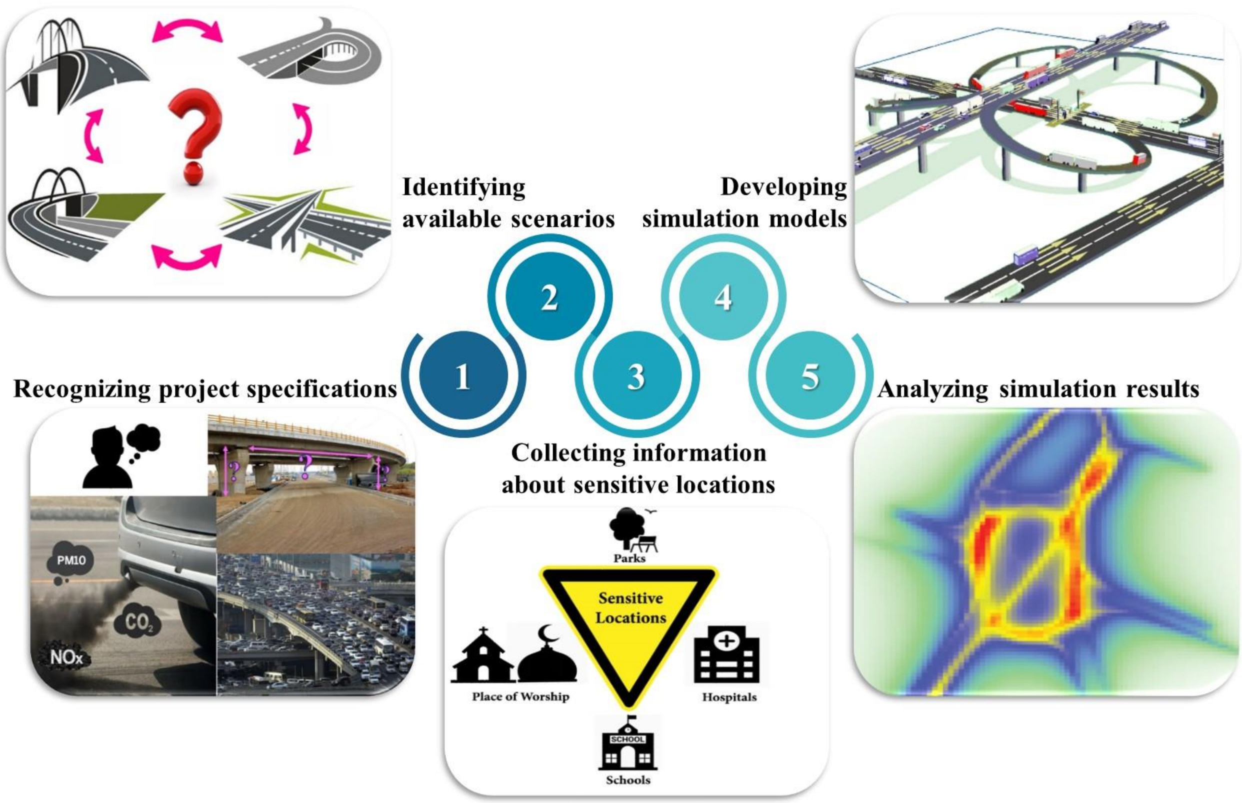


Figure 1. Various steps of the proposed pollution analysis method

3. Case Study

Air pollution has become a dominant phenomenon in different cities of Iran in a considerable part of the year in recent years. Currently, air pollution follows an increasing trend in different regions of the country. It was estimated that annually more than 4000 people die prematurely from excessive PM2.5 air pollution in Tehran (Heger and Sarraf, 2018). Tehran only saw 14 days of clean air in 2017 (Roshani et al. 2017). Isfahan, another major city located in central Iran, only faced 51 clean days in 2012 (Jafari et al. 2017). Meanwhile, Khuzestan, a south-western province in Iran, is among the most polluted places in the world (Walsh, 2011). Ahvaz, Khuzestan's capital city, was ranked the most polluted city in the world in 2011 (Walsh, 2011). Many diseases in the province are the results of air pollution (Goudarzi et al. 2014; Geravandi et al. 2015). Implementation of methods focused on reducing the impacts of air pollution on society in a developing country such as Iran is required for alleviating the current situation.

Application of the proposed method in the case of a grade separation project in Dezful, Khuzestan, Iran, aimed to test the capability of the proposed method in a real grade separation project. This project locates in the major and populated square of the city. The nearby sensitive locations nominated this project as an excellent example for applying the proposed method and testing its capability. Following that, the implementation of different parts of this method is explained in the case study.

3.1. Case specification

Fatholmobin Square is a congested area in Dezful. It connects five main streets in the city and is a major connection point from Andimeshk city in the north to Shush and Shushtar cities in the south. Figure 2 presents the case location on the map. The constructing of a grade separation was planned on the square to reduce the traffic congestion in the area.

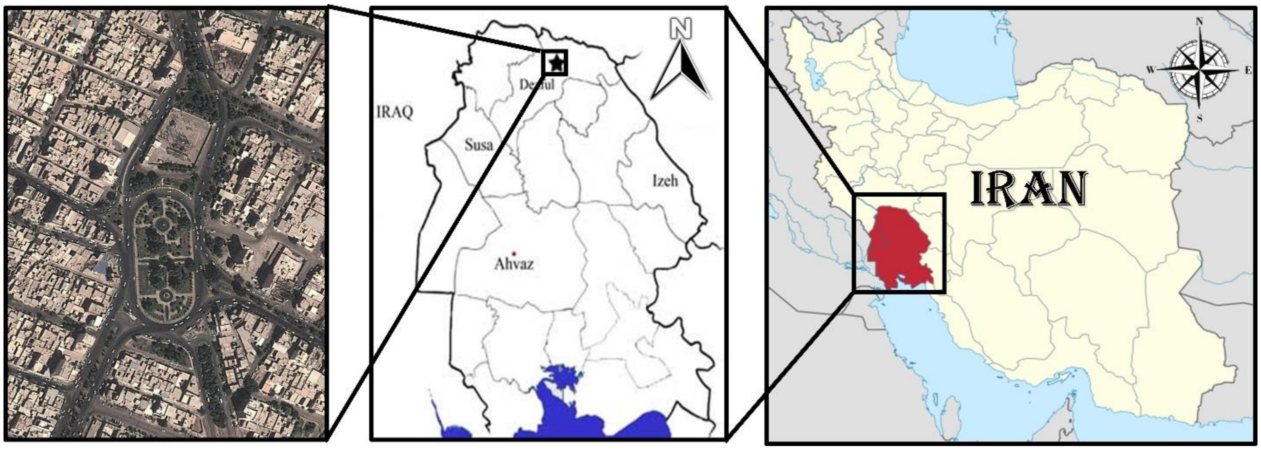


Figure 2. Location of the studied case

3.2. Available scenarios

Four possible scenarios, as valid choices considered by the project decision makers, were identified in the case study. The adopted scenarios assessed in the case included Scenario 1: No overpass or underpass is built, Scenario 2: One overpass is built, Scenario 3: Two overpasses are built, and Scenario 4 (the based scenario): Two overpasses and an underpass are built. The Dezful municipality selected Scenario 4 for building the grade separation. Therefore, this scenario was considered the base scenario to be compared with other scenarios. Scenario 4 includes all grade separation structures considered in three other scenarios. The overpass bridge in this scenario starts with a two-lane in the north-south traffic direction from the northern street of Fatholmobin. However, it splits into two branches in the middle of the road. One branch goes to the south-western street of Moghavemat Boulevard. The other branch goes to the south-eastern street of Police Boulevard. The underpass has the south-north traffic direction and connects the south-eastern street of Moghavemat Boulevard to the northern street of Fatholmobin. Figure 3 sketches directions of the overpass bridges and the underpass considered in Scenario 4, the based scenario.

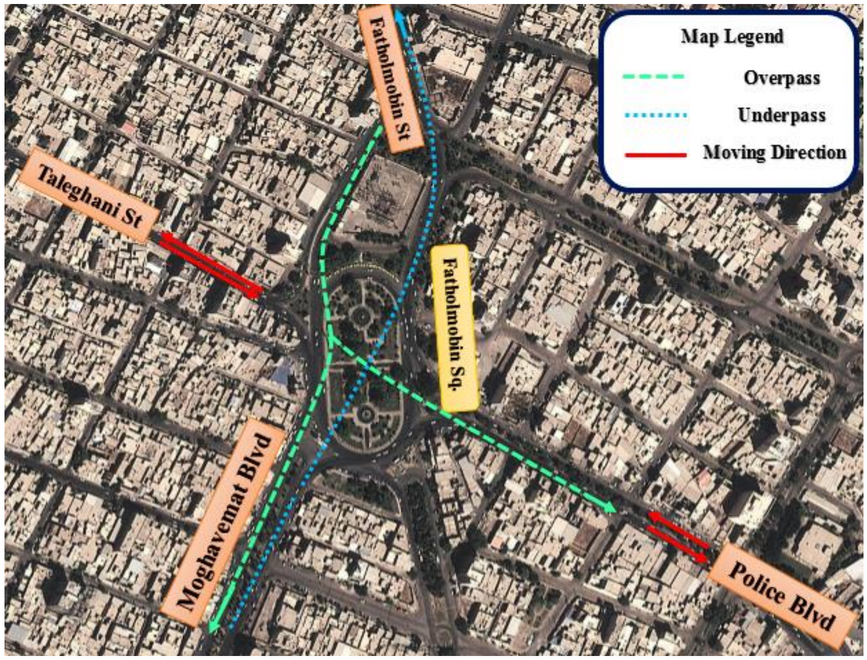


Figure 3. Directions of the overpass bridges and the underpass in the base scenario

3.3. Data collection

Two approaches were followed for the data collection. First, data received from the vehicle traffic control organization of the Dezful municipality was used to analyze the traffic condition in the area. Second, full-HD cameras were directly employed by the research team for capturing the traffic flow rate during peak hours. The traffic rate was found uniformly distributed during this time of the day. Here, data gathering was implemented during the peak hour of 7 pm to 8 pm. According to the data collected from the vehicle traffic control organization during this time of the day, the square faces the highest traffic congestion. The grade separation project's target was to solve the traffic congestion problem for this period of the day. The collected traffic data included the distribution of different types of vehicles, the distribution of the age of the vehicles in the region and the number of passing vehicles for the roads entering to and exiting from the square. Table 1 summarizes the collected traffic data.

Table 1. Summary of the traffic data collected for the project area

	Input Volume (Vehicle / Hour)	Number of Vehicle Lanes	Vehicle Types		
			Light Vehicle	Heavy Vehicle	Motor-Cycle
Fatholmobin St (North of square)	1350	3	90%	1.8%	8.2%
Moghavemat St (South of square)	1554	3	90%	2.3%	7.7%
Police St (East of square)	636	3	92%	3.7%	4.3%
Taleghani St (West of square)	468	3	94%	2.8%	3.2%
Montazeri St (South of square)	80	1	98%	0.9%	1.1%
Moallem St (Southeast of square)	400	3	96%	1.3%	2.7%

According to the achieved results, the average age of vehicles in the region was nine years, and the average longevity of vehicles was assumed 20 years. Several businesses including shops, minimarkets, banks, a shopping center, a children's park, and a busy and popular store were located around Fatholmobin Square. Among them, two sensitive locations were identified as follows:

Location L1: A park and green area, and

Location L2: A large gathering place for locals to buy snacks and daily necessities.

Figure 4 illustrates the exact locations of these two points.

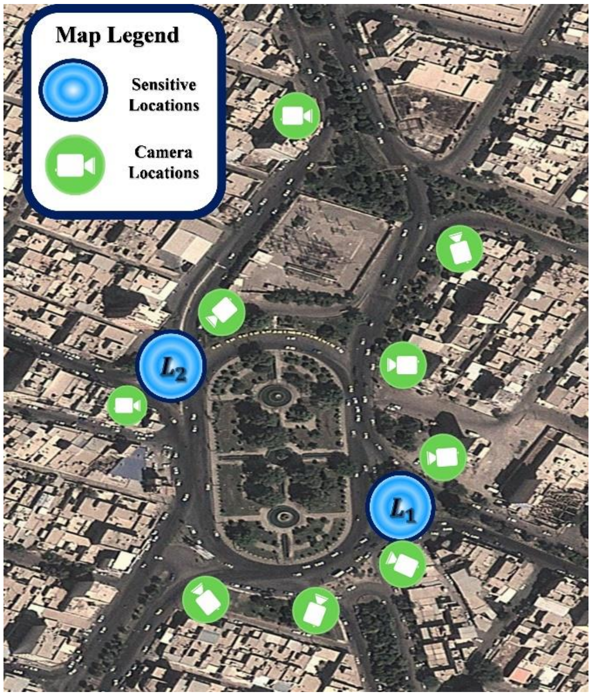


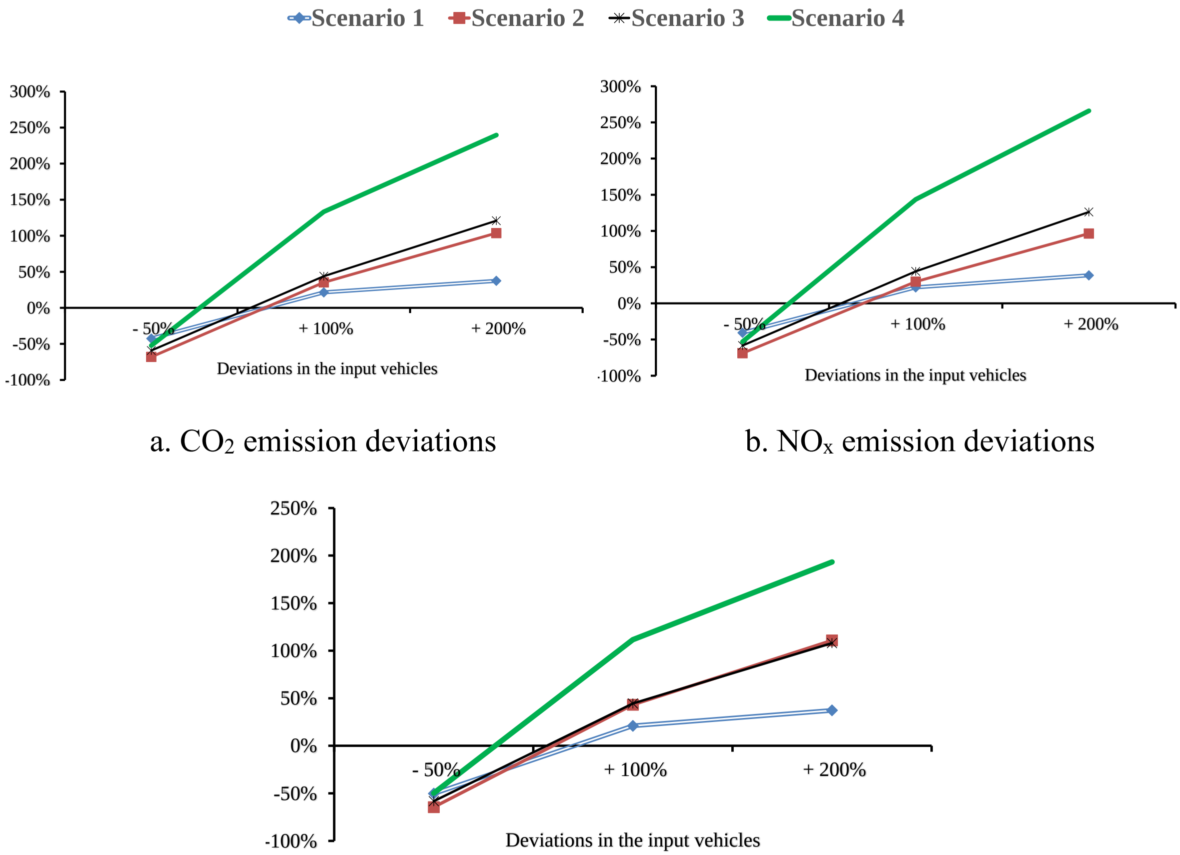
Figure 4. Two sensitive locations around the Fatholmobin Square with the location of cameras

3.4. Traffic simulation

Various air pollution simulation applications are available in the market by the advances made in the information technology in the recent decade. These computer applications can simulate the amount and the concentration of various air pollutants caused by vehicles based on the traffic volume, vehicle types, and geometry of different valid scenarios. In recent years, many studies were conducted to assess the amount of traffic-related air pollution using simulation-based approaches. PTV-VISSIM simulation package is one the simulation packages employed in different research efforts (e.g., Fontes et al., 2014; Borrego C., 2016; Fallah-Shorshani, 2017). It adopts the microsimulation approach for capturing details of the car traffic. Geometry specifications of the project, vehicle volumes, and vehicle modal splits are the main input parameters to the model. One of the main outputs of this software is the distribution of different emitted pollutants, e.g., CO, HC, NO_x, and PM (PTV-Group, 2018). In this study, VISSIM 11 and EnViVer software packages, developed by PTV-Group in 2018, were employed for vehicle traffic simulation and distribution of the resulting air pollutants. Collected field information of the adopted scenarios was entered into these packages; the output emission results of four adopted scenarios were then simulated and analyzed.

3.5. Model Verification

Set of verification tests were performed on the developed simulation model to assess the model legitimacy according to the model verification steps recommended in the literature (Sterman 2000; Banks et al. 2005). In the sensitivity analysis of a model, adequacy of the direction of changes in the model in response to the input parameters deviations are tested (Sterman 2000, pp. 883-887). In the research, the sensitivity of different adopted scenarios was assessed to the deviations in the vehicle inputs in a performed verification test. Simulation model response to the vehicle input decreased by 50% and increased by 100% and 200% were analyzed. Supposedly, in various scenarios, overall air pollution should have the same direction with the change in the traffic volume. Figure 5 represents the achieved results in this sensitivity analysis. As expected in all scenarios, the direction of the vehicle input volume and the traffic congestion conformed to each other.



a. CO_2 emission deviations

b. NO_x emission deviations

c. PM_{10} emission deviations

Figure 5. The sensitivity of the emission to the deviations of the input vehicles

Extreme condition test is another verification approach for the complex simulation models where the adequacy of the model's response to the system's extreme condition is assessed (Sterman 2000, pp. 869-872). An extreme condition test was also conducted by blocking all output roads branching from the square. As expected, the square was fully packed by the input vehicles and all input roads to the square became saturated after 10 minutes. Figure 6 represents the air pollution deviation in this extreme condition. Here, Scenarios 2, 3 and 4 face relatively high emission increase during the traffic blockage. Scenario 1 or the current condition, however, represents the least change in the emission level. The current high traffic congestion condition in Scenario 1 resembles high traffic congestion created in the complete blockage and justifies this low deviation.

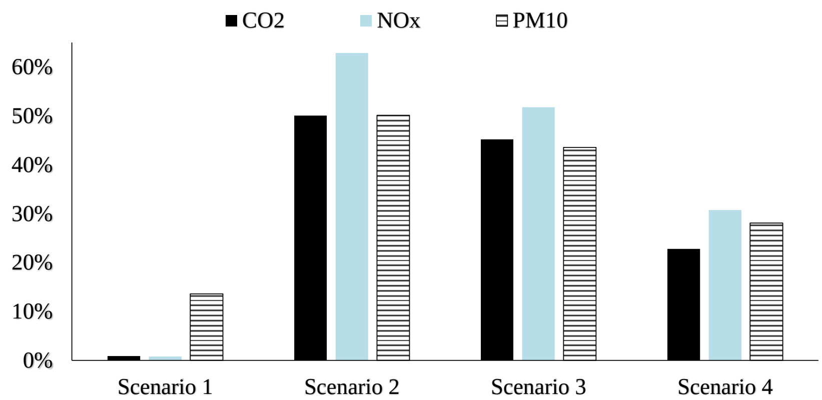


Figure 6. Emission deviations in complete blockage test

Furthermore, according to Banks et al. (2005, p. 317) for verification of the reasonability of the simulation, the achieved results from different aspects of the model was also presented and verified by the experts familiar with the system conditions.

3.6. Emission Results

The amount and the concentration of three air pollutants including CO_2, NO_x, and PM_{10} were estimated using the simulation packages. Figure 7 represents the average vehicle emission of these three air pollutants achieved in the four adopted scenarios during the peak hours. Among different situations, Scenario 2 creates minimal CO_2 with 255 grams per vehicle kilometer, Scenario 4 creates minimal NO_x with 451 grams per vehicle kilometer, and both Scenarios 2 and 4 create minimal PM_{10} with 48 grams per vehicle kilometer.

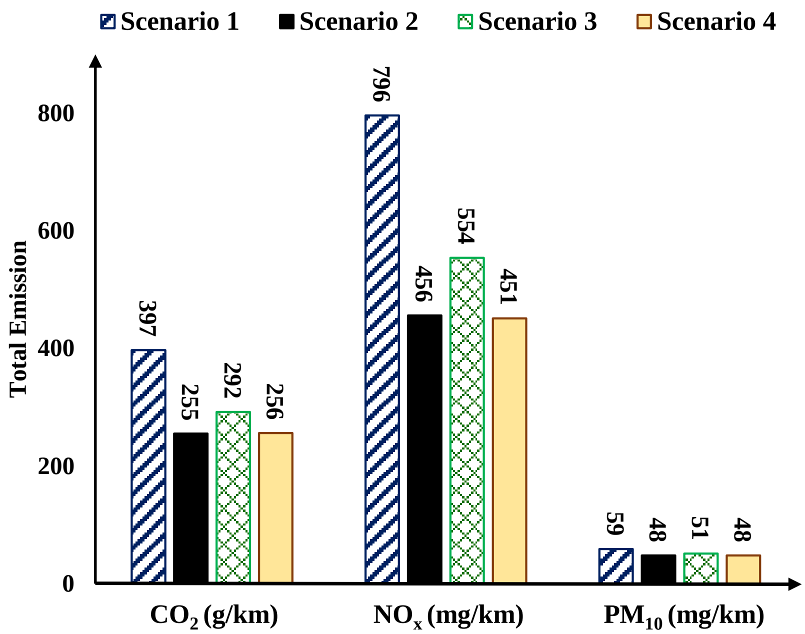
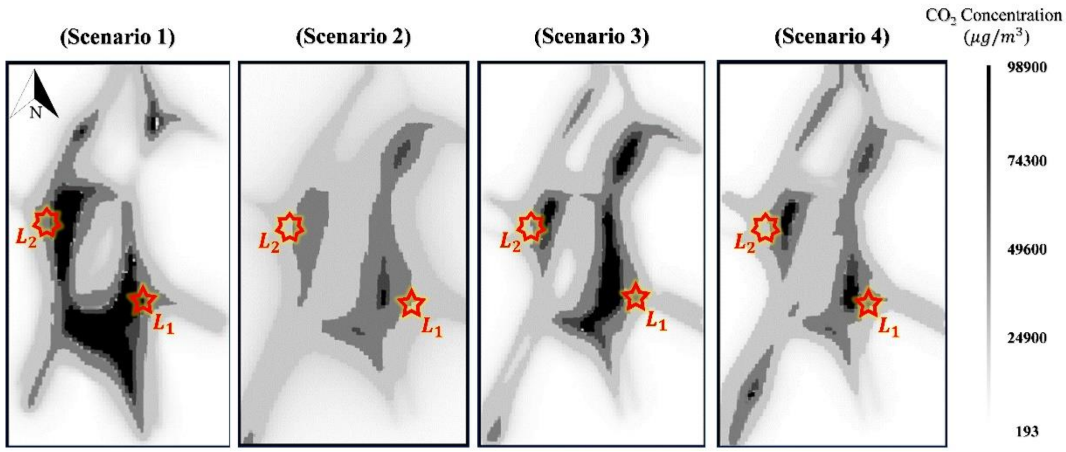
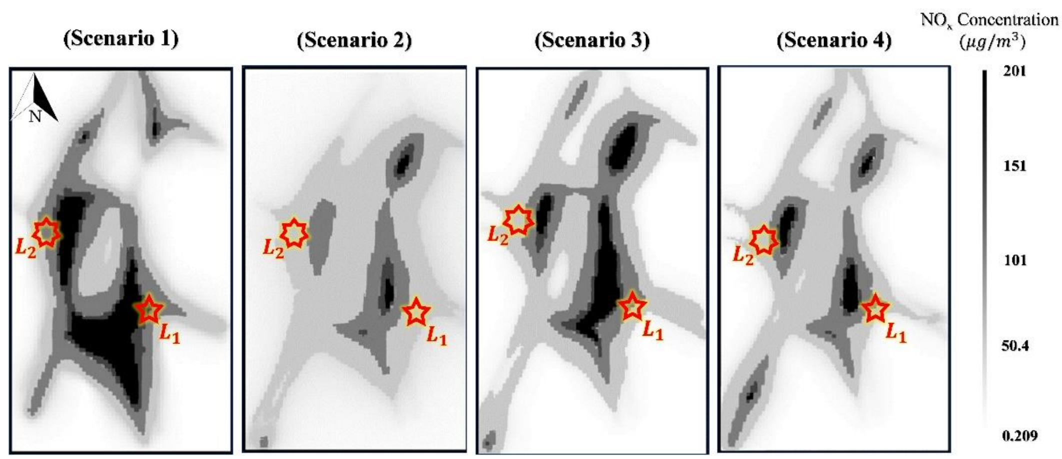


Figure 7. Estimated average vehicle emission in the four adopted scenarios

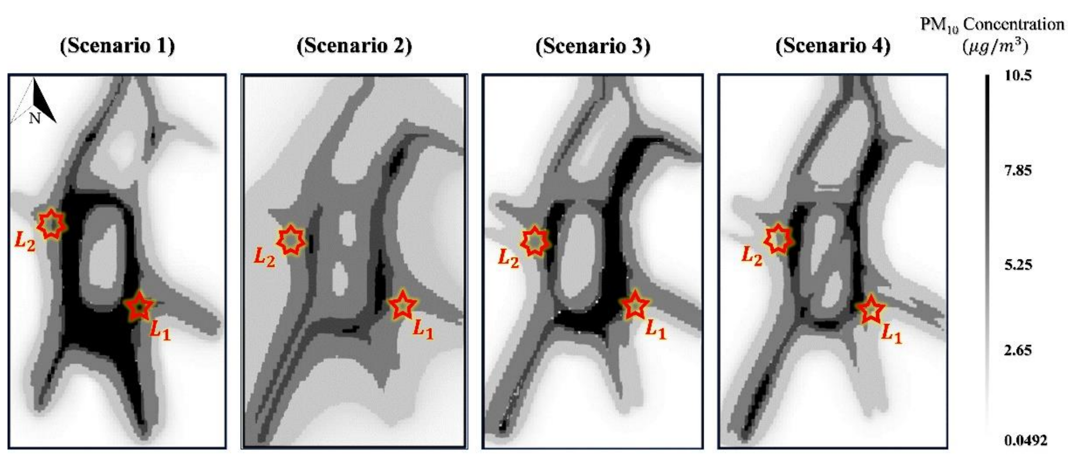
The concentration of the three considered air pollutants near the identified sensitive locations in the project site was also investigated using the simulation packages. Figures 8 represents the estimated level of the three considered air pollutants in the four scenarios. For all three pollutants, Scenario 2 results in minimal air pollution concentration near sensitive locations of L1 and L2. Analysis of the traffic congestion and the average vehicle speed is also an essential indicator for deciding the adopted scenario. VISSIM software is used for analyzing the average vehicles speed during the peak hours. Figure 9 illustrates the estimated average speed of vehicles in different parts of Fatholmobin Square in the four scenarios. Scenarios 2, 3, and 4 involve the construction of new grade separation projects considerably that improve the speed of the vehicles during the peak hour. Insignificant differences between Scenario 2, Scenario 3 and Scenario 4, or the base scenario, are evaluated in the average vehicle speed in different parts of the square during the peak hour.



a. Comparison of CO_2 Concentration between 4 Scenarios



b. Comparison of NO_x Concentration between 4 Scenarios



c. Comparison of PM_{10} Concentration between 4 Scenarios

Figure 8. Air pollution concentration near sensitive locations of L1 and L2

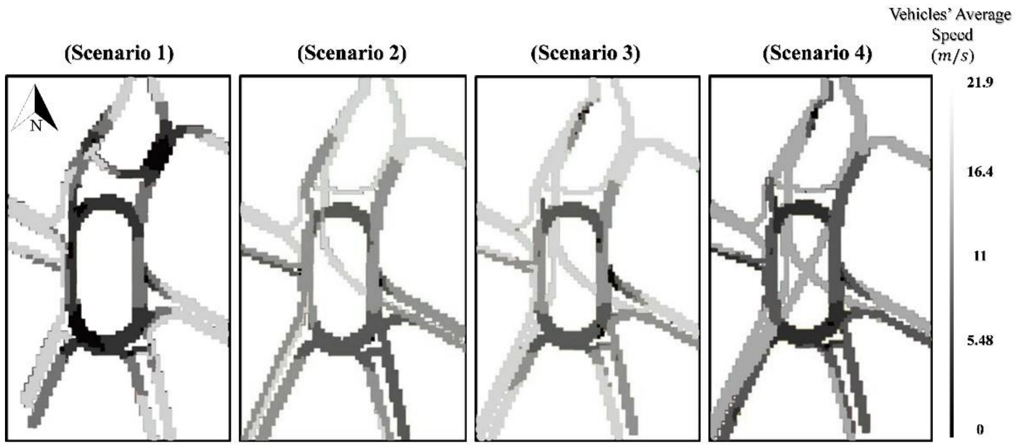


Figure 9. Average vehicle speed in Fatholmobin Square during the peak hour for different scenarios

3.7. Result analysis

In the studied case of Fatholmobin Square, Scenario 2 and the base scenario or Scenario 4 followed a similar trend in the overall air pollution (Figure 7). Overall, emissions in these two scenarios were considerably lower than Scenario 1 and Scenario 3. Nevertheless, pollution concentration near sensitive locations in Scenario 2 was relatively lower than all other three scenarios including the base scenario (Figure 8). CO_2 concentration near location L1 was 71% lower than Scenario 1, 64% lower than Scenario 3 and 39% lower than the base scenario in Scenario 2. A similar trend was followed for NO_x and PM_{10} concentration near location L1. In location L2, Scenario 2 scored 59% less CO_2 concentration than Scenario 1, 18% less CO_2 concentration than Scenario 3 and 24% less CO_2 concentration than the base scenario. Here again, pollution concentration for NO_x and PM_{10} near location L2 was reasonably similar to CO_2. Scenarios 2, 3, and the base scenario demonstrated considerable improvement in the average vehicle speed compared to Scenario 1, bearing no modifications to the square. While average speed in the square was 60 kilometers per hour (km/ hr) in Scenario 2, it was 50 km/ hr in Scenario 3 and 60 km/ hr in the base scenario. Scenario 1 scored an average speed of 20 km/ hr, which is considerably less than the others.

In sum, the proposed modifications in Scenarios 2, 3, and the base scenario demonstrated improvements from the current condition of the square in Scenario 1. The overall air pollution, the air pollution concentration near sensitive locations and the average vehicle speed were improved in these three scenarios. In the comparison between these three scenarios, Scenario 2 can be recommended as the most appropriate scenario in the case. This scenario scored the minimum air pollution concentration near sensitive locations while relatively resulted in low overall air pollution and the average speed. Low air pollution concentration near sensitive locations in Scenario 2 was achieved while this scenario required the minimum modifications and, consequently, the minimum investment. This implication represents that the increasing number of grade separation infrastructures does not necessarily improve the traffic flow in the region. Here, adding new grade separations have increased the number of road merge and road split sections resulting in the interruptions to the free traffic flow. In some parts of the square, these merge and split sections have narrowed the existing roads and increased the traffic congestion locally. Impacts of the road geometry details explain the achieved deviations in the standing of different scenarios regarding the overall air pollution, the average vehicle speed, and the air pollution concentration in sensitive locations. These deviations affirmed the initial assumption of the research for possible differences between the air pollution structure and vehicle congestion in a transportation system. It can be claimed that separate air pollution assessments in transportation system development projects provide complementary information to the decision makers.

4. Conclusions

This research proposes a new method for air pollution assessment of grade separation projects. It was argued that in addition to the overall amount of air pollution, the concentration of the created air pollution near sensitive urban locations is also a point of concern in the development of grade separation projects. Different geometry of the available project scenarios in a grade separation project could lead to varying levels of air pollution concentration near sensitive locations. The air pollution concentration assessment near sensitive locations in the grade separation projects can provide supplementary information to the project managers for their project decisions. The proposed method was successfully applied to the case study of the grade separation project of Fatholmobin Square in Dezful, Iran using a traffic simulation package available in the market. Results achieved in the case study represented the existing deviations in the pollution concentration, overall air pollution, and vehicle traffic congestion in different available project scenarios. The results affirmed the raised argument in the research that the overall air pollution reduction does not necessarily result in air pollution concentration near sensitive locations. This trend can happen in other grade separation projects as well. Complementary, assessments near sensitive locations to the new grade separation projects can help improving air quality in these locations.

Considering the impacts of the grade separation projects on the local pollution concentration with the focus on the existing sensitive locations is proposed for the first time in this research. In this perspective, this research contributes to the sustainable development of urban areas. Similar air pollution concentration assessment is also recommended for other types of urban development projects such as bus stations, train stations, and public parking, neighboring sensitive locations. By following the proposed method for such projects, project managers can prevent unintended negative impacts of air pollution on the susceptible groups of citizens living near the project site.

Implementation of this research was also subject to several limitations. All field studies in the case were implemented at the peak hour in the clear sky under no extreme weather condition. In this perspective, the assessment result of the case study falls short in analyzing off-peak hours and severe weather condition. Modal splits and vehicle distribution of the case study was borrowed from the entire city. However, vehicle distribution in the case location does not necessarily completely follow this vehicle distribution. Furthermore, simulation model development and the required field study for collecting information from sensitive locations impose additional cost to the project.

5. Acknowledgment

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