Alvanchi, A., Rahimi, M., Mousavi, M., & Alikhani, H. (2020). Construction schedule, an influential factor on air pollution in urban infrastructure projects. *Journal of Cleaner Production*, *255*, 120222.

Construction schedule, an influential factor on air pollution in urban infrastructure projects

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Abstract

Urbanization growth and aging infrastructures necessitate new infrastructure construction projects in congested urban areas. Urban construction projects interrupt the regular on-road vehicle traffic flow that affects air pollution concentration in the adjacent areas. The project schedule, however, is a possible contributor to the air pollution which has been neglected to date. This research proposes a new framework to account for the impact of different urban project schedule alternatives on air pollution emission near the construction zones. The proposed framework uses the capabilities of vehicle traffic simulation to evaluate air pollution emission of different construction schedule alternatives and reduce the resulting emission in urban construction projects. The capability of the proposed framework is verified in a real grade separation case. Pollution concentration shows a potential reduction of up to 41% in sensitive locations. The achieved resulting values represent potential emission reduction of 7.8% for CO_2, 8.2% for NOx, and 3.8% for PM_{10}. The achieved results in the case study confirm the impact of the construction schedule on the air pollution emission throughout the project's construction. It justifies the application of the framework in the congested urban areas. The proposed framework in the research contributes to the sustainable improvement of urban infrastructure projects.

Keywords: Air pollution; Urban infrastructure; Construction schedule; Simulation; Traffic congestion; Construction Management

1. Introduction

Air pollution is a global issue causing seven million casualties annually (Guterres, 2019). Many sources, including fossil fuel burning, chemical processes, agriculture, and even natural phenomena, contribute to this global concern (EEA, 2017). Among different identified emission sources, emissions from fossil fuel burning in the transportation sector play an important role. In the recent decade, the transportation sector has experienced a considerable improvement in many air pollutants (EEA, 2019). Nevertheless, transportation is still responsible for the health burden caused by increased fine particulate matter (PM2.5), ozone, and nitrogen dioxide pollutants (Anenberg 2019). In the transportation sector, air pollution emitted from on-road traffic plays the main role (EEA, 2019) with urban traffic congestion taking the main responsibility (Schrank et al., 2015).

Meanwhile, urban population growth mandates municipalities to implement new infrastructure construction projects to improve, or even maintain, the current level of traffic congestion (Lin & Zhu, 2018). Furthermore, infrastructures are deteriorated over years in-service. New construction projects are needed for renovating or rebuilding deteriorated infrastructures. In many construction projects, project managers are forced to schedule interruptions to different parts of the project's neighboring areas following the construction project plan (Sharma et al., 2009). Urban construction projects, however, can go on for several years (Lu & Yan, 2007) and scheduled interruptions can drastically affect vehicle traffic congestion in the area throughout the project (Amin et al., 2017). It was estimated that the resulting traffic congestion from urban construction projects comprises 35% of the overall social cost of the construction projects (Yu & Lo, 2005). Huang et al. (2009) found considerable air pollution increase during an urban road maintenance project due to the interruptions made to the vehicle flow. They recommended shifting the working time to the off-peak hours to reduce the emitted pollution. Increased urban travel time and its resulting cost (Du et al., 2014) and increased air pollution (Noland & Hanson, 2015) are among the reported drawbacks of urban construction projects in the past research.

In many urban construction projects, project managers face multiple project schedule alternatives which result in different lane closure conditions. In this perspective, many researchers have used project schedule adjustments for reducing on-road traffic congestion in urban construction projects. In 2004, Cheu et al. proposed a combined simulation and genetic algorithm-based method for finding a construction schedule with minimal negative impacts on traffic congestion and travel delay in the area. In another research, Lee et al. (2005) used a simulation-based technique to evaluate different road closure scenarios for a road maintenance project and to reduce the travelers and the construction operation cost. Lee (2009) proposed a combined simulation and ant colony method for improving the urban construction project schedule and the resulting delay in the traffic flow. Oh et al. (2011) proposed a genetic algorithm-based method for improving the construction and maintenance of a road network. Morgado and Neves (2014) proposed a multiple-criteria decision model to concurrently improve construction cost, construction schedule and user effects in the pavement maintenance projects. Zheng et al. (2014) used a k-shortest path algorithm to improve the construction schedule of work zones in the urban network. Yang et al. (2018) formulated a day-based work zone scheduling problem in urban road networks into non-linear programming and found optimal crew size and work zone schedule using a genetic algorithm.

In sum, past research has employed the urban project schedule as a tool for reducing on-road vehicle traffic delay and its resulting cost. The possible impact of urban construction project schedule on the on-road vehicle emission near urban construction zones, however, has not been investigated. In contrast, the performed investigation on the air pollution assessment of construction work zone was mainly concerned with the dust emissions (e.g., Wallace & Cheung, 2013; Wu et al., 2016) and emissions from the operation of the off-road construction equipment (e.g., González & Echaveguren, 2012; Zhang et al. 2014) rather than the on-road vehicle. Furthermore, many urban infrastructure projects are implemented near sensitive locations accommodating susceptible individuals to air pollution. Increased air pollution concentration near these sensitive locations during the construction operation poses a high threat to these individuals. Construction zones might neighbor schools where students spend their time even during peak hours (Dadvand et al., 2015). Urban recreational parks near construction zones accommodate visitors with high physical activities who are exposed to the emissions and, consequently, are subject to the possible severe adverse health impacts (Su et al., 2011). Alvanchi et al. (2019) found a significant impact of the project design on the pollution concentration near sensitive locations during the operation period of their studied grade separation project case. While many urban construction projects continue for several years, finding proper construction schedule with reduced on-road vehicle emission impact on sensitive locations can alleviate the created adverse impact. Nevertheless, past research falls short to address this aspect of the urban emission as well.

To address the identified gaps, this research aims to employ the urban construction project schedule for reducing the resulting on-road vehicles' air pollution and air pollution concentration near sensitive locations. First, the proposed framework is explained. The capabilities of the proposed framework are then examined in a real case of grade separation project in Dezful, Iran. Next, the achieved results of the case study are analyzed and discussed. Finally, the research outcome is summarized and concluded.

2. Proposed framework

In the first part of the proposed framework, field investigation is conducted to identify on-road traffic structure and sensitive locations near the construction zone. Traffic inflow of different streets in the area, substitute routes conditions, and vehicle type distribution are among the collected traffic information. In the second part of the framework, the construction project is recognized. Available construction project schedule alternatives and the resulting interruptions to the on-road traffic flow are identified. Here, each construction project schedule alternative is considered as a construction scenario creating a specific combination of the lane closure alternatives. In the third part of the framework, the collected information in the first and second parts is used to develop the simulation models for evaluating emissions resulting from different construction schedule scenarios. The evaluation process of different construction schedule scenarios involves both overall emission concentration and emission concentration near sensitive locations from on-road traffic. Figure 1 represents different parts of the proposed framework and the direction of their interactions. Further details regarding the proposed framework are discussed during the implementation of the framework in a real urban infrastructure construction case in the next section.

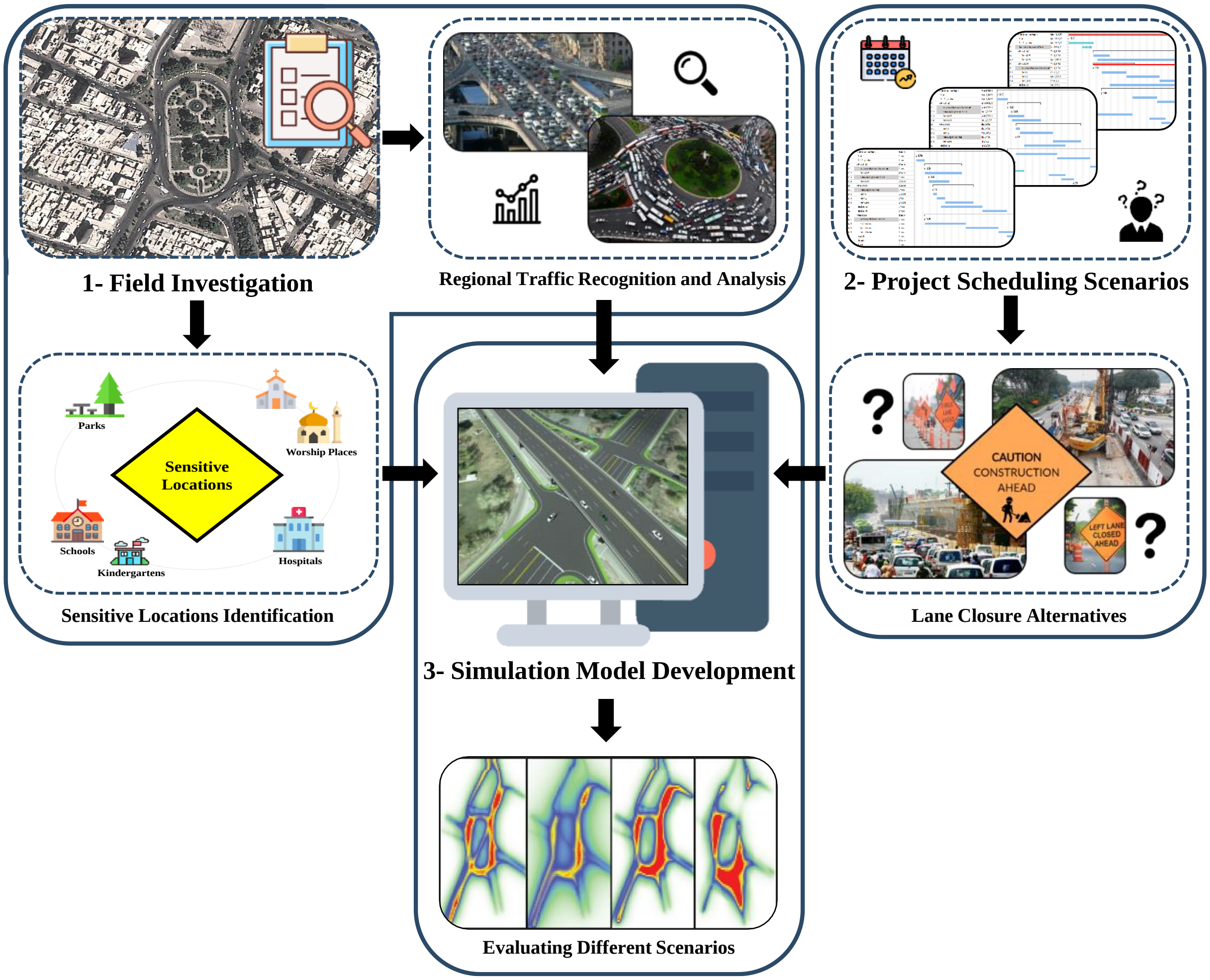


Figure 1. Different parts of the proposed pollution analysis framework.

3. Case Study

Air pollution has become the main concern in many parts of Iran. It is responsible for many diseases and premature deaths in the country. Tehran, the capital city, is amongst the most air-polluted cities in the world (Heger and Sarraf, 2018). Naddafi et al. (2012) estimated that between 7 to 15 percent of deaths in Tehran were due to exposure to air pollution. Air pollution is also a critical issue in the southern province of Khuzestan. In Ahvaz, Khuzestan, a high level of CO concentration is responsible for 4.3% of total cardiovascular deaths (Goudarzi et al. 2014). Furthermore, 5.6% of the respiratory mortality and chronic obstructive pulmonary diseases are due to the increased level of Sulfur and NO2 in Khuzestan (Geravandi et al. 2015). The government has run different programs to alleviate this countrywide problem. The issue, however, is remaining and even worsening in many parts of the country. Introducing new methods for mitigating impacts of air pollution on society is quite essential in the country. The application of the proposed framework in urban construction projects in the country can contribute to the desired emission reduction. It was implemented in a grade separation case in Dezful, Khuzestan, with high air pollution concern, to verify the applicability of the proposed framework. The project locates in Fatholmobin Square, a crowded central part of the city that nominated it as a proper case for implementing the proposed framework. The square is the connection point of five main streets in the city. It connects Andimeshk city, on the north, to Shoosh and Shooshtar cities, on the southwest and southeast. During this case study, the capability of the proposed framework was investigated to properly respond to real-world construction project challenges.

3.1. Project specification

The vehicle traffic congestion was reached its saturation level and construction of the grade separation project aimed to reduce the traffic congestion in the area. No major substitute route was identified for this central point. Therefore, the majority of the traffic was forced to use this square for its commute. The grade separation project constitutes a four-lane wide overpass bridge, starting from Fatholmobin Street on the northeast of the Square, and splits into two two-lane branches in the middle as illustrated in Figure 2. One branch goes to the Moghavemat

Boulevard in the southwest, and the other branch goes to the Police Boulevard in the southeast. The project also encompasses an underpass linking Moghavemat Boulevard to Fatholmobin Street. The underpass requires an excavation volume of 80 thousand cubic meters. The overall length of the grade separation comes to 511 meters for the overpass and 540 meters for the underpass. The construction part of the project was scheduled for 18 months from December 18, 2017, to June 10, 2019. Figure 2 presents a plan view of the project representing traffic directions and bridge column locations on the square. Construction locations of different abutments (represented by “Ab”), piers (represented by “P”), and underpasses (represented by “Up”), are marked in the figure. The adopted construction schedule controls the construction sequence of these grade separation elements and, consequently, determines the lane closure plan in the area. Different street lane closure locations are marked in the figure using the star icon. Figure 2 also presents the selected locations for the traffic survey cameras (using the camera icon), and the identified sensitive locations (represented by “L”).

Figure 2. Project plan view representing traffic directions, grade separation construction elements, and sensitive locations.

3.2. Regional traffic recognition

Traffic information provided by Dezful municipality and direct field data collection using HD cameras was used for regional traffic recognition. Cameral set points were determined in consultation with the experts from the municipality. Figure 2 presents the locations of HD cameras. The focus of traffic recognition, however, was on-peak hours, i.e., from 8 pm to 9 pm. The distribution of vehicle type, rate of vehicle arrival to the square, and exit rate of the vehicles for different roads were identified. Table 1 represents the gathered traffic statistics.

Table 1. Traffic information of the project area in brief

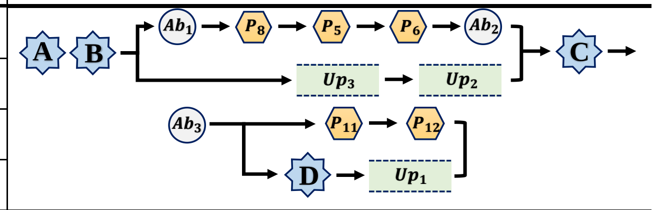
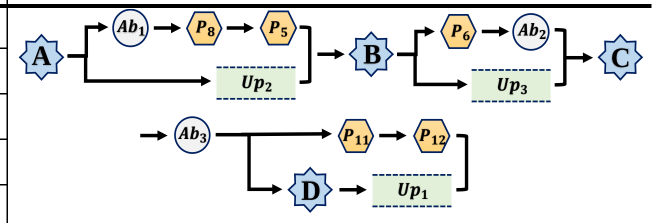
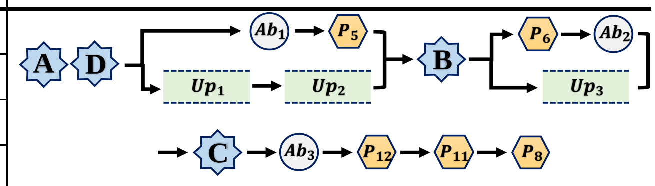
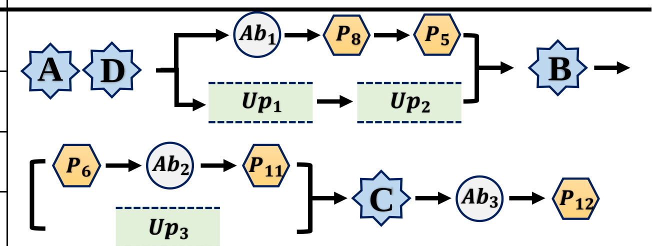
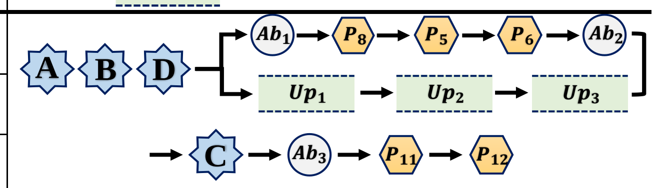
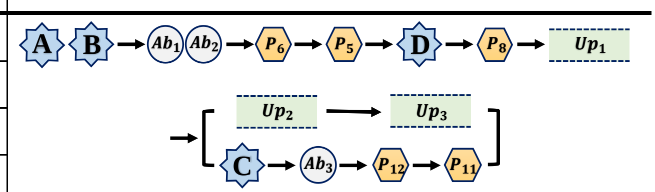
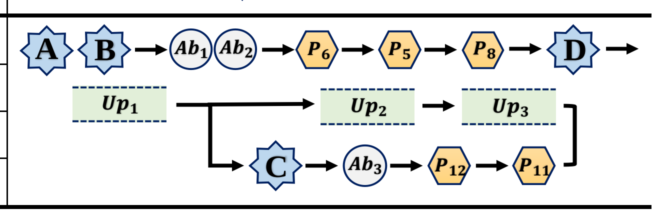
		Fatholmobin St (North of square)	Moghavemat St (South of square)	Police St (East of square)	Taleghani St (West of square)	Montazeri St (South of square)	Moallem St (Southeast of square)
Number of Vehicle Lanes		3	3	3	3	1	3
Input Volume (Vehicle / Hour)		1350	1554	636	468	80	400
Vehicle Types	Light Vehicle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

3.3. Sensitive location identification

The field survey conducted in the area identified two sensitive locations in the neighborhood. A park and green area in the south-east part of the square, location L1, and a famous old café in the town on the north-west of the square, location L2. Figure 2 marks the identified sensitive locations.

3.4. Lane closure scenarios

Seven available construction schedule scenarios were accounted for the project. Each alternative scenario required its particular street lane closure sequence causing different traffic formation throughout the project. Figure 3 represents the resulting street partial lane closure schedules of different schedule scenarios. Dezful municipality selected Scenario 7 as the preferred grade separation construction scenario. Therefore, this scenario was considered as the base scenario to be compared with other alternative scenarios.

Scenario	Lane Closure *	Start	Finish	Duration (Month)	Construction Interval*
1	No lane closure	18/12/2017	13/01/2018	0.9	
	A + B	13/01/2018	23/01/2018	0.3	
	A + B + C	23/01/2018	21/06/2018	5.0	
	A + B + C + D	21/06/2018	10/06/2019	11.8	
2	No lane closure	18/12/2017	24/01/2018	1.2	
	A	24/01/2018	27/01/2018	0.1	
	A + B	27/01/2018	10/03/2018	1.4	
	A + B + C	10/03/2018	12/02/2019	11.3	
	A + B + C + D	12/02/2019	10/06/2019	3.9	
3	No lane closure	18/12/2017	27/01/2018	1.3	
	A + D	27/01/2018	08/02/2018	0.4	
	A + D + B	08/02/2018	20/02/2018	0.4	
	A + D + B + C	20/02/2018	10/06/2019	15.8	
4	No lane closure	18/12/2017	27/01/2018	1.3	
	A + D	27/01/2018	27/03/2018	2.0	
	A + D + B	27/03/2018	27/08/2018	5.0	
	A + D + B + C	27/08/2018	10/06/2019	9.7	
5	No lane closure	18/12/2017	24/01/2018	1.2	
	A + B + D	24/01/2018	12/11/2018	9.6	
	A + B + D + C	12/11/2018	10/06/2019	7.1	
6	No lane closure	18/12/2017	24/01/2018	1.2	
	A + B	24/01/2018	21/06/2018	4.9	
	A + B + D	21/06/2018	12/11/2018	4.7	
	A + B + D + C	12/11/2018	10/06/2019	7.1	
7	No lane closure	18/12/2017	24/01/2018	1.2	
	A + B	24/01/2018	04/09/2018	7.4	
	A + B + D	04/09/2018	08/11/2018	2.2	
	A + B + D + C	08/11/2018	10/06/2019	7.1	

*Same legend as Figure 2 is adopted for all symbols

Figure 3. Partial lane closure schedule in alternative scenarios

3.5. Project traffic simulation

PTV-VISSIM simulation package was used in this research to simulate the traffic flow. This simulation package has previously been used in different research efforts dealing with traffic flow simulation (e.g., Borrego et al., 2016; Fallah-Shorshani et al., 2017; Alvanchi et al. 2019). PTV-VISSIM simulation package uses the microsimulation approach to incorporate traffic flow specifications such as road geometry, vehicle volumes, and vehicle modal splits, in the simulation model. In this simulation approach, the effects of every single element within the system are separately captured (Khavas et al., 2017). EnViVer add-on module in PTV-VISSIM was employed for estimating the resulting air pollution from on-road traffic. This add-on uses modal emission values of different vehicle categories to determine the emission.

In the simulation model, street lanes are the main model resources. The lane closure condition received from the project planning team controls the resource constraint, on-road traffic, and the resulting air pollution. Therefore, the simulation model was separately developed for each lane closure condition. Every construction schedule scenario contains a specified combination of lane closure conditions in different periods as presented in Figure 3. Consequently, air pollution concentration of each construction scenario was calculated based on the weighted average of air pollution concentration of different lane closure conditions in the scenario. The closure duration of each lane closure condition was taken as the weight of each lane closure condition in the averaging operation. A similar approach was also followed in the calculation of air pollution concentration near sensitive locations. Equation 1 presents the adopted averaging operation for air pollution concentration in different scenarios.

$$\text{Air Pollution Scenario}_i = \frac{\sum_{j=1}^{n} \text{Lane Closure Combintation}_{ij} * \text{Duration of Lane Closure}_{ij}}{\sum_{j=1}^{n} \text{Duration of Lane Closure}_{ij}} \tag{1}$$

i: Scenario number

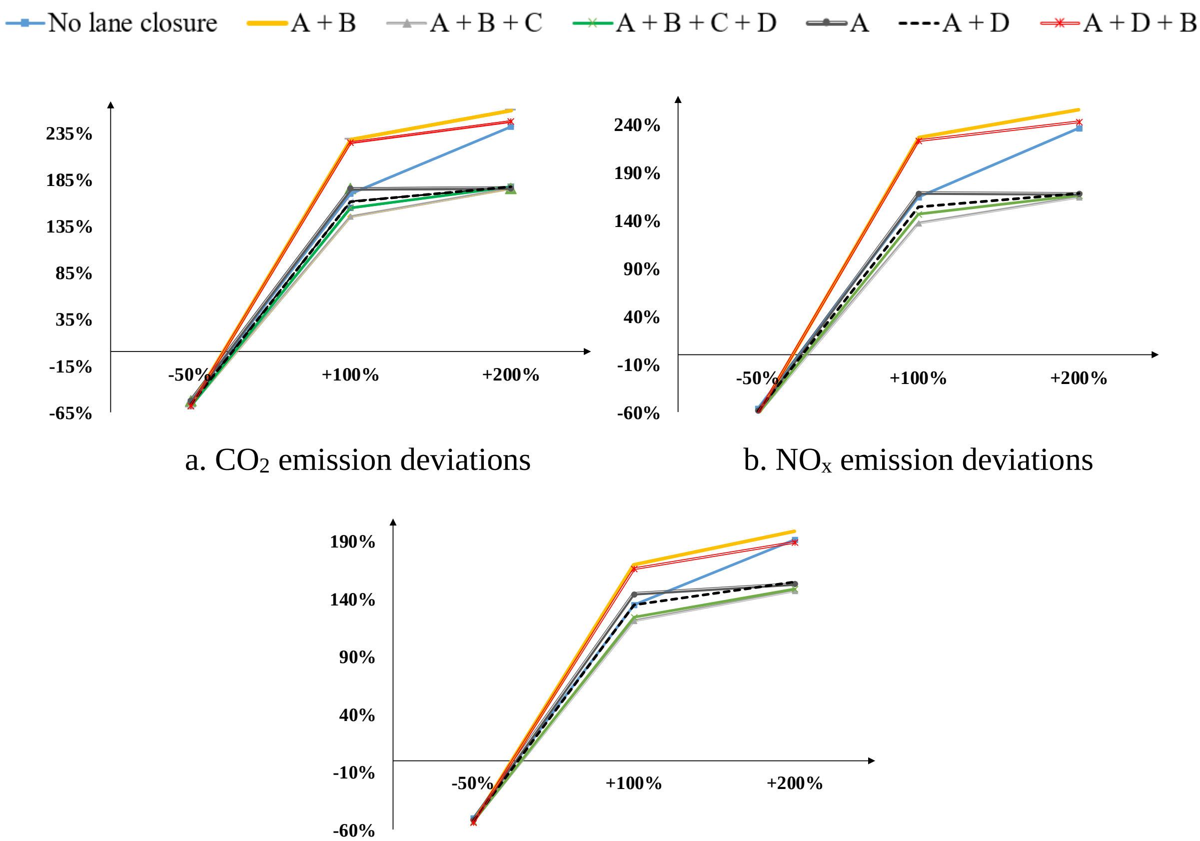
j: number of the lane closure set up

Air Pollution Scenario$_i$ = *Calculated air pollution concentration for the* i^{th} *construction schedule scenario*

$\text{Lane Closure Combintation}_{ij}$ = j^{th} *lane closure set up considered in the* i^{th} *construction schedule scenario*

$\text{Duration of Lane Closure}_{ij}$ = *Scheduled duration for the* j^{th} *lane closure set up considered in the* i^{th} *construction schedule scenario*

Before applying the developed simulation models in the case study, the model was tested following verification and validation steps for simulation models as recommended by Sterman (2000) and Banks et al. (2005). The experts from the municipality were involved in different parts of the simulation model development. The sensitivity of the emission deviations in response to the 50% decrease, 100% increase, and 200% increase in the rate of the vehicle input to the Square was tested for different lane closure conditions. All achieved emission deviations in different lane closure conditions complied with the direction of changes in the vehicle input to the Fatholmobin Square. Figure 4 represents the obtained results in different lane closure conditions for three air pollutants of CO_2, NO_x, and PM_{10}, considered in this research.



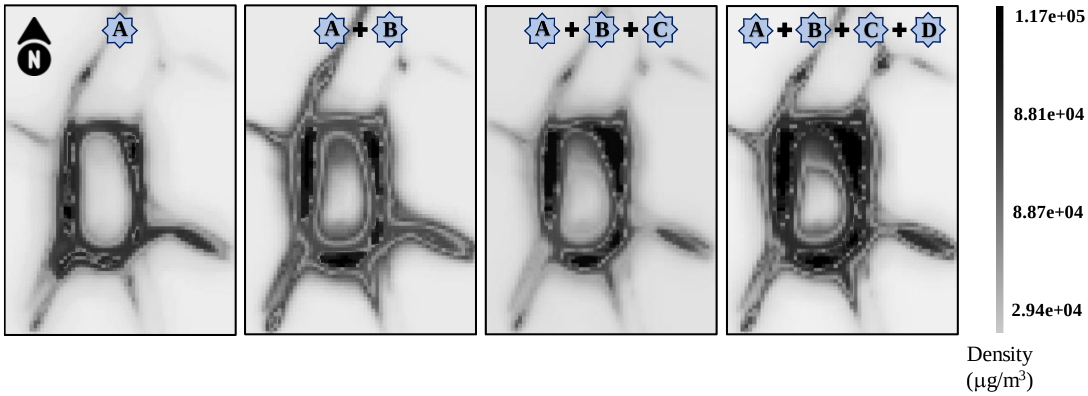
a. CO_2 emission deviations

b. NO_x emission deviations

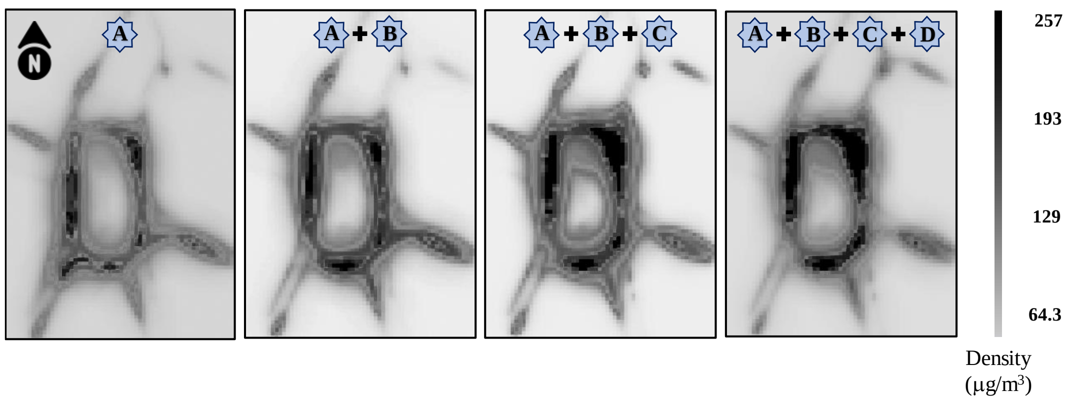
c. PM_{10} emission deviations

Figure 4. The sensitivity of the overall emission from on-road traffic to the deviations of the input vehicles

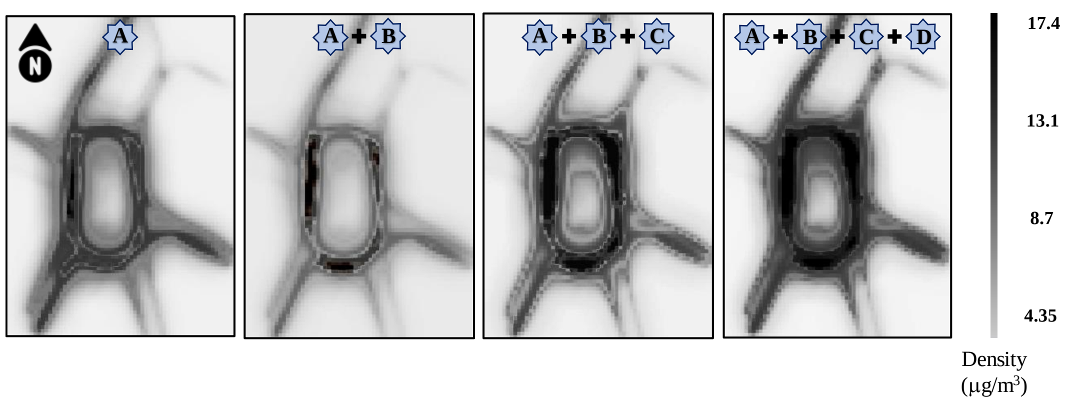
In another set of verification tests, the sensitivity of the simulation model was tested to the increased number of the lane closure. Figure 5 represents air pollution concentration from incremental lane closure in the construction zone. Areas with the darker colors in the diagram represent the higher air pollution concentration. This sensitivity analysis followed the expected trend for all three accounted air pollutants of CO_2, NO_x, and PM_{10}.



a. CO_2



b. NO_x



c. PM_{10}

Lane Closure Area

Figure 5. Air pollution concentration deviation in the construction zone in response to the incremental lane closure condition

The achieved results from complete road blockage were also analyzed in the simulation model as an extreme condition test (Sterman 2000, pp. 869-872). Expectedly, the complete road blockage increases air pollution as a result of additional restrictions created for the traffic flow in the region. In this test, first, the complete blockage of "road A" was assessed. Then, concurrent blockade of roads A+B+D was simulated. The achieved results followed the expectation and indicated air pollution increase under extreme conditions. The pollution was increased by adding the number of blocked roads. Figure 6 represents the achieved emissions for these two road blockage setups. Furthermore, different parts of the developed simulation model were shared and verified with the project crew to test the reasonability of the achieved results (Banks et al. 2005, p. 317).

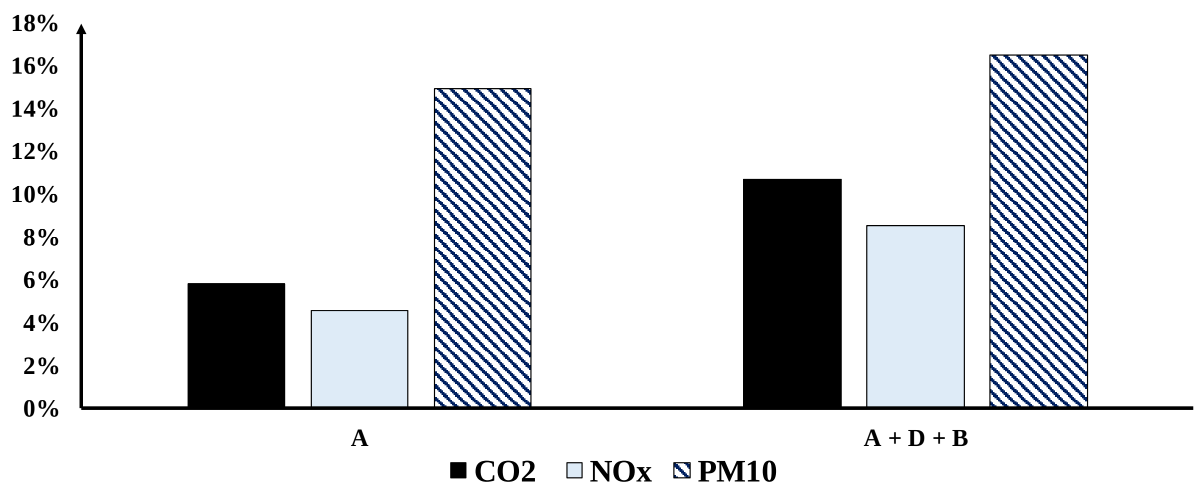
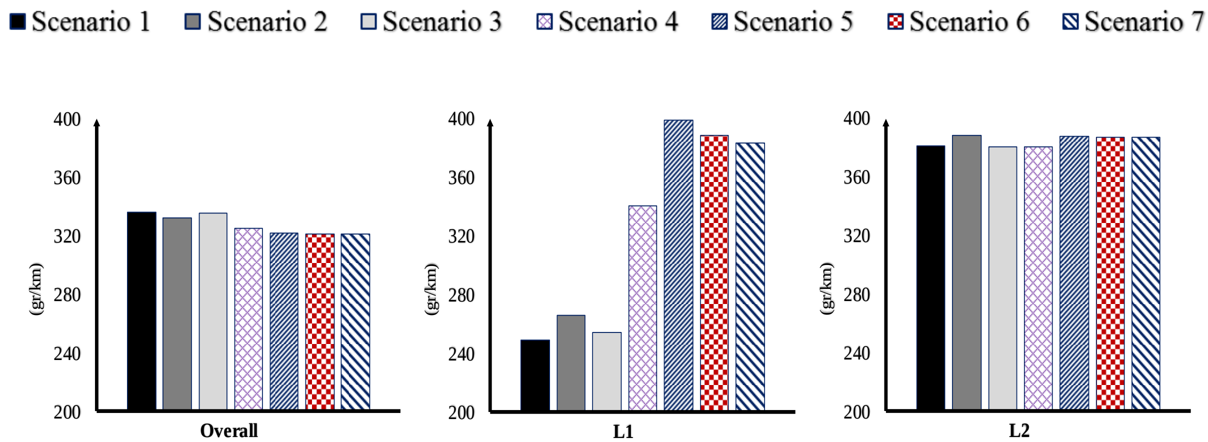


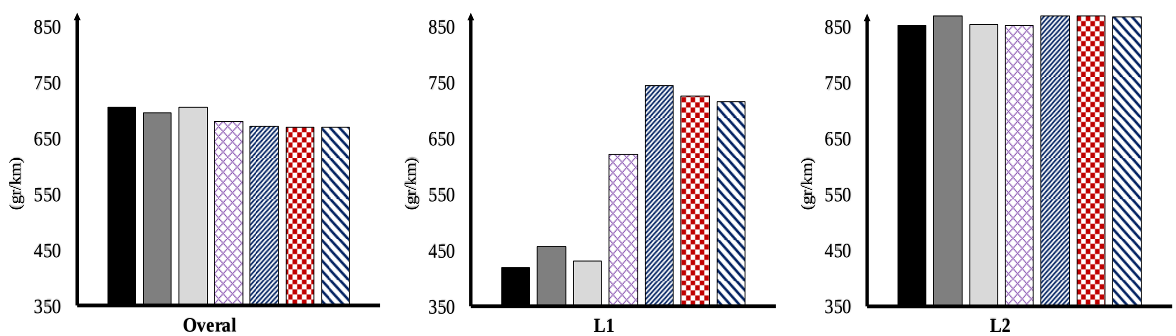
Figure 6. Emission deviations in complete blockage test for two states of lane closure

3.6. Emission Results

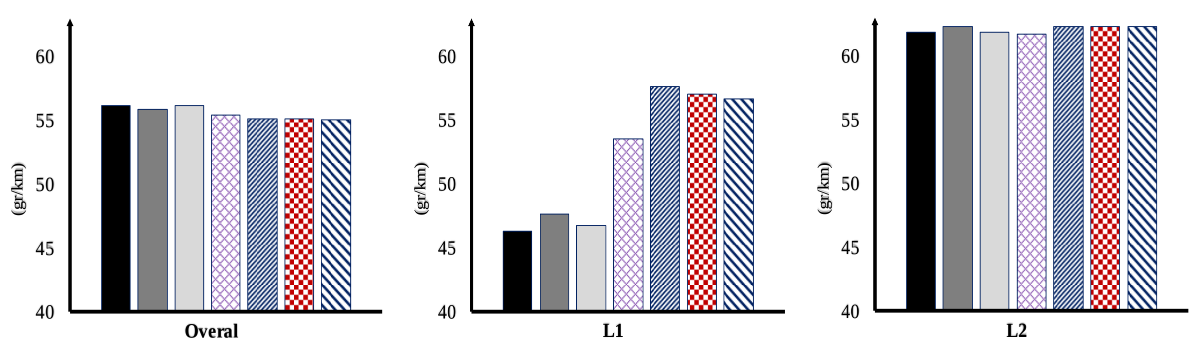
Overall, air pollution emission and air pollution concentration near sensitive locations of L1 and L2 for CO_2, NO_x, and PM_{10} pollutants were the output results of the simulation models as represented in Figure 7. Pollution emission output values from EnViVer were represented in gram per kilometer (gr/km), as the default form of the model outputs. Vehicle volumes and vehicle modal splits were identified as random variables with uniform distribution. To capture the incorporated randomness in the simulation model, the reported results were calculated as the average of 30 different simulation runs. High fluctuations were detected between overall emissions, emissions near location L1 and emissions near location L2 in different scenarios. Figure 7 represents the achieved results in different scenarios.



a. CO_2



b. NO_x



c. PM_{10}

Figure 7. Pollutant emission in each scenario

The ultimate goal of the proposed framework was to determine the construction scenario with the least combined overall air pollution emission and air pollution concentration near sensitive locations. Therefore, importance weights were required for the overall and location-based air pollution concentration to calculate the resulting air pollution concentration of each air pollutant in every scenario. The project management team considered 50% importance weight for the overall pollution emission and 50% importance weight for the pollution concentration near sensitive locations. The assigned importance weight was evenly distributed between sensitive locations since similar sensitivity was assumed for both locations. Therefore, the resulting air pollution concentration of each air pollutant in each construction scenario was calculated as a simple averaging of the achieved results as presented in Equation 2.

$$RAP_{ij} = 50\% * OAP_{ij} + 25\% * L1AP_{ij} + 25\% * L2AP_{ij} \quad (2)$$

RAP_{ij} = Resulting Air Pollution Concentration of Pollutant j in Scenario i

OAP_{ij} = Overall Air Pollution Emission of Pollutant j in Scenario i

$L1AP_{ij}$ = Air Pollution Concentration of Pollutant j in Scenario I for sensitive location of L1

$L2AP_{ij}$ = Air Pollution Concentration of Pollutant j in Scenario I for sensitive location of L2

Table 2 presents the calculated resulting air pollution emission values of different air pollutants for the adopted construction scenarios. The achieved resulting values represent Scenario 1 with the least pollution emission for all three considered pollutants, followed by Scenario 3 and Scenario 2, respectively, at the second and third places. The achieved resulting values represent potential emission reduction of 7.8% for CO_2, 8.2% for NO_x and 3.8% for PM_{10} from Scenario 1 to Scenario 7 or the base scenario.

Table 2. Air pollution emission values calculated for different scenarios

	Scenario	**1**	**2**	**3**	**4**	**5**	**6**	**7**
CO_2 Concentration (gr/km)	Overall (50% weight)	336.0	332.0	335.6	325.4	321.9	321.5	321.4
	L1(25% weight)	248.8	265.9	254.2	340.4	399.1	388.6	383.3
	L2 (25% weight)	381.5	388.2	380.9	*380.6*	387.5	387.1	386.9
	Resulting Value	***325.6***	**329.6**	**326.6**	**343.0**	**357.6**	**354.7**	**353.2**
NO_x Concentration (gr/km)	Overall (50% weight)	706.4	696.7	705.8	680.7	671.5	670.5	670.0
	L1(25% weight)	419.7	457.1	431.8	622.3	744.6	725.3	715.6
	L2 (25% weight)	853.5	870.8	854.4	853.7	870.2	869.5	869.1
	Resulting Value	***671.5***	**680.3**	**674.5**	**709.4**	**739.4**	**734.0**	**731.2**
PM_{10} Concentration (gr/km)	Overall (50% weight)	56.2	55.9	56.2	55.4	55.1	55.1	55.1
	L1(25% weight)	46.2	47.6	46.7	53.5	57.7	57.0	56.7
	L2 (25% weight)	61.8	62.3	61.8	61.7	62.3	62.3	62.3
	Resulting Value	***55.1***	**55.4**	**55.2**	**56.5**	**57.6**	**57.4**	**57.3**

3.7. Discussion

The achieved results represented relatively slight deviations in the overall air pollution emission from on-road traffic in different construction scenarios for all three accounted air pollutants. A similar trend was repeated for air pollution concentration near the sensitive location of L2. However, high deviations were received in the air pollution concentration near the sensitive location of L1. Therefore, the achieved pollution concentration near the sensitive location of L1 drove the calculated resulting values in different scenarios. Scenarios 1, 3, and 2, which respectively demonstrated the least resulting air pollution concentration, represented the least air pollution concentration near location L1 (Figure 7). For example, overall NO_X emission from on-road traffic represented a 5.4% increase in Scenario 1, with the least achieved resulting value for air pollution concentration, compared to Scenario 7, or the base scenario. Slight decrease close to 1.8% was observed in NO_X concentration near the sensitive location of L2 in Scenario 1 compared to Scenario 7. However, NO_X concentration represented the maximum decrease of 41% from Scenario 1 to Scenario 7 near the sensitive location of L1. Consequently, the achieved result indicated a potential room for up to 8.2% reduction in the resulting NO_X air pollutant concentration by adopting the proper construction schedule. The result affirmed the impact of the construction schedule on the air pollution concentration during the construction period of the studied grade separation project.

4. Conclusions

The recent improvement in the computer-based technologies has created new opportunities for analyzing new aspects of construction projects which could not be done previously. This research used the capabilities of microsimulation to tackle an absent aspect of urban infrastructure construction projects, i.e., on-road air pollution concentration. In this viewpoint, current research contributes to cleaner production by utilizing the construction project schedule as a tool for reducing air pollution in urban areas. Although the proposed framework was applied to a real grade separation project in Iran, no limiting assumption was considered in the case. The proposed framework can be implemented for urban construction projects forcing interruptions to the on-road traffic. Construction project managers can employ the framework for improving sustainability in urban areas. Implementation of the proposed framework is especially recommended for projects implemented in the populated urban areas with sensitive locations. Collecting field information and simulation model development, however, might impose additional costs on the projects. Furthermore, predicting impacts of the created restrictions in the construction zone on the travelers' behavior might be subject to inaccuracy. This inaccuracy can be transferred to the final achieved results of the framework implementation. Emissions from off-road construction equipment can also be affected by a developed project schedule. Nevertheless, current research only addresses emissions from on-road vehicles. Future research can augment the achieved results from the current research by integrating the impacts of the construction schedule on both on-road and off-road traffic.

5. Acknowledgment

We would like to show our gratitude to the PTV Group which kindly provided full-version of the PTV-VISSIM and EnViVer software packages in this project. We are also immensely grateful to the Magma Construction Company and the Behran Traffic Consulting Engineering

Company for providing traffic data. The authors also thank the Dezful Municipality for sharing their information during field studies.

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