Modeling Methods for Assessing the Ecological Impact of Road Maintenance Site

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Road transport is a major source of environmental pollution. Cars and trucks, which are the most common types of vehicles, exhaust a variety of pollutants (e.g. NOx and PM) that are detrimental to human health. Research on the ecological impacts of road vehicles has highlighted the importance of reducing pollutant emissions. This chapter aims to investigate the impacts of road maintenance sites on pollution in the surrounding environment, which is a slightly different and interdisciplinary aspect of the problem.

Road pavement and infrastructure (bridges, viaducts, and tunnels) must be maintained for the road network to function properly. Maintenance sites interrupt the normal flow of traffic, which leads to traffic jams, higher travel times, and pollutant emissions.

This chapter explores a variety of approaches to traffic emissions modeling to identify a numerical model capable of determining the ecological impacts of maintenance sites on the surrounding environment. A simple simulation will be conducted to demonstrate the importance of the subject. Research gaps are presented at the end of the chapter to guide future studies.

Keywords: Maintenance Sites, Traffic Modeling, Emissions Modeling, Environmental Impacts, Numerical Simulation

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1. Introduction

Although air quality has slowly improved in Europe, more than 400,000 premature deaths are annually attributed to air pollution in the continent (EEA, 2020). Therefore, air quality assessment through emission modeling is of great importance. Emission models determine the amounts of various pollutants emitted by vehicles in transportation facilities. Dispersion models are then employed to determine the concentration of a particular pollutant at a specific location and time. Then, exposure models are used to estimate exposure to air pollution (the number of individuals who inhale pollutants). The effects of the pollutant on the population (health effects) can then be calculated (health impact assessment) using the above information. Finally, the total economic effects of pollution are calculated using the combination of the effects of air pollutants on humans and the environment.

The transportation sector is a major source of air pollution, with Road Maintenance Sites (RMSs) releasing a considerable amount of emissions. Road maintenance comprises a wide range of activities that keep road structures and assets as close to their as-constructed or renewed conditions as possible (Wisconsin Department of Transportation, 2017).

By causing delays in traffic and increasing fuel consumption, road maintenance activities result in multiple environmental and ecological impacts. However, a limited number of studies have directly investigated the impacts of RMSs on emissions exhausted on roads and highways. In other words, the majority of previous studies have neglected the application of traffic emission modeling in investigating emissions exhausted by maintenance-related traffic. Moreover, some of these studies have reported conflicting results. Therefore, there is a need to thoroughly examine the impact of RMSs on the amount of traffic emissions to identify the best modeling methods and the most important factors and variables affecting the amount of emissions. This research aims to address the above gap and to assess the existing emission models to determine the environmental impact of RMSs. Thereby, this chapter offers recommendations on enhancing the accuracy of the existing models.

To investigate the environmental impact of RMSs on roads, the second section defines RMS activities and explores the different types of effects that RMS can have on the road network. The third section presents explanations regarding traffic simulation since the first step in estimating the environmental impact of RMSs is the calculation of their traffic impacts. The fourth part of this chapter consists of an introduction to various types of pollutants and how they are exhausted. Section 5 explores various approaches to traffic emissions modeling in different traffic conditions, mainly in the presence of RMSs. A simple simulation is also presented in section 6 to illustrate the negative environmental impacts of RMSs. Finally, suggestions are made to improve the performance of existing models (section 7).

2. Road Maintenance

Transport accounts for a quarter of greenhouse gas emissions, a figure that continues to rise as demand grows (European Commission, 2019). Demand for mobility will continue to grow over the next three decades. By 2030, annual passenger traffic will surpass 80 trillion passenger kilometers (fifty percent increase); global freight volumes will grow by 70 percent; and an additional 1.2 billion cars will be on the road by 2050 (double today's total) (The World Bank, 2017). Higher demand means higher levels of pollution and an increased need for infrastructure maintenance. As a result, modern societies are seeking to develop a sustainable transport sector in which less pollution is exhausted. Under current trends, road transport and private cars remain dominant and have an ever-greater role to play in meeting this additional demand. One way to develop a sustainable transport sector is to reduce road transport pollutants since road transport is responsible for more than 70 % of emissions (Alonso et al., 2019). RMS plays a major role in transport emission, which will be discussed below.

2.1. What is Road Maintenance and Why is it Important?

The Highway Capacity Manual (HCM) 2010 defines a work zone as "A segment of highway in which maintenance or construction operations reduce the number of lanes available to traffic or affect the operational characteristics of traffic flowing through the segment" (Transportation Research Board, 2010). Therefore, since an RMS is a subset of work zone segments, this chapter uses the word "RMS" instead of a "work zone".

Road maintenance activities are one of the main factors affecting the mobility of road networks. Although the cost of road maintenance activities is relatively high, such activities help avoid massive construction costs. Road maintenance activities are essential for a variety of reasons including safety, economic, environmental, and social well-being. In particular, such activities are important because they (O'Flaherty, 2001; PIARC, 2014):

- Promote road safety;
- Increase the availability and mobility of the transport network;
- Support the local and national economy by ensuring that freight and businesses can move efficiently and safely;
- Reduce vehicle operating costs;
- Improve travel time in the long-term; and
- Reduce vehicle emissions (by improving traffic conditions and vehicle speeds) in the long-term.

Therefore, road maintenance involves significant activities that lead to major advantages in the long run despite their short-term environmental impacts and costs. What follows presents the classification of road maintenance activities. Given the wide variety of such activities, it is beyond the scope of this chapter to provide an in-depth overview. The readers can refer to the relevant references cited below to find out more about each of these activities. It should be noted that given the purpose of the present chapter, which is to examine the environmental and ecological impacts of road maintenance activities, what matters is whether these maintenance activities result in lane closures. Previous surveys have shown that most pavement rehabilitation activities result in lane closures.

Road maintenance activities can be categorized based on 1. The road assets on which they are performed; 2. The type of activity being performed and 3. The time and period of the activity. The following presents a brief explanation of each category.

1- Road maintenance activities are classified by the road assets on which they are performed (Alberta Department of Transportation, 2000; Illinois D.O.T., 2008; Texas Department of Transportation, 2018; Shahin, 2005) into the following categories: pavement, roadside, bridge, traffic control, right of way, drainage, signs, safety items, and illumination activities.

2- Road maintenance activities are divided by the time and period of the activity into the following groups (Robinson et al., 1998; CIHT, 2012; Wisconsin Department of Transportation, 2017; CORNWALL Council, 2018):
   - Routine Maintenance: Activities, such as vegetation control, drain clearing, and culvert clearing, that are planned, scheduled and performed (sometimes annually) to maintain or preserve the condition of the highway system to achieve an adequate level of service.
   - Programmed Maintenance (Preventive Maintenance): Activities that form part of a capital program and are usually carried out according to a planned schedule. These activities promote system service life by preventing deterioration. Examples include surface dressing, resurfacing, and the strengthening or reconstruction of roads and footways.
   - Reactive Maintenance (Corrective Maintenance): These activities are carried out as a response to inspections, complaints, or emergencies. Examples include filling potholes, clearing, and restoring safety measures following traffic accidents. These activities cannot be scheduled with certainty in advance.
   - Emergency: These activities are intended as a response to severe weather and other emergencies affecting highway networks. Examples include snow removal and the removal of debris or obstacles left by natural disasters, etc.
   - Restorative Maintenance: These activities restore the pavement section to an acceptable service level by removing or repairing existing distress. Besides, such activities retain the existing pavement while increasing width throughout the length of the section. Restorative maintenance activities are not the same as preventative activities since they are performed on degraded pavements.

3- Road maintenance activities are classified into the following categories according to actions specific to seasonal weather conditions (Alberta Department of Transportation, 2000):
   - Winter maintenance (snow and ice control) activities such as snow plowing, sanding, snow removal, and snow fencing.
   - Spring clean-up activities such as sweeping, bridge washing, culvert/drainage clearing.
   - Summer surface maintenance activities such as dust control, line painting (center, shoulder, and lane lines), and message painting (stop bars, pedestrian crosswalks).

2.2. What Are the Impacts of Road Maintenance Sites on the Road Network?

RMSs can be divided into short-term and long-term sites based on the duration of their activities. The longer the duration of the activities, the higher their environmental effects. The presence of RMSs on roads causes numerous changes in road conditions. The effects of RMS on the road network in the short term include (Robinson et al., 1998):

1. Higher Level of Service (LOS)
2. Higher road user and administration costs
3. Socio-economic impacts
4. Lower road safety
5. Environmental degradation (Pollutant emissions)

Since the objective of this chapter is to investigate the environmental and ecological impacts of RMSs, it only considers environmental-related impacts or impacts that lead to environmental and ecological issues (e.g. LOS, road safety, and pollutant emissions).

2.2.1 Level of Service (LOS)

As stated by HCM, LOS is “a quantitative stratification of a performance measure or measures representing the quality of service.” The existence of RMS causes changes in road LOS. In other words, RMSs may cause lane closure, road closure, and the reduction of lateral clearance between vehicles and roadside objects (Transportation Research Board, 2010). These circumstances influence capacity, speed, or both (which are indicators of LOS). How RMSs affect road capacity and vehicles speed depends on various factors such as heavy vehicle percentage (HVP), ramp, work zone speed, driver composition, weather conditions, work zone length, lane closure location, lane width, work time, work zone activity duration, number of closed lanes, number of opened lanes, road type, work zone intensity, and work zone grade (Weng and Meng, 2013). The impact of RMSs on capacity, speed, and road safety has been investigated by many studies. The most important of such studies are discussed below.

There are several approaches to the estimation of work zone capacity, which are categorized into parametric, non-parametric, and simulation groups. In parametric approaches, the predictor takes a predetermined form. Nonparametric approaches do not assume that the structure of a model is fixed (e.g. artificial neural network etc.).

HCM is one of the most important authorities on how to calculate LOS for highway facilities. The manual states that work zones (RMSs) affect the capacity and speed of vehicles as well as the speed-flow relationship. The impact of RMSs on capacity is different from their impact on speed. The impact of RMSs on capacity and speed in HCM is estimated using the parametric approach. In what follows, the impacts of RMS on capacity and speed are discussed separately.

The following factors should be specified to determine the impact of RMSs on capacity: Lane closure type (e.g., shoulder closure, three-to-two lane closure), barrier type, area type, lateral distance, and time of the day (daytime or nighttime). First, the Lane Closure Severity Index (LCSI) must be calculated by specifying the ratio of the number of open lanes during road work to the total (or normal) number of lanes (decimal) and the number of open lanes in the work zone. Then, barrier type (concrete and hard barrier for the long term; cone, plastic drum, or soft barrier for the short term), area type, lateral distance, time of the day (daytime or nighttime), and the amount of Queue Discharge Rate (QDR) is calculated using the LCSI value. Finally, the amount of capacity at RMS can be obtained by using QDR and the percentage of capacity reduction before breakdown. When using this methodology, the calculated capacity should not be greater than the capacity of the non-work zone.

RMSs also affect the free-flow speed (FFS), which cannot be calculated using equations developed for non-work zones. To obtain FFS at RMSs, we need an equation that takes the ratio of the non-work zone speed limit to the work zone speed limit, the work zone speed limit, lane closure severity, barrier type, time, and total ramp density into account. The work zone speed limit has a direct relationship with FFS at RMSs while, LCSI, ramp density, soft barrier type, and time of the day (night time) have an indirect relationship with FFS at RMSs.

The above HCM methodology, as well as estimates by previous studies, can be employed to calculate the ratio of capacity and free-flow speed in the RMS condition to the non-RMS condition (the capacity reduction factor and the free-flow speed reduction factor). The results show that the capacity reduction factor for different work activities is from 0.68 to 0.95, while the free-flow speed reduction factor is from 0.78 to 1.0 (Edara et al., 2018).

A review of the effects of RMSs on capacity and speed reported by previous studies reveals that the presence of RMSs causes reductions in capacity and speed, which consequently leads to lower LOS and higher traffic congestion (Transportation Research Board, 2016).

2.2.2 Road Safety

The presence of RMS affects road safety in two ways: 1- Through speed changes in the RMS sections (since speed is one of the most critical factors in road safety (Bamdad Mehrabani and Mirbaha, 2018)) 2- Through the threat it poses to workers. Although the data available for RMS crashes is limited and incomplete, previous studies have indicated that crash rates at RMSs are generally higher than non-RMS locations (Paolo and Sar, 2013). The majority of previous studies have concluded that the presence of a work zone (RMS) increases both crash severity and crash rate (Yang et al., 2015).

Some types of collisions are more likely to occur at RMSs. Previous research indicates that rear-end crashes are more common at RMSs, which is due to higher speeds at the beginning of RMSs compared to the temporary speed limit. Drivers reduce their speeds only when the lane width is reduced, resulting in high deceleration rates and a higher likelihood of rear-end crashes (Paolo and Sar, 2013). The main factors contributing to road crashes at RMSs are as follows:

- **Driver Expectations**: In many cases, drivers do not expect the presence of RMSs due to improper road signage
- **Roadside Hazards**: Occasionally, the configuration of tools, signs, and maintenance vehicles leads to collisions
- **Driver Behavior**: Driver behavior is one of the most important contributing factors in all types of crashes, including RMS collisions. For instance, whether a driver is a commuter or not might affect driving behavior at RMSs.

- **Unsuccessful Mitigation Strategies**: Although strategies have been developed to increase RMS safety, some measures might actually increase the risk of collisions.
- **Roadway Characteristics**: Road features such as lighting and pavement conditions are among the most critical factors in increasing crash risk at RMSs.
- **Environmental Conditions**: Weather conditions, driver visibility, etc., have a significant impact on crash risk.
- **Secondary Crashes Caused by Roadway Incidents**: Crashes occurring within the work zone may contribute to congestion and aggressive driving, leaving the upstream roadway susceptible to additional incidents. On the other hand, the crash rate in the congested traffic flow condition is nearly three times higher compared to the non-congested condition (at RMSs) (Waleczek et al., 2016).
- **Combined Effects**: Previous studies have shown that combined effects such as the combination of light conditions and weather conditions are among the most critical factors for RMS safety (Ghasemzadeh and Ahmed, 2019).

2.2.3 Pollutant Emissions

The transport sector is responsible for around 26% of the overall Greenhouse Gas (GHG) emissions in Europe (Nocera et al., 2018), 70 percent of which is attributed to road transport. Emissions exhausted by road maintenance activities constitute the second most crucial factor in GHG emissions caused by roads (Deng, 2010). Therefore, it is important to examine the factors affecting such emissions caused by such activities.

RMSs usually lead to the closure of several lanes or the whole road, which severely impacts the transport network. Such impacts cause delays in traffic flow, which leads to additional emissions. On the other hand, road maintenance activities themselves produce emissions through fuel consumption by the maintenance equipment. Therefore, the existence of RMSs causes extra emissions in the road environment in two ways (Figure 1): 1- Emissions caused by on-site activities and 2- Emissions exhausted by delayed traffic due to lane closure

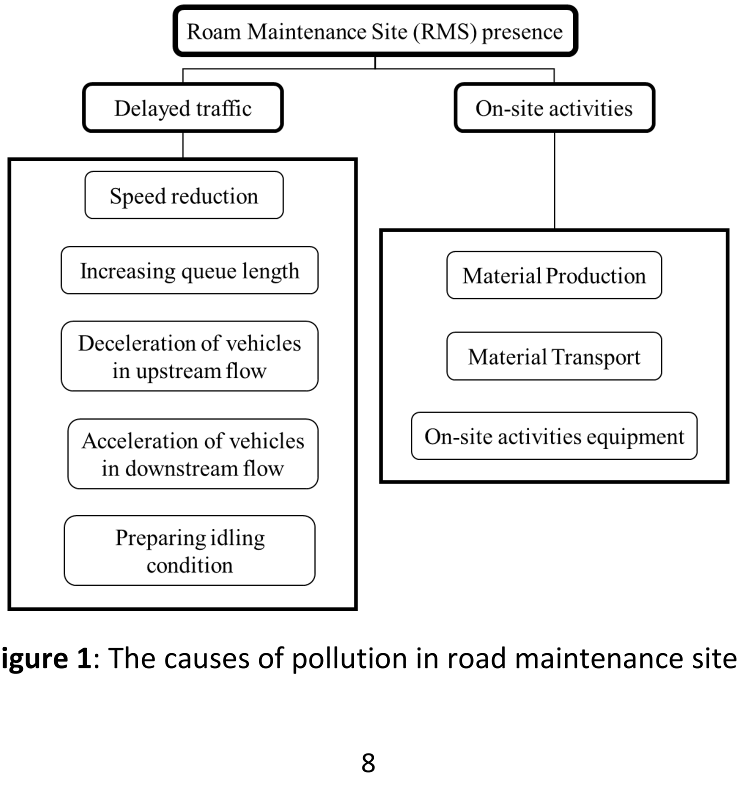

Figure 1: The causes of pollution in road maintenance sites

Numerous models have employed speed and queue length, which are significant traffic-related factors, as criteria for evaluating vehicle emissions. As mentioned in the previous section, vehicle speed decreases at maintenance sites. Previous studies indicate that higher traffic flow speeds (up to 60 km/h) lead to lower fuel consumption and vehicle emissions. Thus, the speed reduction in RMSs leads to extra emission. The relationship between speed and fuel consumption is shown in Figure 2.

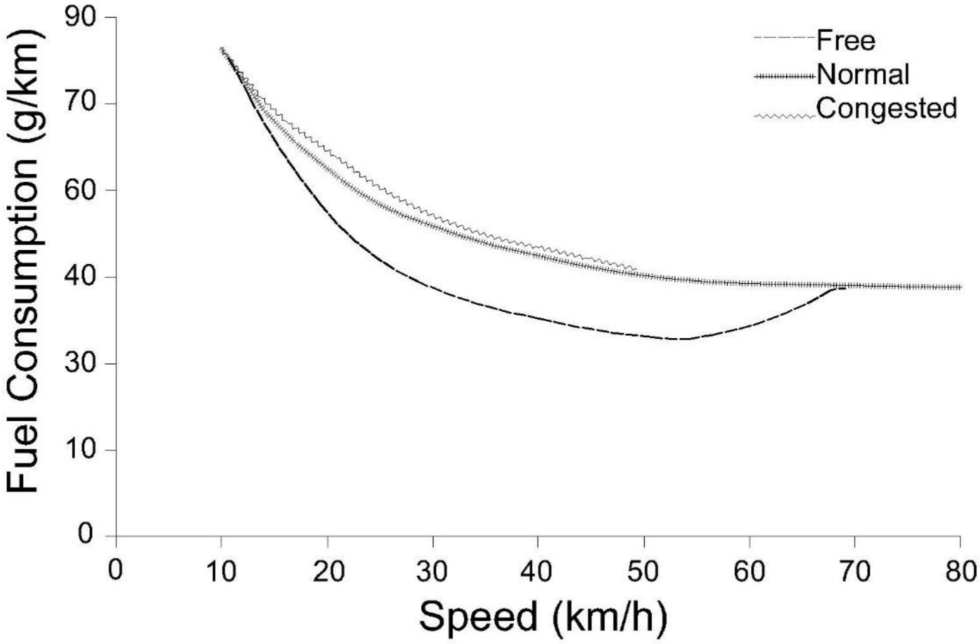

Figure 2: Fuel consumption factors for free and congested traffic (Samaras et al., 2019)

Another traffic-related factor affecting vehicle emissions at RMSs is queue length. Vehicle emissions are highest under long queue length and congested traffic flow conditions (Dong et al., 2019; Lizasoain-Arteaga et al., 2020; Pandian et al., 2009).

In addition, the vehicle speed is decreased (deceleration) when approaching an RMS and increased (acceleration) once the queue starts to discharge (outside the RMS). Acceleration increases pollutant emissions, especially at high speeds when the engine and emissions control systems are highly loaded. On the other hand, the emissions and fuel consumption rates of decelerating vehicles are independent of speed.

Another aspect of emissions caused by RMSs is the on-site activities themselves. On-site activities cause emissions in three ways: 1-Material production, 2-Material transport, and 3-equipment and machines. To estimate material production emissions, an emissions factor, which is available for each material type, is multiplied by the amount of material (Liu et al., 2019; Liu et al., 2018). In addition, fuel consumption by construction equipment such as bulldozers and excavators is used to calculate the amount of emissions exhausted by the transport of materials and operations performed at RMSs. However, previous research (Huang et al., 2009) suggests that on-site activities constitute a small fraction (e.g., less than 10%) of the total energy consumption and pollutant emissions at RMSs. Therefore, this chapter does not consider the effects of on-site activities.

Among the impacts of RMSs on the road network described above, this chapter investigates the environmental effects of RMSs. Delayed traffic emissions are the most important factor in investigating the environmental impacts of RMSs. Delayed traffic caused by such sites has a variety of effects on the environment, which can be measured through traffic simulation. The following section provides a brief explanation of various approaches to traffic simulation.

3. Traffic Simulation

3.1. What is Traffic Simulation Modeling and Why do We Need it?

Researchers have long employed simulation as a powerful tool for simplifying reality. May (1990) defines simulation as a “numerical technique for conducting experiments on a digital computer.” Simulations employ mathematical models and might include microscopic or macroscopic stochastic characteristics. Simulation is a viable alternative to analytical models since such models have the highest degree of simplification in model representation.

On the other hand, traffic systems are very complex, nonlinear, and affected by multiple external and internal factors. Thus, there is a need to simplify reality to evaluate different options and scenarios. Simulation is capable of assessing the performance of several alternatives, supplied externally to the model by the decision-maker.

3.1.1 The Definitions and Assumptions of Microscopic, Mesoscopic, and Macroscopic Traffic Simulation

Based on the intended application, there are three distinct approaches to simulation: 1- Microscopic, 2- Macroscopic, and 3- Mesoscopic. The main differences between these approaches are the level of aggregation and the trade-off between optimizing simulation speeds and estimating traffic states (or traffic phenomena) as accurately as possible. These approaches are briefly described in what follows.

- **Microscopic Traffic Simulation Modeling**: This approach considers the dynamics of individual vehicles (or the response of individual drivers). Microscopic traffic simulation modeling is based on the description of the motion of individual vehicles in the traffic stream. In other words, microscopic models consider the interactions of *individual* vehicles. Information considered by these models includes acceleration, deceleration, speed, and the lane-changing behavior of individual vehicles. Microscopic models describe vehicles (as well as their drivers) individually in the form of varying characteristics and multiple classes. This type of simulation takes highly detailed information from road sections into consideration and is usually used for modeling on the street or intersection level. Microscopic parameters for describing traffic flow are headway, gap, and occupancy.
- **Macroscopic Traffic Simulation Modeling**: These models are the aggregated versions of microscopic models. Macroscopic models are based on the aggregate behavior of the traffic flow and do not consider individual vehicles. Instead of tracking vehicles on an individual level, macroscopic simulations take place on a section-by-section basis, which is why they are employed by studies that address the behavior of the entire transport network. The variables employed by macroscopic models are general descriptors representing traffic conditions as flows at a high level of aggregation without distinguishing their parts. Macroscopic parameters, which characterize the traffic stream as a whole, are volume (rate of flow), speed, and density.
- **Mesoscopic Traffic Simulation Modeling**: These models combine some of the characteristics of macroscopic and microscopic models. Mesoscopic models consider most parameters at a high level of detail but describe the activities and the interactions between vehicles at a much lower level of detail compared to microscopic

models. Mesoscopic models assume that vehicles move together as packets or platoons. The simulation of the flow of buses on a Bus Rapid Transit (BRT) lane is an example of mesoscopic simulation.

4. Pollution

Although the transportation sector creates economic value by increasing mobility, it leads to environmental issues such as pollution. Water, soil, and air pollution are three main types of contamination resulting from the activities of the transportation sector. Transport has long been a significant source of air pollution and, consequently, there is substantial concern over the effects of transport emissions on human health.

RMSs usually lead to air pollution, rather than soil or water pollution. To explore the environmental effects of RMSs more accurately, various types of contaminants, especially those emitted by RMS, are discussed below.

4.1. What Are the Different Types of Air Pollution?

Air pollution can be defined as "the presence of any liquid, solid, or gas compound in the atmosphere at such concentration values that can directly or indirectly affect humans, animals, and/or plants." (Hussain and Keçili, 2020). There are two types of air pollutants: primary pollutants and secondary pollutants. Primary pollutants are compounds that are emitted as such (i.e. they are directly emitted in the atmosphere). Secondary pollutants are formed through chemical reactions in the atmosphere (i.e. they are formed indirectly). Most of the pollution caused by the transportation sector results from primary pollutants.

Four major types of sources that contribute to air pollution are stationary sources (those that are fixed in location), mobile sources (primarily transportation), fires, and biogenesis (naturally occurring emissions) (USEPA, 2018). Each of these sources produces different types of pollutants. Nevertheless, the National Ambient Air Quality Standards (NAAQS) recommends that the following criteria air pollutants be taken into account by air pollution studies (U.S. Environmental Protection Agency, 2016): Lead (Pb), Carbon Monoxide (CO), Oxides of nitrogen (NOx), Volatile Organic Compounds (VOCs), Sulfur Dioxide (SO2), and Particular Matters(PM). The following is a brief description of each of the six criteria pollutants.

- **Lead (Pb)**: Lead is a soft, blue-gray metal, usually found in the form of lead compounds.
- **Carbon Monoxide (CO)**: CO is a toxic, colorless, and odorless gas, which is generated through the incomplete combustion of hydrocarbons. The amount of produced CO depends on the air to fuel ratio (A/F) in the combustion process.
- **Oxides of Nitrogen (NO_X)**: Mixtures of nitrogen monoxide and nitrogen dioxide –Σ(NO, NO_2) – are generally described as nitrogen oxides (NO_x). NOx is produced during combustion.
- **Volatile Organic Compounds (VOCs)**: VOCs react with NOx to form ozone. Hydrocarbon (HC) emissions, which are classified as Volatile Organic Compounds (VOCs), are a result of incomplete combustion and fuel evaporation.
- **Sulfur dioxide (SO_2)**: The compound is emitted by sulfur-containing fuels such as coal and oil. It is colorless and has a sharp nasty smell.
- **Particulate Matter (PM)**: Particulates are fine particles of material suspended in the air. Particulate matter is produced by industries, natural sources, motor vehicles,

agricultural activities, mining and quarrying, and wind erosion. Primary particles are emitted directly from sources such as construction sites, unpaved roads, fields, smokestacks, and fires. Secondary particles are generated through reactions between sulfur dioxides, nitrogen oxides, and other compounds in the atmosphere. Most fine PMs are secondary particles. Criteria matters are categorized into two groups. 1- Particulate matter with a size of 10 microns or less (PM10), and 2- Particulate matter with a size of 2.5 microns or less (PM2.5).

4.2. What Types of Air Pollution are Caused by Road Maintenance?

Pollution emitted by the transportation sector is commonly referred to as mobile source air pollution, which includes pollution emitted by aircraft, commercial marine vessels, locomotives, nonroad equipment, and on-road vehicles (USEPA, 2018). On-road vehicles, which are investigated by the present research, emit pollutants in three ways (Tsanakas, 2019): 1- Exhaust emissions (CO_2, CO, NO_x, HC, PM, etc.): Emissions produced primarily from the combustion of petroleum products such as petrol, diesel, natural gas, and liquefied petroleum gas; 2- Evaporative emissions (HC, VOC, etc.): Vapors that are emitted by fuel and engine systems; and 3- Tire and clutch abrasion (PM, etc.): The mechanical abrasion and corrosion of vehicle parts (tires, brakes, and clutch), the road surface wear and the corrosion of the chassis.

The role of RMSs in causing pollution is similar to that of other subsets of the transportation sector. As mentioned in section 2, RMSs can emit pollution in two ways: 1- Through delayed traffic and 2- Through on-site activities. Delayed traffic (mobile sources) exhausts significant amounts of only four of the six criteria pollutants; VOC, CO, NO_x, and PMs (Kutz, 2004; Meyer and Elrahman, 2019). As a result, the majority of studies on vehicular emissions (Lizasoain-Arteaga et al., 2020) have evaluated the above four pollutants to measure air pollution. On the other hand, the primary source of pollution emitted by on-site activities is fuel consumption by equipment and machines employed at the site. Therefore, the type of emissions caused by on-site activities is similar to the type of emissions produced by delayed traffic. However, previous studies have recommended that the following six pollutants be examined to enhance the accuracy of life-cycle assessment studies (Lizasoain-Arteaga et al., 2020): CO_2, CO, NO_x, CH_4, C_6H_6, NH_3, VOC, and PM2.5.

5. Modeling Approaches

Emissions modeling, which is described below, is the first step in evaluating the health and economic effects of air pollutants. The amount of exhausted emissions caused by RMSs can be calculated using traffic emissions models. To more precisely examine various approaches to modeling, section 5.1 introduces traffic emissions modeling methods and section 5.2 presents the models that analyze the effects of RMSs on exhausted emissions.

5.1. Traffic Emissions Modeling

There are various approaches to emissions modeling. In a few studies, regression modeling has been employed to determine the relationship between exhausted emissions and various road features such as slope and elevation. However, the majority of past studies have employed models based on emissions factors. These models employ emissions factors, traffic-related data, vehicle fleet composition, and other local characteristics to estimate the exhausted emissions in grams per vehicle and gram per kilometer. The emissions factor is a critical component in emissions modeling. An emissions factor is "a representative value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant." (Cheremisinoff, 2011). A dynamometer test usually provides the emissions factor for each vehicle type in gram per kilometer, gram per second, or gram per fuel burned.

Many parameters affect the emissions factor and, consequently, the total traffic emissions. In general, these parameters can be categorized into four groups: traffic-related data, local characteristics, vehicle characteristics, and fuel. Each of these parameters is listed in Table 1.

Table 1: Parameters affecting traffic emissions

Characteristics	Parameters
Traffic-Related Data	Speed, Traffic flow, Queue length and delay, Traffic Density, Driving Behavior, Driving mode (accelerating, decelerating, idling, stop-and-go), Driving style (e.g. aggressive driving), Vehicular composition, Startup Mode
Local Characteristics	Road type, Road Geometry (e.g. Curvature and Longitudinal grade), Ambient Temperature, Altitude, Relative Humidity, Weather Conditions, Atmospheric Pressure, Pavement quality
Vehicle characteristics:	Vehicle Type, Vehicle Age, Mileage, Emissions Control Equipment, Engine Load, Vehicle Weight and Size, Maintenance Frequency, Engine Size, Engine Type, Engine Dynamics (Engine Speed, Power Demand, Etc.), Air-To-Fuel Mass Ratio
Fuel	Fuel Type, Oxygen Content, Sulfur Content, Volatility, Density

Like traffic simulation models (section 3), emissions models are divided into three general categories: microscopic, macroscopic, and mesoscopic (Quaassdorff et al., 2016; So et al., 2018; Samaras et al., 2019). Microscopic emissions models are as detailed as traffic flow microscopic models. These models typically require a wide range of detailed geometric and driving behavior data (the exact speed profile of the vehicles as input). However, some macroscopic models estimate fleet emissions on a regional or country-wide scale. Most macroscopic emissions models utilize average speed as input. Some mesoscopic emissions models combine the capabilities of the two models mentioned above. These models can be used in traffic-link based urban emissions modeling. In mesoscopic emissions models, both average speed and driving dynamics are incorporated into emissions calculations.

Below is a brief explanation of how these models work, the software used for modeling, and the most important models in each category.

5.1.1 Microscopic Emissions Models

Microscopic emissions models estimate emissions by evaluating the driving speed and acceleration characteristics/profiles on a vehicle-by-vehicle and second-by-second basis. These models are more suitable for the assessment of interventions on single roads, single junctions, or short sections of highways. The data for this type of modeling is usually imported from microscopic traffic models. These models provide the instantaneous emissions factors of each vehicle from all vehicle categories as output.

Microscopic emissions models are categorized into two groups: 1- Cycle variable models and 2- Modal models. Cycle-variable models do not use instantaneous information. Several driving cycle variables (e.g., idle time, average speed, and acceleration) determine the emissions factors in the cycle variable model. On the other hand, modal emissions models use instantaneous information directly from the trajectory information. These models depend on specific engine or vehicle operating modes. There are two types of modal models: 1- Speed-based models and 2- Engine-based models. The instantaneous speeds and accelerations of each vehicle are essential data for speed-based models. Speed-based microscopic emissions models are based on empirical measurements relating vehicle emissions to the type, instantaneous speed, and acceleration of the vehicle (Panis et al., 2006). The mathematical formula of these models is as follow (ma et al., 2012):

$$E_{i,j}(t) = f\left(C_j, a, v, \ldots, t, \Phi_{i,j}\right) \; (1)$$

In which:

$E_{i,j}(t) = \; the\ emissions\ or\ fuel\ consumption\ of\ gas\ type\ i\ for\ the\ vehicle\ category$ j

$$C_j\ and\ \Phi_{i,j} = Model\ parameters$$

$$a = acceleration$$

$$v = speed$$

Moreover, in some speed-based models, instantaneous speed and acceleration data are not directly imported. Instead, such models use the Vehicle Specific Power (VSP) and Engine Stress (ES) to describe the relationship between transient operating conditions and vehicle emissions. VSP and ES are functions of instantaneous speed, instantaneous acceleration, road grade, and vehicle mass.

The most crucial disadvantage of speed-based models is that although such models can account for driving dynamics, they cannot explain the operating characteristics of the engine. In engine-based emissions models, engine functions such as power and speed are modeled based on speed profile and road grade input. Fuel consumption and pollutant emissions are calculated based on such engine functions (So et al., 2018).

Many microscopic emissions models have been developed by previous research. Some examples are as follows (Ma et al., 2012; Samaras 2019):

- AVL CRUISE
- Comprehensive Modal emissions Model (CMEM)
- Emissions from Traffic (EMIT)
- International Vehicle emissions (IVE)
- Motor Vehicle emissions Simulator (MOVES)
- Panis emissions model
- Passenger Car and Heavy Duty emissions Model (PHEM)
- POLY
- Virginia Tech Microscopic model (VT-Micro)

5.1.2 Macroscopic Emissions Models

Macroscopic traffic emissions models use average aggregated network parameters to estimate traffic emissions. In principle, such models are used together with macroscopic traffic flow models. Macroscopic traffic emissions models are usually used for modeling emissions at the network-level or large road sections and mostly utilize average speed as input. In other words, in macroscopic emissions models, the analysis of single-vehicle emissions is not necessary. Total emissions are calculated by multiplying vehicle activity with the corresponding emissions factor expressed in gram per kilometer. The conceptual formula for calculating traffic emissions is as follow:

$$Traffic\ emissions = Vehicle\ Activity * emissions\ Factor\ (2)$$

Vehicle activity is usually expressed as vehicle kilometers traveled. Moreover, vehicle fleet composition is another crucial parameter since emissions factors are provided based on various types of vehicles. Ease of use and the limited amount of required data have made such models widely popular.

Macroscopic emissions models can be categorized into three groups (Kanagaraj and Treiber 2019): 1- Area-wide models, 2- Average-speed models, and 3- Traffic-variable models. For further detail about the above models, please refer to Kanagaraj and Treiber 2019.

Here are some of the most important models in this category:

- Emissions Factors (EMFAC)
- Assessment and Reliability of Transport emissions Models and Inventory Systems (ARTEMIS)
- UK's National Atmospheric emissions Inventory (NAEI)
- Computer Program to calculate emissions from Road Transport (COPERT)
- Handbook emissions Factors for Road Transport (HBEFA)
- Mobile-Source emissions (MOBILE)

5.1.3 Mesoscopic Emissions Models

Mesoscopic and macroscopic emissions models employ similar processes to estimate emissions. The only difference is the level at which they are employed. Macroscopic emissions models are usually employed at the regional or county-wide levels while mesoscopic models are used at the link level. In other words, mesoscopic models are traffic-link based. It should be noted that many studies have not differentiated between macroscopic and mesoscopic emissions models and have referred to both models as macroscopic emissions models (Kanagaraj and Treiber 2019; Tsanakas 2019). Besides, many of the presented macroscopic emissions models are also applicable to mesoscopic emissions modeling.

The most important category of mesoscopic emissions models is traffic situation models. In these models, the provided emissions factors correspond to different vehicle classes, road categories, and traffic situations. Traffic situations are divided into four classes: Free flow, Heavy, Saturated, and Stop-and-go. Roads are categorized by their environment, speed limit, and type. Each traffic situation is qualitatively defined based on the characterization of the traffic situation. Please refer to Quaassdorff et al., 2016; Samaras et al., 2016; and Liu et al., 2018, for more information.

The most widely used models referred to by previous studies as both mesoscopic and macroscopic models are:

- The Handbook Emissions Factors for Road Transport (HBEFA)
- Computer Program to Calculate Emissions from Road Transport (COPERT)

5.2. Traffic Emissions Modeling in the Presence of RMSs

Few studies have directly assessed the impact of work zones or RMSs on vehicle emissions. The majority of previous research on the effects of RMSs on emissions has employed Life Cycle Assessment (LCA). Section 5.2.1 presents studies that have examined the effects of delayed traffic caused by RMS using LCA. Then, section 5.2.1 explores the studies that have directly investigated the effects of different lane closure scenarios (different RMS configuration) on exhausted emissions (without using LCA).

5.2.1 Evaluating the Effects of RMSs in Life Cycle Assessment

LCA is a methodology that comprehensively evaluates the total environmental burden of roads. Five stages are commonly identified during the life cycle of roads: material production, construction, use (which includes leaching, rolling resistance, albedo, and lighting), maintenance (which includes delayed traffic emissions in addition to the replacement of the layers) and end of life. In most of these studies, it has been concluded that the emissions exhausted during the maintenance phase should be considered in the life cycle assessment (Lizasoain-Arteaga et al., 2020; Liu et al., 2019).

One of the studies that have evaluated the effects of RMSs in LCA has been conducted by Huang et al., 2009. This study concludes that the existence of RMSs increases the amount of emissions. It recommends the application of microscopic emissions modeling instead of macroscopic emissions models since the latter usually overestimate the amount of exhausted emissions. This research recommends that the duration of maintenance operations be limited to reduce exhausted emissions.

Galatioto et al., 2015 concluded that increases in traffic levels result in an exponential increase in emissions during road activities due to the oversaturation and delay caused by reduced capacity after lane closure. Although the microscopic approach performs well in emissions modeling, the study recommends that the effects of RMSs on exhausted emissions be examined at the network level as well since RMS operations are usually performed at the network level, rather than the link level. The factors affecting emissions exhausted by RMSs are identified by the researchers as the type, duration, and timing of road activities.

Another study examining the effects of RMSs on vehicle emissions using LCA was conducted by Hanson and Noland, 2015. The study used a model called "completed Greenhouse Gas Assessment Spreadsheet for Transportation Capital Projects (GASCAP)" for calculating emissions during the whole life cycle of a road. To estimate the exhausted emissions, the model employs the HCM methodology to obtain road capacity and queue length in work zones and MOVES to obtain the emissions factors. The study, which investigated the effects of the presence of an alternative route through macroscopic modeling, found that the amount of exhausted emissions increases significantly in full closure scenarios.

Inti et al., 2016, also concluded that the delayed traffic cause by RMSs should be considered in LCA. Using macroscopic emissions modeling in the MOVES environment, they found that the longer the duration of lane closure, the higher the amount of exhausted emissions. The following parameters are incorporated in the model developed by the study: projected AADT at maintenance time, hourly demand distributions, vehicle classification, work zone speed, vehicle speeds during queues, lane closure duration, timing, work-zone length, and lane capacity during maintenance.

Lizasoain-Arteaga et al., 2019 investigate the effects of congestion during RMS operations using two approaches: 1-Macroscopic and 2-Microscopic emissions modeling. A model developed by Panis et al., 2006, which is integrated into AIMSUN, is applied for microscopic emissions modeling. The results of this study indicate that congestion levels play a significant role in the amount of emissions exhausted by RMSs. The study also found that the accuracy of microscopic modeling is higher than that of macroscopic modeling, as macroscopic models may overestimate the amount of emissions. According to the authors, the existence of alternative routes is one of the most critical factors that should be taken into account.

In short, it can be concluded that LCA studies indicate that RMSs use fossil fuels (and consequently exhaust emissions) in two ways: 1- Gasoline and diesel used by delayed traffic and 2- The fuel and electricity used for machinery and equipment. These studies have found that fuel used by delayed traffic exhausts more emissions than the machinery and equipment employed by RMS activities (Liu et al., 2019).

5.2.2 Evaluating the Effects of RMSs in Different Lane Closure Scenarios

Studies that directly examine the effects of RMSs in different lane closure scenarios have employed both microscopic and macroscopic emissions models. Zhang et al., 2011, who used the microscopic emissions modeling (CMEM), compared the amount of emissions exhausted in the presence of RMSs and lane closure conditions with the amount of emissions in the free flow condition. According to this study, the effects of RMSs on exhausted emissions is not the same for different vehicle types (light-duty and heavy-duty vehicles) and pollutants. For instance, the amount of CO, HC, NOx, and CO2 emissions exhausted by heavy vehicles is higher compared to the free-flow condition, which is not true for light vehicles. The study also found that the amount of emissions exhausted by both light-duty and heavy-duty vehicles in transition zones was higher compared to the other parts of RMSs. This indicates that the acceleration and deceleration behavior of vehicles has a major influence on the amount of emissions.

Gu et al., 2018, have recently conducted a study on the impact of lane closure caused by RMSs by utilizing the macroscopic emissions modeling approach (using average speed as input) and the microscopic emissions modeling approach (using vehicle operating model as input). Traffic data was obtained using VISSIM software and used as input for the MOVES model. The study investigates the effect of RMS schedule (daytime or nighttime) on the amount of emissions and concludes that road maintenance operations at nighttime exhaust less emissions due to less traffic congestion. It should be noted that Alvanchi et al., 2020, who used VISSIM and the ad-on emissions model EnViVer (which is integrated into the VISSIM), found similar results and stated that maintenance schedule has a significant effect on the amount of vehicle emissions.

The above studies have used the microscopic emissions modeling approach. However, few studies have employed the macro modeling approach. For instance, a study by Kim et al., 2018, which employed the macroscopic emissions modeling approach, indicates that mitigating traffic congestion from heavy (average speed 5 mph) to medium congestion (average speed 15-25 mph) in a work zone would reduce fuel consumption and GHG emissions by 40 percent on a freeway and by 32 percent on a multilane road. This study, which incorporates Average Annual Daily Traffic (AADT) data into its emissions model, evaluates different levels of congestion at RMSs. It is worth mentioning that this research does not compare the congested traffic condition in the presence and absence of RMSs. The comparison carried out by the authors is limited to the congested traffic condition at RMSs and the free-flow conditions in the absence of RMSs.

Although the majority of past studies have concluded that the existence of RMSs increases the emissions exhausted by vehicles, a limited number of studies have concluded that RMSs can actually decrease pollutant emissions. For instance, research by Avetisyan et al., 2014 used the On-road Simulation Emissions Estimation Model (ORSEEM) (Microscopic emissions modeling approach) to investigate the impact of the work zone and traffic incidents on exhausted emissions. The authors concluded that the existence of a work zone reduces emissions. The reason behind this result can be stated as follows 1- The researchers have only used vehicle speed for emissions modeling, which means that the modeling is not accurate enough, and 2- The congested conditions are not evaluated (the evaluation is limited to scenarios without queues).

Another study that reached similar results was conducted by Wang et al., 2014. The authors first estimated the road capacity and the queue length in the presence of RMSs using the HCM work zone methodology. Then, these data were presented as input to the MOVES model (Macroscopic approach). The study concluded that in the absence of congestion, the amount of delayed traffic emissions caused by RMS is less significant in comparison with other road construction and maintenance phases. They recommended that the delayed traffic emissions caused by RMSs be evaluated in the presence of congestion.

In summary, it can be concluded that the presence of RMSs increases exhausted emissions. A few studies have identified the delayed traffic emissions caused by RMSs as insignificant because the scenarios evaluated by such studies do not examine the congestion condition. As a result, congestion caused by lane closure (RMS) can be identified as the most critical factor in exhausting emissions.

A review of the methodologies employed by previous studies reveals that there are two distinct approaches to the evaluation of the effects of RMSs on emissions: 1- Macroscopic emissions modeling and 2- Microscopic emissions modeling. The majority of studies use microscopic emissions modeling because of its superior performance compared to macroscopic emissions modeling, which is because vehicles experience different operating modes at RMSs. Thus, aggregated data may lead to inaccurate estimations. The microscopic emissions modeling approach first simulates traffic flow using traffic simulator software (such as AIMSUN, VISSIM, etc.). Second-by-second and vehicle-by-vehicle traffic-related data (e.g., instantaneous speed, instantaneous acceleration, etc.) are then imported into emissions models such as MOVES, CMEM, etc. Another group of studies has employed the emissions models integrated into traffic simulation software such as the Panis model in AIMSUN or the EnViVer model in VISSIM. On the other hand, macroscopic emissions models studies typically obtain aggregated traffic data by HCM methodology and then incorporate these traffic data (such as average queue length or average speed) into emissions models. In other words, it can be stated that previous studies have only used existed emissions modeling approaches, and to the best of the authors' knowledge, researchers have not yet developed a specific methodology for delayed traffic emissions caused by RMSs.

The following simulates a very simple case study in the AIMSUN environment using the Panis microscopic emissions model to demonstrate that the delayed traffic (congestion condition) caused by RMSs increases emissions.

6. Application

Given that some studies have reported conflicting results, a simple simulation is presented in order to thoroughly examine emission modeling in RMS and to determine whether delayed traffic caused by RMS increases or decreases the amount of emission in road sections. AIMSUN was selected because of its ability to model road network geometry, the behavior of individual vehicles in response to traffic, and its easy-to-use graphical interface. In particular, the software is capable of modeling traffic emissions and provides three pollution emissions models: the QUARTET Pollution Emissions Model, the Panis Pollution Emissions Model, and the London Emissions Model. As reported by past research, microscopic emission models exhibit superior performance compared to macroscopic emission models. The Panis model, which is a microscopic emissions model first released in 2006 and widely employed by previous studies, is used for microscopic emissions modeling in this chapter. The model provides the exhausted emissions of four pollutants (CO2, NOx, VOC, and PM) based on the type, the instantaneous speed, and the acceleration of the vehicle. Please refer to Panis et al., 2006 for more information on this model.

Figure 3 illustrates the case study for the simulation. As can be seen in this figure, two links are simulated in this chapter. The first link is a six-lane highway (three-lane in each direction) with a total length of 5 km, and a 1.6 km length lane closure in midsegment. The second link is also considered as an alternative road, which is a two-lane (one lane in each direction) rural road. For the sake of simplification, traffic flow is only simulated in one direction. Traffic flow is set to 6000 personal cars per hour (pc/hr), which leads to LOSE.

In reality, alternate routes usually have a higher length compared to the main road. In addition, they have an intersection with other routes. The alternate route length is therefore set to 7 km in this simulation to promote accurate results. There are two signalized intersections on link 2. The signalized intersections cycle is set to 80 seconds with a green time of 50 seconds for link 2.

It should be noted that since the purpose of this study is to investigate the extra emissions exhausted in the presence of RMSs, the cycle length of intersections in the alternative road was assumed to be a hypothetical value. Moreover, the volume of other approaches in these intersections was not taken into account.

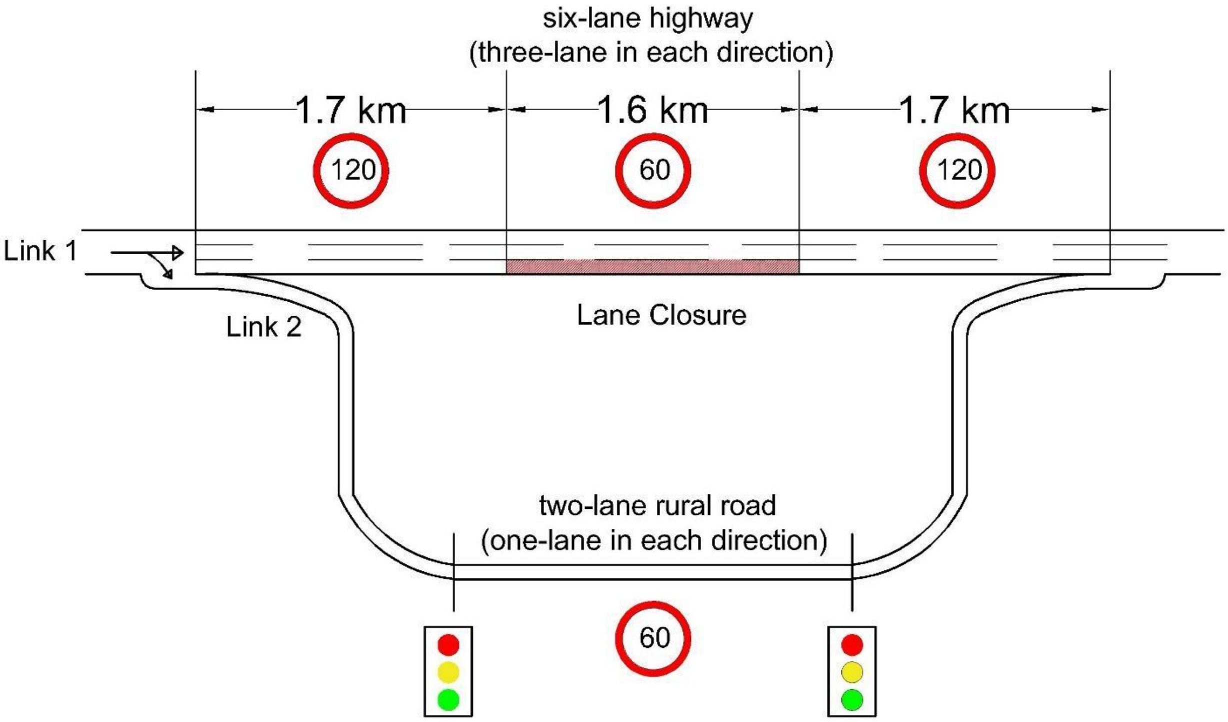

Figure 3: The simulation case study

Different scenarios intended for simulation are presented in Table.2. As shown in this table, four scenarios are simulated. There is no-lane-closure in the first scenario. In the second scenario, one lane is closed in the midsegment of link 1 due to RMS operations. To consider the effects of the existence of an alternative route, half of the traffic flow is assigned to the alternative route (scenarios 3 and 4). Figure 4 shows the emissions exhausted by vehicles during a 1-hour simulation.

Table 2: Scenarios for RMS lane closure

Scenario	Operating type		Link flow (Pc/h)		Signalized intersection	
	Link 1	Link 2	Link 1	Link 2	Link 1	Link 2
1	no-lane-closure	no-lane-closure	6000	0	No signalized intersection	-
2	Lane Closure		6000	0		-
3	no-lane-closure		3000	3000		Yes
4	Lane Closure		3000	3000		Yes
Simulation Duration: 1 hr.						

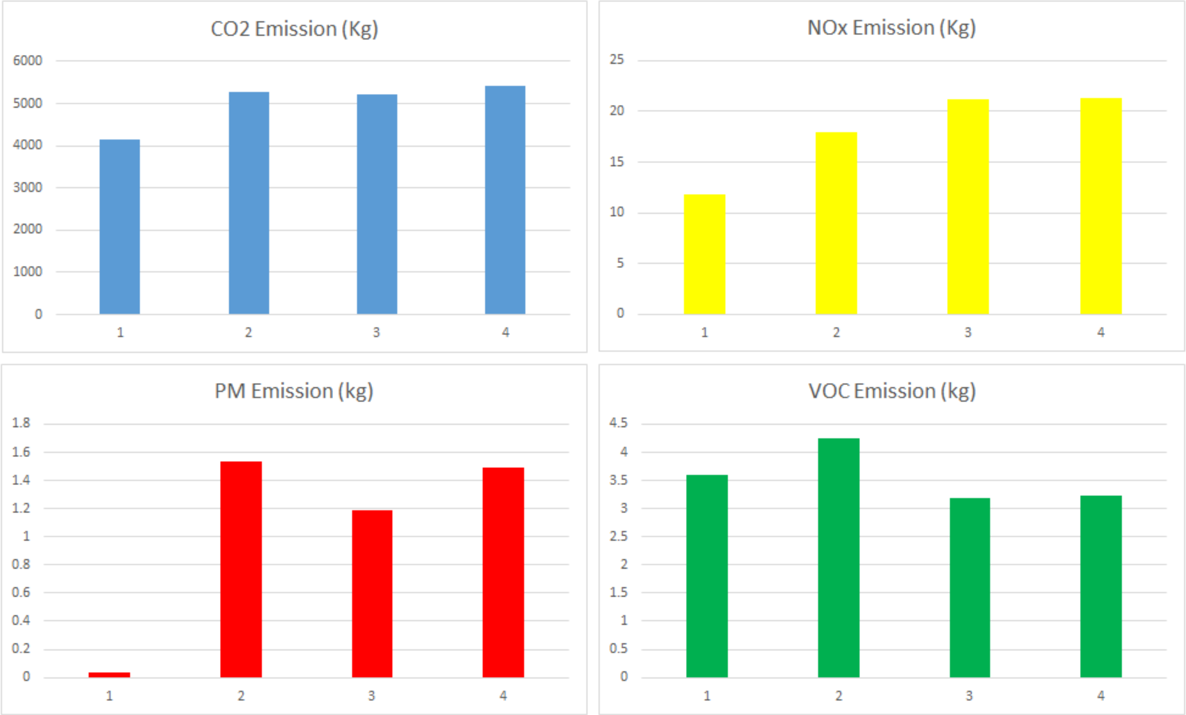

Figure 4: Exhausted emissions for different scenarios

As shown in Figure 4, the amount of all pollutants in the presence of lane closures (scenario 2) is higher than the no-lane-closure scenario (scenario 1). The presence of alternative routes has also been investigated in scenarios 3 and 4. An examination of the emissions exhausted by vehicles in these scenarios (in lane closure conditions) shows that when there is an alternative route (scenario 4), the emissions values of CO2 and NOx are higher compared to the no-alternative-route condition (scenario 2). However, this is not the case for PM and VOC emissions. On the other hand, when there is an alternative route, the amount of exhausted emissions for all pollutants for the lane-closure condition is higher than the no-lane-closure condition. Therefore, the results reported by the majority of previous studies, which indicate that exhausted emissions are higher in the lane closure condition compared to the no-lane-closure condition, are confirmed.

In this study, the alternate route was considered as a two-lane highway (one lane in each direction). It was also assumed that when there is an alternative route, the existing demand is split 50/50 between the two available routes. It is therefore suggested that future studies consider different traffic assignment scenarios and functional classes for alternative routes, as the amount of exhausted emissions in the alternative route depends on these two parameters.

7. Conclusion

The following conclusions can be drawn regarding the ecological effects of RMSs:

- In addition to vehicle and local characteristics (as mentioned in Table 1), the following factors, which are specific to RMSs, affect the amount of exhausted emissions:
    - Congestion formation
    - Closure schedule
    - The length of the transition zone
    - RMS length
    - Acceleration, deceleration, idling, and stop-and-go behavior at RMSs
    - The exitance of an alternative route
    - The type, duration, and timing of road work
    - Lane closure configuration
    - The RMS speed limit
    - Vehicle speeds in case of queue formation
    - Number and capacity of lanes during maintenance
- The amount of emissions exhausted at RMSs can be various for different types of pollutants.
- The amount of RMS emissions can vary for light-duty and heavy-duty vehicles. Therefore, future research should thoroughly investigate the behavior of each vehicle type at RMSs.
- Previous studies have only used the existing approaches to emissions modeling and, to the best of the authors' knowledge, researchers have not developed a specific methodology to model delayed traffic emissions caused by RMSs to date. Therefore, there is a need to calibrate the existing emissions models since the acceleration, deceleration, stop-and-go, and idling behavior of drivers at RMS congestion may differ from ordinary traffic congestion.
- In general, microscopic emissions models have superior performance in modeling RMS emissions. It can be stated that the MOVES model and the Panis model are most widely used due to their higher accuracy.
- In future studies, it is advisable to investigate the impact of RMSs at the network level, where such activities are usually performed.
- In some cases, when there is an RMS in one direction, traffic from the opposite direction is affected as well, which should also be investigated by future research.
- In future studies, the impact of different lane closure configuration scenarios (e.g. different transition zone lengths) should be considered because the configuration can affect the acceleration and deceleration behavior of vehicles (which are the most critical factors in exhausted emissions).
- The presence or absence of traffic congestion in RMSs is the most critical factor in the amount of emission exhausted at these zones. Therefore, it is necessary to perform a sensitivity analysis for the amount of exhausted emission in different LOS scenarios.
- In reality, usually, when a maintenance operation is performed on a highway, an alternative route is specified, or some drivers experimentally use alternative routes.

The traffic assignment is very important in these cases. Therefore, the drivers' route choice in these cases should be investigated in future studies.

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