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Theoretical Comparison of the Effects of Different Traffic Conditions on Urban Road Environmental External Costs

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Abstract: External costs that are associated with air pollution, climate change linked to greenhouse gas emissions (GHG), and noise are among the most important environmental externalities that are generated by road transport, which have been well monetized. This paper theoretically investigates the effects of different traffic conditions on the environmental external costs of urban roads where traffic flow is more complicated than un-interrupted traffic flows. A Monte Carlo method is used to theoretically simulate traffic speed in different traffic conditions. Subsequently, the emitted carbon dioxide (CO_2), nitrogen oxides (NO_x), carbon monoxide (CO), particulate matter (PM), sulfur dioxide (SO_2), and noise were estimated in each of the theoretically simulated traffic conditions. Finally, the environmental external costs in each traffic condition were calculated taking the EU average costs values into account. The results showed that, when compared to free-flow condition, the total air pollutant and GHG external costs (€2010) have been increased by 6%, 31%, 44%, 50%, and 93% in under-saturated flow, accelerated flow, decelerated flow, congestion, and over-saturated congestion, respectively. Furthermore, the total noise cost (€2010/year/person exposed), as compared to free-flow condition, has been decreased by 2%, 11%, 12%, 36%, and 69% in accelerated flow, under-saturated flow, congestion, over-saturated congestion, and decelerated flow, respectively.

Keywords: environmental external cost; traffic condition; urban road; road traffic air pollution; road traffic noise; environmental externalities

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1. Introduction

Although road transport plays an important role in growing the economy, it also may negatively affect society [1]. Externalities (In this paper, the term "externalities" refers to negative externalities) generated by road transport, such as environmental damage, road damage, road accidents, and congestion damage [2], are among the examples by which transport negatively affect society.

These externalities impose a cost upon society that is generally not borne by transport users and do not have any impact on their travel decision-making, in contrast to the benefits. The externalities that are associated with the environmental damages of road transport are called road transport environmental externalities, also known as environmental external costs of road transport. The environmental externalities from road transport can be divided into two main categories. The first category includes the externalities that have been best quantified and monetized (i.e., impacts from air pollution, climate change linked to greenhouse gas emissions (GHG), and noise), and they are relevant for quantitative analysis. The second category includes the ones that tend to be assessed using qualitative techniques (i.e., impacts from changes to the landscape, impacts on biodiversity, the heritage of historic resources, and water) [3]. In this paper, the effects of different traffic conditions on urban road environmental external costs that are related to the first category (i.e., air pollution, climate change linked to greenhouse gas emissions (GHG), and noise) are theoretically investigated.

1.1. Road Transport air Pollution Externality

Road transport plays a considerable role in the emission of several air pollutants at the local and regional level, which may cause several effects on the health and the environment. NO_x, CO, SO_2, and PM are among road transport emissions with effects at the local level. In Europe, road transport contributes approximately 30% of NO_x emissions, and 12% of the emissions of PM that have aerodynamic diameters less than or equal to 2.5 µm ($PM_{2.5}$) [4].

In general, air pollutants create adverse effects on health that can be valued by dose–response relationships derived from the loss of healthy life years in epidemiological studies [5]. In particular, NO_2, acute morbidity among children (reduced lung-growth [6], pulmonary effects in asthmatics [6], asthma [7,8], and leukaemia [9]). Moreover, CO could cause acute mortality among adults (congestive heart-failure [1] and children (sudden infant death syndrome [10]), as well as acute morbidity among adults (cardio-vascular [1]) and children (reduced birth weight [10]). Furthermore, SO_2 could cause acute and chronic mortality and morbidity [1]. Moreover, PM could cause chronic mortality among adults and infants (1–11 months) [1], as well as acute and chronic morbidity among adults (Respiratory [1], cardio-pulmonary [1], carcinogenic [11], cerebrovascular [12], and children (otitis media [13], asthma [7]). Figure 1 represents the linkage between Europe's major air pollutants, air quality, and their impacts on the climate, eco-system, and human health.

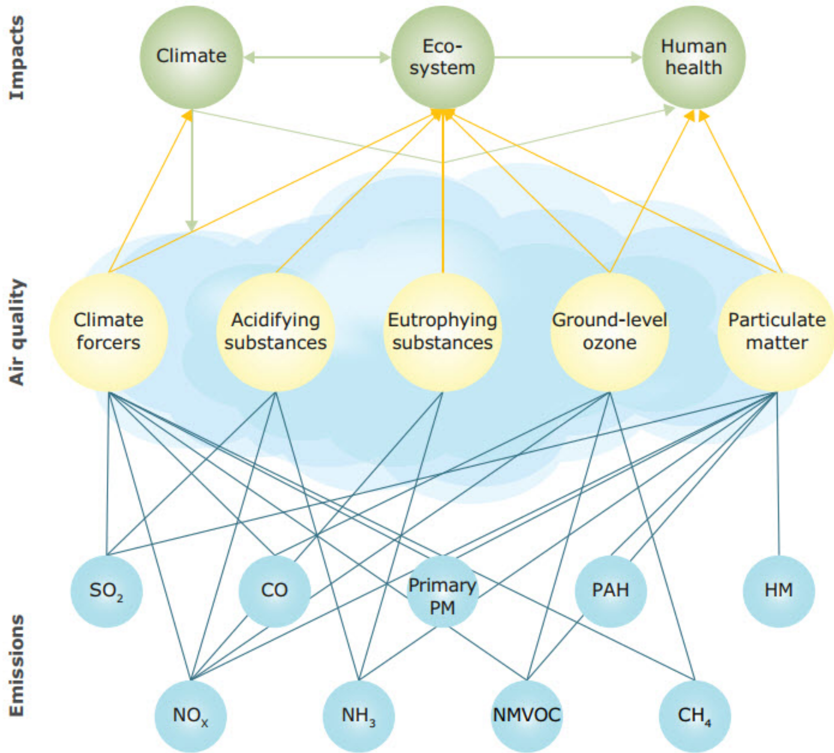

Figure 1. Linkage between Europe's major air pollutants, air quality, and their impacts on climate, eco-system and human health. [11]

1.2. Road Transport Climate Change Externality

CO_2, the anthropogenic GHG that most contributes to global warming, is the main road transport pollutant with effects at the global level. CO_2 is the unavoidable fuel combustion product, which is closely related to the amount of fuel consumed.

In Europe, road transport contributes approximately 23% of the EU's total emissions of CO_2 [4].

1.3. Road Transport Noise Externality

Not just the external costs that are associated with air pollution and climate change linked to GHG are the important road transport environmental externalities, but also the external costs of traffic noise, is another important road traffic environmental externality, since the environment noise has become a worldwide problem [14]. In urban areas, traffic flow is said to play the main role in noise annoyance, due to the close gathering of city inhabitants and road networks, which needs to be carefully studied in sustainable urban transportation policies. The European division of the World Health Organization estimates, besides the annoyance experienced due to noise exposure, every fifth European citizen is exposed to traffic noise levels at night that could have adverse effects on their health [15]. In general, exposure to road traffic noise could increase the risk of stroke [16], increase the risk of developing diabetes [17], increase the risk of heart attacks [18], and it could cause cardiovascular and hypertension problems [19].

1.4. Traffic Condition and Environmental Externalities

The literature mostly investigated the effect of traffic congestion on vehicle emissions and noise with particular attention to vehicle emissions.

Barth and Boriboonsomsin [20] examined the impact of traffic congestion on CO_2 emissions by linking the energy and emission models and real-world driving patterns and traffic conditions, and highlighted the considerable impact of traffic congestion on the CO_2 emissions [20]. Jacyna et al. [21] investigated the effects of congestion on road traffic noise and harmful emissions through a simulation-based approach [21]. Zhang and Batterman [22] estimated the pollution impacts and characterized the health risks that are caused by congestion through an incremental analysis approach. Their results highlighted that the incremental risks have dramatic increases at high traffic volumes for the arterial road, while having a "U" shaped pattern with increased traffic volume in the freeway [22]. Gately et al. [23] integrated a large database of hourly vehicle speeds that are derived from mobile phone and vehicle GPS data with multiple regional datasets of vehicle flows, fleet characteristics, and local meteorology, and quantified the excess emissions from traffic congestion up to 75% for individual roadways in key corridors [23]. Thaker and Gokhale [24] investigated the effect of free flow traffic and traffic congestion on pollutant dispersion by using the analytical and semi-empirical dispersion models, in the urban areas. Their results showed a considerable reduction of pollutant concentrations in free flow condition due to the high range of vehicle induced turbulence during the free flow condition. However, the congested traffic condition had higher pollutant concentrations. Based on their results, they concluded that facilitating free flow traffic pattern on urban roads can reduce pollutant concentrations, which may lead to better air quality, public health, and wellbeing [24]. Zhong et al. [25] examined the relationship between traffic congestion, ambient air pollution (NO_2, PM, and SO_2), and health by using regression analysis. Their results showed the substantial negative health externalities of traffic congestion [25]. Lu et al. [26] examined the effects of traffic congestion on PM through a two-stage least squares (2SLS) regression method. In their study, traffic congestion is represented in five different levels via a traffic congestion index (e.g., TCI: an index calculated by the Beijing Transportation Research Center as the aggregate measure of motorized traffic speed and road congestion in Beijing's metropolitan area). Their results showed that the observed reduction in TCI leads to a significant decrease in PM concentration [26]. Recently, Wang et al. [27] investigated the emissions of PM, CO_2, NO_x, and volatile organic compounds (VOC) in a mixed traffic condition using cellular automaton. They pointed out that from free flow condition towards congestion condition, the emissions rise to a peak on congestion. Furthermore, they investigated the effects of acceleration and deceleration conditions, and highlighted the fact that the aforementioned motion states have a considerable impact on the emissions [27].

To sum up, the literature investigated the effect of limited traffic conditions (mostly traffic congestion) on vehicles emissions and noise (mostly air pollutants as compared to noise) and did not pay considerable attention to (1): the effect of a wider range of traffic conditions on the emitted air pollutants; (2): the effect of different traffic conditions on road traffic noise; and, (3): the effect of different traffic conditions on environmental external costs that are associated with (1) and (2).

This paper attempts to extend this scope by conducting a theoretical investigation of the effects of diverse traffic conditions on urban road environmental externalities.

The paper is structured, as follows. In Section 2, the Monte Carlo method is used to simulate traffic speed in different traffic conditions. Subsequently, the air pollutants, GHG, and noise generated in the investigated traffic conditions are estimated and, further, their associated environmental external costs are calculated. The obtained results are presented and discussed in Sections 3 and 4, respectively. Finally, Section 5 provides the conclusions of this paper.

2. Methodology

On the one hand, transport plays an important role in the social and economic development of the countries [28] and, on the other hand, the transport sector is the main source of environmental pollution. Therefore, the sustainable development of the transportation sector is of great importance.

In the current paper, the effect of the investigated traffic conditions on urban road environmental external costs has been theoretically investigated. The following three main environmental externalities have been considered in the current paper:

1. Air pollution: CO, NO_x, PM, and SO_2 are the considered air pollution-related environmental externalities.
2. Climate change: all emissions of GHG expressed in CO_2 equivalents have been considered in the current paper.
3. Noise exposure: a distinction has been placed between six levels of persistent exposure: below 51 dB(A), 51–55 dB(A), 55–60 dB(A), 60–65 dB(A), 65–70 dB(A), and 70–75 dB(A) according to [1]. Each level is assessed with the corresponding health impacts.

The paper follows the research steps that are shown in Figure 2.

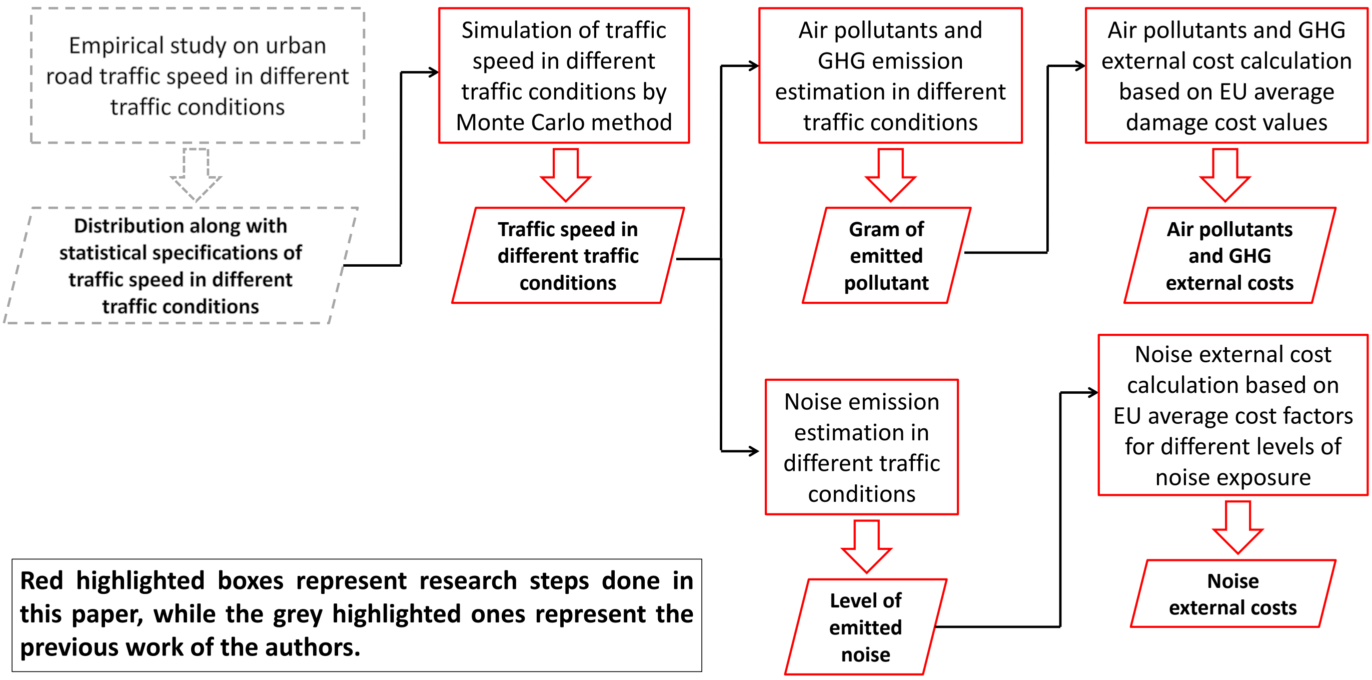

Figure 2. Research steps.

2.1. Traffic Speed in Different Traffic Conditions: Monte Carlo Method

The variations of traffic speed have been considerably studied in the literature. Jun [29] argued that the change or variability of speed distributions on a specified roadway during a certain period of time may explain the trends or patterns of how the characteristics of traffic on the roadway vary [29]. Zou and Zhang [30] used skewed distributions for mixture modeling of traffic speed [30]. Wang et al. [31] used truncated distributions to represent the traffic speed in their study [31]. Wang et al. [32] considered different traffic speed distributions for different levels of traffic density in their proposed stochastic speed-density function [32]. Yu and Abdel-Aty [33] proposed the normal, gamma, exponential, lognormal, and weibull speed distributions as the candidate distributions, which might represent their real-time traffic speed data well [33]. Maurya et al. [34] argued that lognormal and gamma distributions could represent their on-field collected speeds well. Furthermore, they found beta, normal, and weibull distributions to significantly represent their collected speed data [34]. Recently, Maghrour Zefreh and Török [35] empirically studied the distribution of the urban road traffic speed, taking a series of traffic conditions into account [35]. They fitted various parametric distributions to the urban road traffic speed, while taking diverse traffic conditions into account. Table 1 shows the results of their empirical study.

Table 1. Empirical results of traffic speed in diverse traffic conditions [35].

Traffic Condition	Fitted Speed Distribution	Minimum Speed (km/h)	Maximum Speed (km/h)	Average Speed (km/h)	Standard Deviation of Speed (km/h)
Free flow	Log-normal distribution	35	55	47.18	5.5
Accelerated flow	Beta distribution	1	45	27.41	13.15
Over-saturated congestion	Exponential distribution	1	15.5	10.37	2.74
Undersaturated flow	Normal distribution	25	55	38.14	6.46
Decelerated flow	Chi-square distribution	1	35	18.76	11.82
Congestion	Gamma distribution	10	25	14.53	3.91

In the current paper, the Monte Carlo method is used to simulate traffic speed in different traffic conditions based on Table 1, in which the number of vehicles remains unchanged in all the scenarios (1600 vehicles) to release the effect of the number of vehicles on further environmental external costs calculations. The Monte Carlo method encompasses a computational algorithm that relies on generating random objects [36]. The Monte Carlo method is considerably used in literature in the context of the transportation science [37–40]. Generally, Monte Carlo methods are mainly used in the three main problems of numerical integration, optimization, and generating samples from a probability distribution [36]. In this paper—following the previous work of the authors, in which distribution of traffic speed in different traffic conditions is empirically investigated (see [35])—generating samples (traffic speed in different traffic conditions) from a probability distribution (parametric distribution of traffic speed in the investigated traffic conditions, as suggested by [35]), is done by Monte Carlo method. Subsequently, the theoretically simulated traffic speeds in the investigated traffic conditions were used to assess the effects of different traffic conditions on the emitted air pollutants, GHG, and noise, and subsequently their associated external costs. Figure 3 shows the theoretically simulated traffic speed in different traffic conditions using the Monte Carlo method.

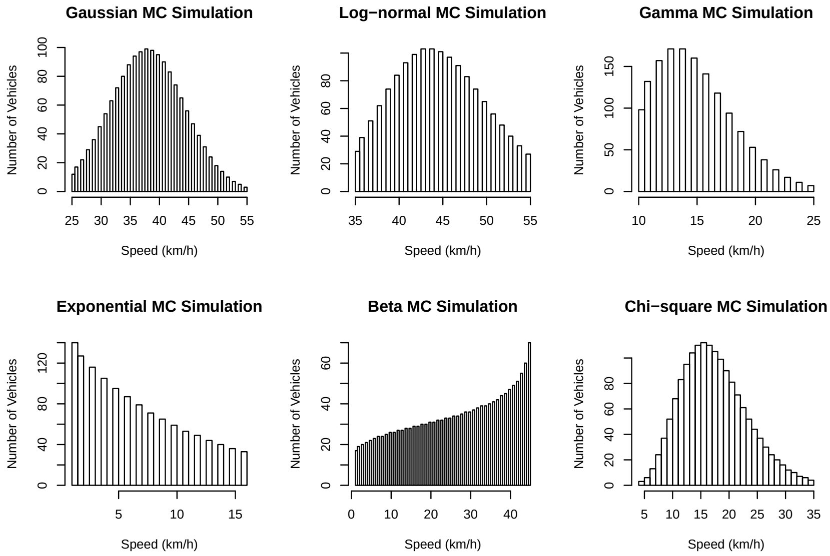

Figure 3. Theoretical simulation of traffic speed in different traffic conditions using Monte Carlo (MC) method.

2.2. Air Pollutants and GHG Emission Estimation

Within the context of the urban areas, air pollution problems originating from road traffic are considerably studied in the literature from different perspectives [41,42]. Jandacka et al. [43] investigated the contribution of road traffic to PM and metals in air pollution in the vicinity of an urban road. They identified the non-combustion emissions from road traffic followed by combustion emissions from diesel vehicles as the two key sources of PM [43]. Rodríguez et al. [44] investigated the linkages between air pollution and urban structures with an emphasis on urban fragmentation. They found that the urban structure has significant effects on pollution concentration [44]. Sun et al. [45] investigated the relations between urban traffic infrastructure investment (UTII) and air pollution. They argued that increasing the UTII may have a negative effect in the short-run and a positive effect in the long-run. Thus, in general, it may mitigate air pollution [45]. Almeida et al. [46] assessed the influence of urban forest on traffic air pollution and childhood respiratory health. They found a positive and strong correlation between school children's respiratory symptoms and the primary pollutants and highlighted the importance of creating and maintaining green areas in urban space [46]. Smith et al. [47] assessed the association of the concentration of NO_2 with traffic exposure zones. They showed that greater NO_2 levels occurred in delay, high volume, and bus route sections [47].

In general, road transport vehicles emissions can be categorized into three groups:

- Exhaust emissions: are the emissions that are produced primarily from the combustion of different petroleum products which are mixtures of different hydrocarbons. Due to the imperfect combustion process, vehicle engines emit many different pollutants in addition to water and CO_2 including CO, NO_x, PM, etc.
  The exhaust emissions would be further divided into "HOT" emissions when the engine is at its normal operating temperature, and "COLD-START" emissions, emissions during transient thermal engine operation.
- Abrasion emissions: are the emissions that are produced from the mechanical abrasion and corrosion of vehicle parts. Abrasion is only important for PM emissions and emissions of some heavy metals.
- Evaporative emissions: are the emissions from evaporating gasoline that contain a variety of different Hydrocarbons (HCs), which can occur during vehicle refuelling, vehicle operation, and even when the vehicle is parked.

Among the above-mentioned emissions, exhaust emissions-which could drastically increase the risk of health issues [48]-have been considered to be studied in this paper, since they are more dependent on traffic conditions [49]. Among exhaust emissions, the "HOT" emissions are considered since the "Cold-Start" emissions are produced during the warm-up period and they mostly occur on average during the first 5.9 km of a vehicle's journey [50].

It is worth noting that, to release the effect of other factors than traffic condition on air pollutants and GHG emission estimation, the following are assumed in emission estimation of the investigated traffic conditions: type of vehicles, type of vehicle's engine, road length, and traffic volume. The preliminary assumptions for HOT emission estimations are presented in Table 2. It is worth highlighting that the main aim of the current paper is to theoretically investigate the effects of different traffic conditions on urban road environmental external costs. In other words, a theoretical comparison between different traffic conditions. Thus, 1 km of urban roads has been theoretically studied for the sake of comparison.

Table 2. Preliminary assumptions for HOT emission estimation in different traffic conditions.

# Vehicles	Vehicle Type	Engine Type	Engine Size	Road Length
1600 passenger car	Euro IV	Diesel engine	<2.0	1 km of urban road

Hot emissions in the investigated traffic conditions have been calculated as follows [49].

$$E_{HOT;\,p,v,w} = N_v \times D_{v,w} \times EF_{HOT;\,p,v,w} \tag{1}$$

where, $E_{HOT;\,p,v,w}$ represents a gram of hot exhaust emissions of the pollutant p (g) produced by vehicles with the technology of v driven on roads with the type of w, N_v represents the number of vehicles with the technology of v, $D_{v,w}$ represents mileage per vehicle (km/veh) driven on roads with the type of w by vehicles with the technology of v, $EF_{HOT;\,p,v,w}$ represents the factor of emission for pollutant p (g/km), relevant for the vehicle with the technology of v, operated on roads with the type of w.

2.2.1. CO_2 Emission Estimation

In recent decades, in contrast to the other main sectors of the economy, GHG emissions in the transport sector have been increased. Urban mobility accounts for approximately 40% of total greenhouse gas emissions from road transport in the European Union [51]. Therefore, on the one hand, road transport contributes about 23 % of the EU's total emissions of CO_2 [4]; on the other hand, CO_2 is the most considerable GHG affecting climate change and threatening the environment and public health. When considering the aforementioned, investigating the factors that would have an impact on the CO_2 emissions in the road transport sector is of vital importance. In this Section, the effect of the investigated traffic conditions on CO_2 emissions has been theoretically studied. To this end, the emitted CO_2 in the investigated traffic conditions has been calculated using Equation (1), in which the factor of emission of CO_2 has been calculated, while taking the assumption of Table 2 into account, as follows [49].

$$EF_{CO_2} = CON \times EF_{CO_2/fuel} \tag{2}$$

where, EF_{CO_2} represents the factor of emission of CO_2 in (g CO_2/km), CON represents consumption of fuel in (g fuel/km), and $EF_{CO_2/fuel}$ represents fuel consumption-specific factor of emission in (g CO_2/g fuel). Moreover, consumption of fuel, CON, in the above Equation has been calculated, as follows.

$$CON = \frac{\alpha + \gamma \times S + \lambda \times S^2}{1 + \beta \times S + \theta \times S^2} \tag{3}$$

where, CON represents the consumption of fuel in (g fuel/km), S represents vehicle's speed in (km/h), and $\alpha, \beta, \gamma, \theta, \lambda$ are the coefficients for each type of vehicle.

2.2.2. NO_x Emission Estimation

In urban areas, NO_x are mainly comprised by NO_2 and NO, and are precursors for secondary air pollutants, including $PM_{2.5}$ [52], and O_3 [53]. Furthermore, NO_x contributes in eutrophication and acid deposition [54]. Furthermore, in short-term exposures, NO_2 threatens human health [55]. When considering the aforementioned, investigating the factors that would have an impact on the NO_x emissions in the road transport sector is of vital importance. In this Section, the effect of the investigated traffic conditions on NO_x emissions has been theoretically studied. To this end, the emitted NO_x in the investigated traffic conditions has been calculated while using Equation (1), in which the factor of emission of NO_x has been calculated, taking the assumption of Table 2 into account, as follows [49].

$$EF_{NO_x} = \alpha + \gamma \times S + \lambda \times S^2 \tag{4}$$

where, EF_{NO_x} represents the factor of emission of NO_x in (g NO_x/km), S represents vehicle's speed in (km/h), and α, γ, λ are the coefficients for each type of vehicle.

2.2.3. CO Emission Estimation

CO is a highly toxic gas and will be created due to the incomplete combustion of vehicles' engine in the traffic flow, which has serious adverse health effects [4]. Therefore, investigating the factors that would have an impact on the CO emissions in the road transport sector is of vital importance. In this Section, the effect of the investigated traffic conditions on CO emissions has been theoretically studied. To this end, the emitted CO in the investigated traffic conditions has been calculated while using Equation (1), in which the factor of emission of CO has been calculated, taking the assumptions of Table 2 into account, as follows [49].

$$EF_{CO} = 17.5 \times 10^{-3} + 86.42 \left[1 + e^{-\frac{S + 117.67}{-21.99}} \right]^{-1} \tag{5}$$

where EF_{CO} represents the factor of emission of CO in (g CO/km) and S represents vehicles' speed in (km/h).

2.2.4. PM Emission Estimation

Negative health impacts of PM, emitted from vehicles in traffic flow, has been frequently highlighted in literature [56–62]. Therefore, investigating the factors that would have an impact on PM emissions in the road transport sector is of vital importance. In this Section, the effect of the investigated traffic conditions PM emissions has been theoretically studied. To this end, the emitted PM in the investigated traffic conditions has been calculated using Equation (1), in which the factor of emission of PM has been calculated, while taking the assumption of Table 2 into account, as follows [49].

$$EF_{PM} = \alpha + \gamma \times S + \lambda \times S^2 \tag{6}$$

where EF_{PM} represents the factor of emission of PM in (g PM/km), S represents vehicles' speed in (km/h), and α, γ, λ are the coefficients for each type of vehicle and pollutant.

2.2.5. SO_2 Emission Estimation

SO_2 is a toxic gas that causes serious respiratory Diseases and ecosystem degradation [63,64]. On average, an increase of 10 thousand tons in industrial SO_2 emissions in a certain city will lead to an increase of 0.035 and 0.03 per ten thousand persons in local mortalities from lung cancer and respiratory diseases, respectively [65]. Road transport-related SO_2 emissions are largely dependent on fuel type and the extent of the consumption of fuel. Furthermore, fuel consumption has a direct relation with vehicles speeds and traffic conditions. Therefore, the traffic conditions would have an effect on road traffic SO_2 emissions.

When considering the aforementioned, investigating the factors that would have an impact on the SO_2 emissions in the road transport sector is of vital importance. In this Section, the effect of the investigated traffic conditions on SO_2 emissions has been theoretically studied. To this end, the emitted SO_2 in the investigated traffic conditions has been calculated using Equation (1), in which the factor of emission of SO_2 has been calculated, while taking the assumption of Table 2 into account, as follows [49].

$$EF_{SO_2} = 2 \times K_{SO_2/fuel} \times CON \tag{7}$$

where, EF_{SO_2} represents the factor of emission of SO_2 in (g SO_2/km), CON represents consumption of fuel in (g fuel/km), and $K_{SO_2/fuel}$ represents the weight-related sulfur content of fuel in (g SO_2/g fuel).

It should be underlined that the sulfur content in the fuel has been assumed to be 40 ppm according to [49]. Moreover, it is worth mentioning that the consumption of fuel (CON) in the above Equation is calculated while using Equation (3).

2.3. Noise Emission Estimation

Road traffic noise is the most important source of noise in urban areas [66] and said to play the main role in noise annoyance in urban areas, due to the close gathering of city inhabitants and road networks, which needs to be carefully studied in sustainable urban transportation policies. In general, exposure to environmental noise may create adverse effects on health [67–69], may cause annoyance [70,71], and sleep disturbance [19], and it may have adverse effects on cognitive ability in schoolchildren [72]. Road traffic noise is one of the major environmental impacts of roadways [73], and it may lead to a burden of disease that is second only in magnitude to that from air pollution [74].

Noise prediction is an important tool for noise abatement and control. Many scientific models have been developed and validated in the literature to perform noise prediction, such as the FHWA model (Federal Highway Administration Traffic Noise model) of USA [75], CoRTN model (Calculation of Road Traffic Noise) of UK [76], RLS 90 model (Richtlinien für den Lärmschutz an Straben) of Germany [77], ASJ RTN-Model (Acoustical Society of Japan Road Traffic Noise prediction model) of Japan [78], HARMONOISE model (Harmonised Accurate and Reliable Methods for the EU Directive on the Assessment and Management of Environmental Noise) of Europe [79], Son Road model of Switzerland [80], Nord 2000 model of Scandinavian countries [81], and NMPB-Routes model of France [82]. In the current paper, the ASJ RTN model is used due to the fact that this road traffic noise prediction model is capable of doing road traffic noise prediction in urban road traffic conditions (capable of doing road traffic noise prediction for steady, non-steady, acceleration, and deceleration conditions). Furthermore, it is a speed-dependent model, which is the investigated traffic flow characteristic of the current study. For further details, readers are referred to [83] for a critical comparison among the above-mentioned models. The ASJ RTN model predicts the noise emitted by each vehicle in different categories as a function of the vehicle speed in various traffic conditions match with urban road traffic conditions [78].

In the current paper, the following are assumed in noise emission estimation of the investigated traffic conditions in order to release the effect of other factors than traffic condition on noise estimation: the same vehicle classification (passenger cars) for the entire traffic flow with the same engine rotational speed, same engine load, same road geometry, and the same road pavement type. Thus, the emitted noise (A-weighted sound power level, L_{WA} (dB(A)) in the investigated traffic conditions has been calculated according to [78], as follows:

$$L_{WA} = a + b\log(V) + c \tag{8}$$

where, V represents speed of vehicle (km/h), a and b represent coefficients of regression, and c represents the correction component for road conditions (road gradient and pavement type).

Furthermore, the following are assumed in sound propagation estimation of the investigated traffic conditions in order to release the effect of other factors than traffic condition on sound propagation estimation: same distance from the prediction point to the source position (20 (m)), same ground effect, same diffraction, and the same atmospheric absorption. Thus, the noise level at the receiver (A-weighted sound pressure level, L_A (dB(A)) from the ith source position to the prediction point in the investigated traffic conditions has been calculated according to [78], as follows:

$$L_{A,i} = L_{WA,i} - 8 - 20\log r_i + \Delta L_{cor,i} \tag{9}$$

where, r_i represents direct distance from the the prediction point to the ith source position (m), and $\Delta L_{cor,i}$ represents correction for atmospheric absorption, diffraction, and ground effect (dB(A)).

The estimated L_A (dB(A)) were further used to calculate a constant sound level with the same amount of energy in 1 s as the original noise level (single event sound exposure level, L_{AE} (dB(A))), according to [78], as follows:

$$L_{AE} = 10\log\left(\frac{1}{T_0}\sum_i 10^{L_{A,i}/10}.\Delta t_i\right) \tag{10}$$

where, T_0 represents the reference time (1 s), $L_{A,i}$ represents A-weighted sound pressure level in the ith section (dB(A)), and Δt_i represents the time when the sound source exists in the ith section (s).

By applying the traffic volume N_T during the time interval T (s) to the calculated L_{AE} (dB(A)), $L_{Aeq,\,T}$ (time-averaged value of the noise at a prediction point) is calculated according to [78], as follows:

$$L_{Aeq,\,T} = 10\log\left(10^{L_{AE}/10}.\frac{N_T}{T}\right) \tag{11}$$

where, L_{AE} represents the sound exposure level (dB(A)), N_T represents traffic volume during time interval (veh/investigated time period), and T represents time interval (s).

In order to calculate noise external costs using the available cost factors for noise exposures in Europe, the average sound level over a 24 h period (L_{den}) while considering the day time period of 12 h, the evening four hours, and the night eight hours, with a penalty of 5 (dB) added for the evening hours and a penalty of 10 (dB) added for the nighttime hours has been calculated according to [84], as follows:

$$L_{den} = 10\log\frac{1}{24}\left(12\times 10^{\frac{L_{day}}{10}} + 4\times 10^{\frac{L_{evening}+5}{10}} + 8\times 10^{\frac{L_{night}+10}{10}}\right) \tag{12}$$

where, L_{day} represents A-weighted average sound level over 12 h of the day (dB(A)), $L_{evening}$ represents A-weighted average sound level over 4 h of the evening (dB(A)), and L_{night} represents A-weighted average sound level over 8 h of the night (dB(A)).

2.4. Air Pollutants and GHG Cost Calculation

In the current paper, the air pollutants and GHG external costs were calculated following the cost values of air pollutants and the climate change linked to GHG emissions that are expressed in CO_2 equivalent value (€(2010)/tonne), as shown in Table 3.

Table 3. Damage costs of main air pollutants and greenhouse gas emissions (GHG) in €(2010)/tonne [1,85].

	Air Pollutant/GHG				
	PM (Urban Area)	NO_x	SO_2	CO_2	CO
EU average cost	270178	10640	10241	90	497.8

It should be highlighted that the CO damage cost is based on [85] that has been adjusted to average European values using the average exchange rate (1 USD = 0.730 EUR) in 2007 [86]. Furthermore, the calculated €(2007) value has been transferred to €(2010) value using the EU average $(\text{GDP/Capita})_{2007}$ and the EU average $(\text{GDP/Capita})_{2010}$ [87], as suggested by [88]. Thus, the external costs of the estimated air pollutants and GHG emissions in the investigated traffic conditions have been calculated according to [1], as follows:

$$EC_{HOT,\,i} = E_{HOT,\,i} \times C_i \tag{13}$$

where, $EC_{HOT,\,i}$ represents external cost of hot exhaust emissions of the pollutant i (€2010), $E_{HOT,\,i}$ represents hot exhaust emissions of the pollutant i (tonne), and C_i represents the damage cost of pollutant i (€2010/tonne).

2.5. Noise Cost Calculation

In the current paper, the noise external costs were calculated following the unit values of noise exposure (€(2010)/year/person exposed), as shown in Table 4.

Table 4. Cost factors for noise exposure in €(2010)/year/person exposed [1].

	L_{den} (dB(A))					
	51	55	60	65	70	75
EU average cost	8.28	41.04	82.32	123.24	164.48	273.36

It should be highlighted that the external costs for noise exposures between the mentioned intervals have been calculated using extrapolation.

Having estimated the average sound level over a 24 h period, L_{den} (dB(A)), and considering the cost factors that are shown in Table 4, the related external cost for noise exposure in the investigated traffic conditions have been calculated according to [1], as follows:

$$EC_{Noise} = L_{den} \times CF_{L_{den}} \tag{14}$$

where, EC_{Noise} represents external cost for noise exposure (€2010/year/person exposed), L_{den} represents day-evening-night noise level (dB(A)), and $CF_{L_{den}}$ represents the cost factor for different levels of L_{den} exposure (€2010/year/person exposed).

3. Results

Figures 4–9 illustrate the estimated air pollutants and GHG emissions as well as the estimated sound pressure level over the theoretical ranges of speed in the investigated traffic conditions. Figure 4 shows the theoretical range of emitted CO_2 in the investigated traffic conditions over the theoretical ranges of traffic speed in the investigated traffic conditions following the simulation assumptions that are presented in Table 2.

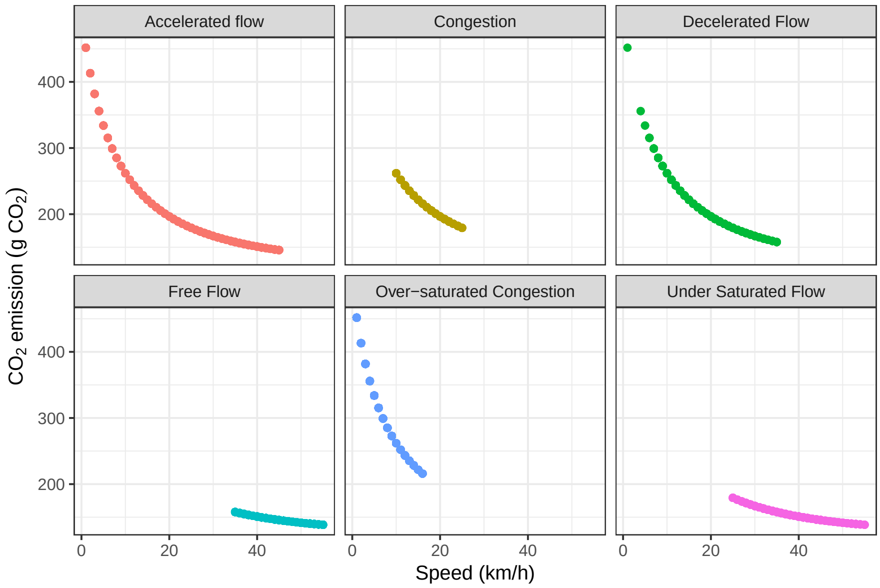

Figure 4. Estimated CO_2 in the investigated traffic conditions.

Poor air quality is a serious health and environmental problem. Certain harmful air pollutants are directly emitted from vehicles, including NO_x [4]. In this paper, apart from the most significant GHG influencing climate change, CO_2, the effect of the investigated traffic conditions on NO_x emission in the urban roads have been investigated following the assumptions that are mentioned in Table 2. Figure 5 shows the theoretical range of emitted NO_x in the investigated traffic conditions over the theoretical ranges of speed in the investigated traffic conditions following the simulation assumptions that are presented in Table 2.

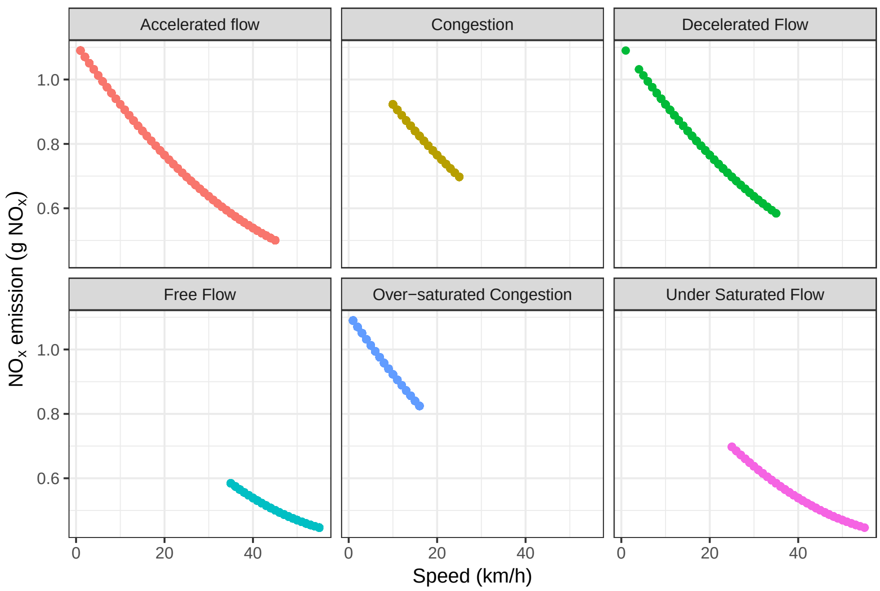

Figure 5. Estimated NO_x in the investigated traffic conditions.

CO is another investigated exhaust emission in this paper. *CO* is toxic, acting by reaction with haemoglobin and reducing its capacity for oxygen transport in the blood. Therefore, the theoretical investigation of the emitted *CO* would be of great help for the decision-makers in order to be fully aware of the consequences of their traffic and transportation policies. Figure 6 shows the theoretical range of emitted *CO* in the investigated traffic conditions over the theoretical ranges of speed in the investigated traffic conditions.

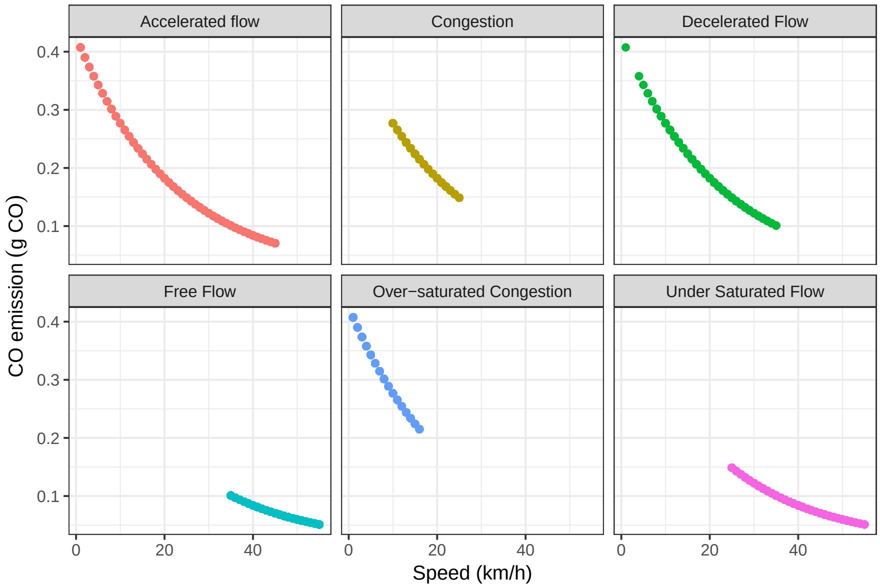

Figure 6. Estimated *CO* in the investigated traffic conditions.

Apart from studying the effects of the investigated traffic conditions on the emitted CO_2, NO_x, and *CO*, the *PM* emissions in different traffic conditions have been investigated in this paper, since the *PM* from vehicle emissions has been identified as a major public health risk, particularly in urban areas [89]. Figure 7 shows the theoretical range of emitted *PM* in the investigated traffic conditions over the theoretical ranges of speed in the investigated traffic conditions.

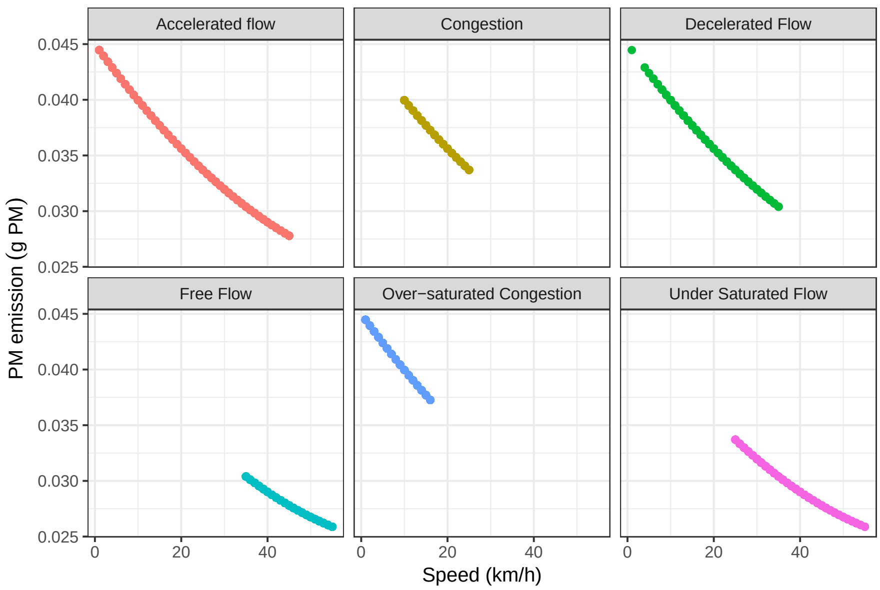

Figure 7. Estimated *PM* in the investigated traffic conditions.

The last investigated air pollutant in this paper is SO_2. In road transport, the emission of SO_2 heavily depends on the amount of fuel consumption and type of fuel. Because different traffic conditions would generate different speed ranges in traffic flow (see Table 1) and different speed ranges would influence SO_2 emission, the effect of different traffic conditions on SO_2 emission in the urban roads have been investigated following the assumptions that are mentioned in Table 2. Figure 8 shows the theoretical range of emitted SO_2 in the investigated traffic conditions over the theoretical ranges of speed in the investigated traffic conditions.

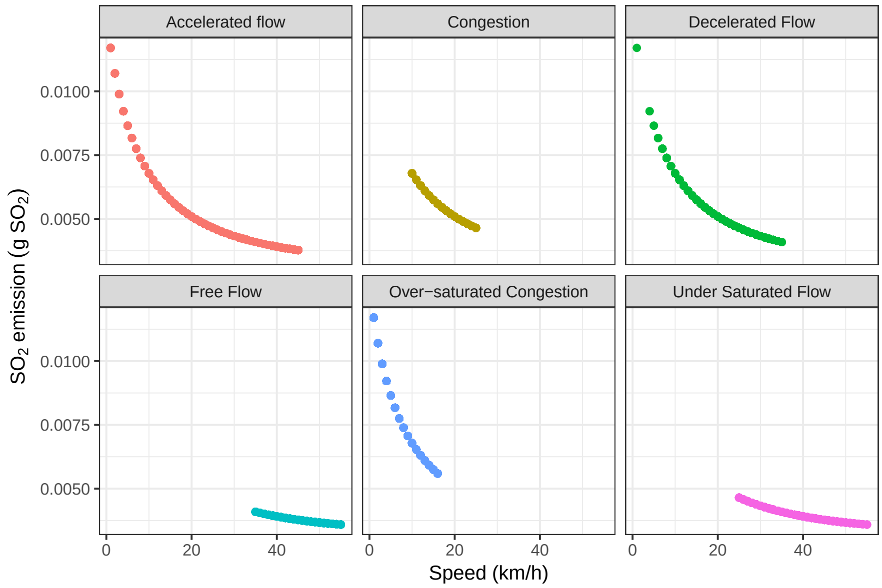

Figure 8. Estimated SO_2 in the investigated traffic conditions.

Figure 9 shows the estimated sound pressure level in the investigated traffic conditions. It is worth noting that Figure 9 shows the same sound pressure level for the vehicles with a speed of 10 km/h and the ones with speeds that are lower than 10 km/h in the decelerated flow. The reason is that in deceleration condition the sound power level generated at the speed of 10 km/h is applied to the speeds of less than 10 km/h according to [78].

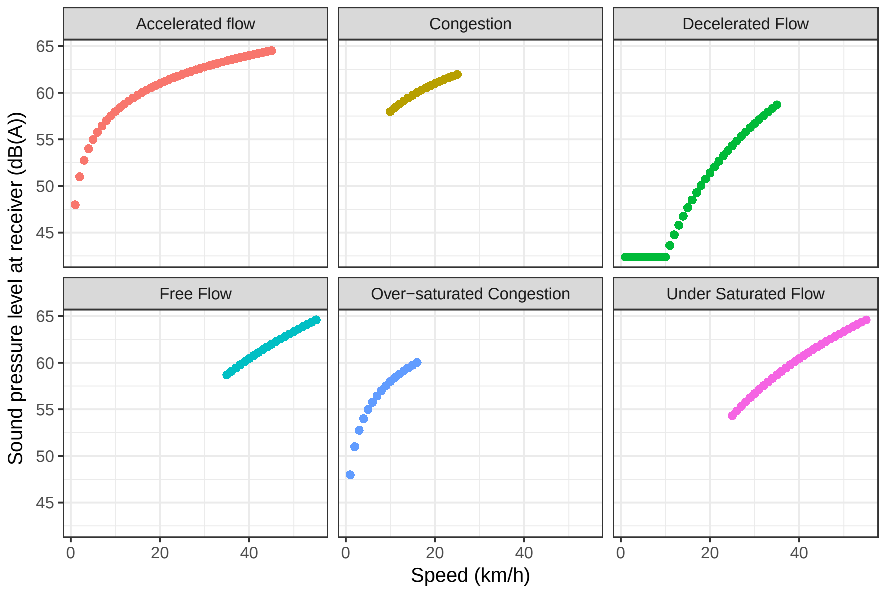

Figure 9. The estimated sound pressure level at receiver in the investigated traffic conditions.

Having estimated the air pollutants and GHG emissions as well as the emitted noise in the investigated traffic conditions, their related environmental external costs have been calculated using Equations (13) and (14), respectively. Figure 10 shows the total air pollutants and GHG emission costs in each traffic condition. As is clear from the Figure, the three main cost components in each traffic condition are CO_2 cost, NO_x cost, and PM cost forming a considerable portion of the total costs shown in Figure 10 (although the legend of the Figure shows the costs of CO, CO_2, NO_x, PM, and SO_2, the cumulative values on the Figure shows that just CO_2, NO_x, and PM are considerable air pollutants and GHG external costs, since the CO and SO_2 costs are too small to be illustrated with the other costs). But it should be emphasized that although these two environmental external costs (CO and SO_2 external costs) are lower than the other air pollutants and GHG external costs, they have to be paid attention since the environmental external cost calculations are based on a limited traffic volume and infrastructure length (see Table 2).

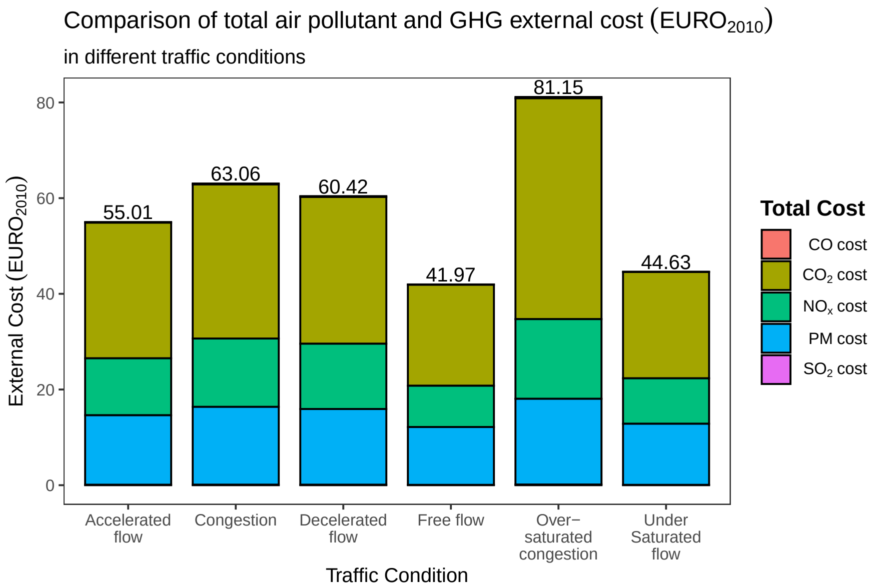

Figure 10. Comparing the total air pollutants and GHG external cost in different traffic conditions

The results showed that the total air pollutants and GHG costs, as compared to free flow condition, has been increased by 6%, 31%, 44%, 50%, and 93% in undersaturated flow, accelerated flow, decelerated flow, congestion, and over-saturated congestion, respectively. Furthermore, the effect of different traffic conditions on each air pollutant and GHG costs has been studied in Table 5. By taking a deeper look in Table 5, it turns out that, as compared to free flow condition, the CO_2 external costs have been increased by 5.19%, 34.26%, 45.29%, 52.59% and 118.64% in undersaturated flow, accelerated flow, decelerated flow, congestion, and over-saturated congestion respectively. In the same way, compared to free flow condition, NO_x external costs have been increased by 10%, 37.86%, 58.10%, 65.41%, and 92.88% in undersaturated flow, accelerated flow, decelerated flow, congestion, and over-saturated congestion, respectively. Moreover, as compared to the free flow condition, PM external costs have been increased by 5.68%, 20.22%, 30.91%, 34.63%, and 48.21% in undersaturated flow, accelerated flow, decelerated flow, congestion, and over-saturated congestion respectively. Furthermore, as compared to free flow condition, SO_2 external costs have been increased by 5.19%, 34.26%, 45.29%, 52.59%, and 118.64% in undersaturated flow, accelerated flow, decelerated flow, congestion, and over-saturated congestion, respectively. Lastly, when compared to free flow condition, CO external costs have been increased by 25.88%, 121.85%, 182.17%, 208.94%, and 339.99% in the undersaturated flow, accelerated flow, decelerated flow, congestion, and over-saturated congestion, respectively.

Apart from the environmental external costs associated with the air pollutants and GHG, the effect of different traffic conditions on the environmental external costs that are associated with road traffic noise has been theoretically investigated in this paper.

Figure 11 shows the total noise external cost in different traffic conditions. In fact, as compared to free flow traffic, the noise external costs have been reduced in accelerated flow, undersaturated flow, congestion, over-saturated congestion and decelerated flow by 2%, 11%, 12%, 36%, and 69%, respectively.

Table 5. Theoretical comparison of the urban road environmental external costs in different traffic conditions.

Traffic Condition	Air Pollutants and GHG Cost € (2010)						Noise Cost € (2010)/ Year/Person Exposed Noise
	CO_2	NO_x	PM	SO_2	CO	Total	
Free flow	21.12	8.63	12.09	0.06	0.06	41.97	149.44
Under sat. flow	22.22	9.50	12.78	0.07	0.07	44.63	132.68
compared to free flow	5.19%	10%	5.68%	5.19%	25.88%	6%	−11%
Congestion	32.23	14.28	16.28	0.10	0.18	63.06	132.16
compared to free flow	52.59%	65.41%	34.63%	52.59%	208.94%	50%	−12%
Over-sat. congestion	46.18	16.65	17.92	0.14	0.26	81.15	95.62
compared to free flow	118.64%	92.88%	48.21%	118.64%	339.99%	93%	−36%
Accelerated flow	28.36	11.90	14.53	0.08	0.13	55.01	146.27
compared to free flow	34.26%	37.86%	20.22%	34.26%	121.85%	31%	−2%
Decelerated flow	30.69	13.65	15.83	0.09	0.16	60.42	46.93
compared to free flow	45.29%	58.10%	30.91%	45.29%	182.17%	44%	−69%

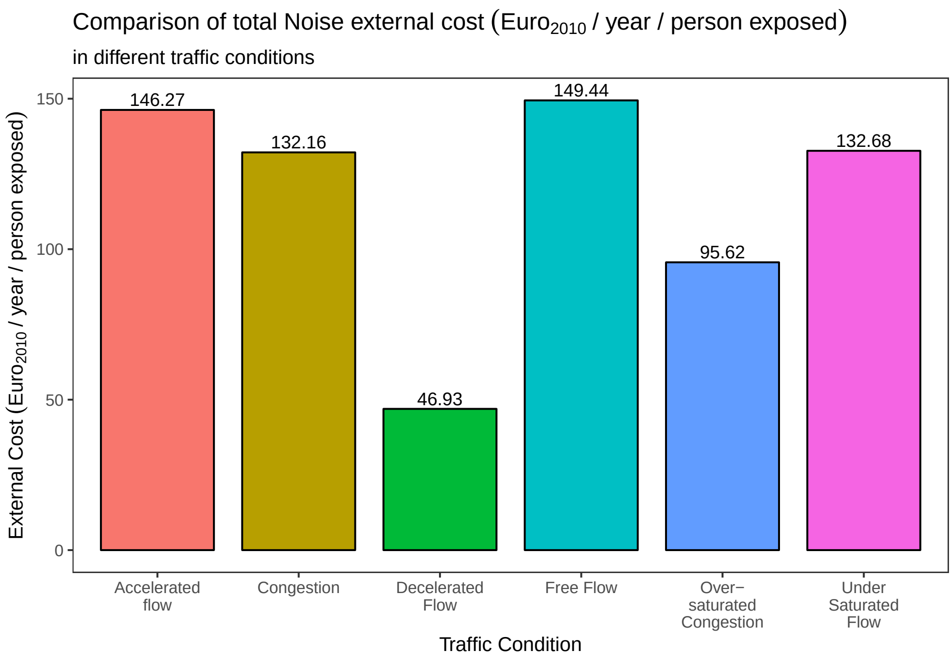

Figure 11. Comparing total noise external cost in different traffic conditions

4. Discussion

Different sectors are responsible for the environmental problems [90–93], including transportation sector. In the current paper, the effects of different traffic conditions on the urban road environmental external costs are theoretically studied. Regarding the CO_2 emissions, the results showed that each traffic condition that has more vehicles with lower speeds (km/h) generates more gram of CO_2 (g CO_2) compared to the other traffic conditions. For instance, the over-saturated congestion condition has generated the highest theoretical amount of CO_2 (g CO_2) in 1 km since the vehicles in this traffic condition would have the lowest possible speeds in traffic flow conditions. Regarding the NO_x emissions, it is evident that the theoretical traffic flow (1600 Euro IV Diesel engine <2.0 passenger cars) produced gram of NO_x (g NO_x) in the higher ranges in over-saturated congestion condition compared to other investigated traffic conditions. Additionally, the free flow traffic produced the lowest possible range of g NO_x when compared to the other traffic conditions. This is due to the fact that traffic flow in free flow condition is in higher ranges of speed (see Table 1) compared to the other investigated traffic conditions. Regarding the CO emissions, similar to CO_2 and NO_x, investigating the relationship of theoretical CO emission (for the Diesel passenger cars) and speed ranges in the investigated traffic conditions illustrates the fact that each traffic condition that has more vehicles with the lower speeds would produce more gram of CO (g CO) in 1 km of the urban roads. Regarding the PM emission, the results showed that the emitted gram of PM (g PM) is by far lower than the emitted g CO_2, g NO_x and g CO. Furthermore, the traffic conditions with higher speed ranges (e.g., free flow and undersaturated flow) emitted lower g PM compared to the other investigated traffic conditions. Regarding the SO_2 emissions, it is evident that the vehicles in the over-saturated congestion emitted the SO_2 in higher ranges when compared to the other investigated traffic conditions (pay attention to the vertical axis of Figure 8). Regarding the noise in different traffic conditions, the results showed the sound pressure level in free flow condition—in which the range of traffic speed is the highest when compared to the other investigated traffic conditions—was in a higher range when compared to the other investigated traffic conditions. Furthermore, the sound pressure level in decelerated traffic flow was in a wider range as compared to the other investigated traffic conditions.

Regarding the external costs that are associated with the investigated air pollutants and GHG emissions, the external costs associated with CO_2, NO_x and PM formed a considerable portion of the total costs and were the main components of the total cost. The results showed the fact that free flow traffic had considerably generated lower total air pollutants and GHG environmental external costs when compared to the other investigated traffic conditions. Overall, the air pollutants and GHG costs were all in their Minimum values in free flow condition and their Maximum values in over-saturated congestion. Moreover, the results showed that the CO cost is the most affected air pollutant externality (by traffic condition), as compared to the other air pollutants and GHGs environmental external costs. The second most affected air pollutant external cost (by traffic condition) is NO_x, except in over-saturated congestion where CO_2 and SO_2 costs (the two fuel consumption related pollutants) are the most affected pollutants environmental external costs. Furthermore, the environmental external cost associated with PM is the less affected external cost (by traffic condition) when compared to the other air pollutants and GHGs costs, except in undersaturated flow, where CO_2 and SO_2 costs (the two fuel consumption related pollutants) are the less affected pollutants in terms of environmental external costs.

Regarding the external costs that are associated with road traffic noise, the results showed that, in contrast to the environmental external costs associated with the air pollutants and GHGs, free flow condition generated the highest environmental external costs associated with noise when compared to the other investigated traffic conditions. This is an important result that should be considered by traffic engineers and urban road transport decision-makers. Generally, to reduce pollutant concentrations, the literature suggests the traffic flow management strategies aiming to facilitate free flow traffic on urban roads (see, for example, [24]). This is consistent with the results obtained in this paper; however, this is just one side of the coin. The other side is actually the fact that the free flow condition generates more noise when compared to the other traffic conditions. Thus, taking both the air pollutants and noise into account, the results clearly suggest finding a balance point in between.

5. Conclusions

External costs that are associated with air pollution, climate change linked to greenhouse gas emissions, and noise are among the most important environmental externalities generated by road transport. Growing the city population and consequently, the number of vehicles might result in generating road transport negative externalities that should be carefully studied. The effects of various traffic conditions on urban road environmental external costs have been theoretically investigated. In the current paper, distributions of traffic speed, along with the statistical specifications of traffic speed in different traffic conditions, were the main element for generating random speed in different traffic conditions by using the Monte Carlo method. The generated speeds were further assigned to each vehicle to calculate the emitted air pollutants, GHG, noise, and their associated external costs.

The obtained results showed that the environmental external cost that is associated with CO was the most affected air pollutant environmental external cost (by traffic condition), when compared to the other air pollutants and GHGs external costs. Furthermore, the environmental external cost associated with PM was the less affected environmental external cost (by traffic condition), compared to the other air pollutants and GHGs costs, except in undersaturated flow, where CO_2 and SO_2 costs were the less affected environmental external costs, although they were quite close to the PM changes (as compared the percentage changes of PM, CO_2, and SO_2 in undersaturated flow in Table 5).

Furthermore, the result showed that accelerated and decelerated conditions will have a considerable impact on the air pollutants and GHG externalities. Thus, traffic calming strategies are expected to have a positive impact on reducing these externalities. Likewise, the accelerated traffic demonstrated a positive impact on the generated noise with almost the same as free flow condition (-2% lower than free flow condition, to be exact). Thus, traffic management strategies aiming to avoid accelerated traffic flow are expected to reduce traffic noise in urban areas.

Moreover, on the one hand, the results showed that each traffic condition that has more vehicles with lower speeds generates more gram of air pollutants and GHG and, consequently, more external costs that are associated with the emitted pollutants. This suggests considering traffic flow management strategies aiming to facilitate free flow traffic on urban roads to reduce air pollutants and GHG externalities. However, on the other hand, free flow traffic generated higher noise externalities when compared to other traffic conditions. Thus, the results suggest considering a balance point in between.

However, the current paper suffers from the following limitations. (1) This study theoretically assessed the effect of different traffic conditions on 1 km of urban road with 1 lane for the sake of comparison of the effects of different traffic conditions on the generated environmental externalities; (2) a limited traffic flow is investigated in this paper; and, (3) other determinants that might have an indirect effect via traffic conditions on urban road environmental externalities are kept unchanged in this study.

The scope of the current study, to overcome the aforementioned limitations, is to: (1) assess the effects of the investigated traffic conditions on a real-world network through a simulation-based study; and, (2) conduct on-field measurements of air pollutants and noise in different traffic conditions to investigate the indirect effects of other determinants on the environmental externalities in different traffic conditions.

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