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Estimation of road traffic induced environmental pollutants based on a point-to-point traffic detection system

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Abstract
This paper aims at the estimation of road traffic induced environmental pollutants for the city of Thessaloniki, based on travel time detections of a point-to-point detection system. The hourly and daily pollutant emissions (NO_x, CO, HC) and fuel consumption (FC) were estimated based on the COPERT model and include hot emissions of passengers' cars circulating in high hierarchy links of the transport network. The system detections (travel time) were correlated based on each path's length, in order to determine the average vehicle speed per analyzed time interval, which was the main determinant for calculating traffic induced emissions. The paper concludes with a sensitivity analysis based on link capacity and the prevailing traffic flow characteristics for optimally determining the vehicle speed and flow that minimize environmental pollutants.

Keywords: traffic induced pollutants; point-to-point detection system; environmental modeling

1. INTRODUCTION

This paper aims at presenting a methodology for estimating traffic-induced pollutant emissions (CO, HC, NO_x) and fuel consumption in the city of Thessaloniki, Greece. The estimation of these pollutants is based on a point-to-point traffic detection system, forming 10 individual paths throughout Thessaloniki's road network, using Bluetooth technology for estimating travel times of passenger vehicles. The estimated travel time is then transformed into average vehicle speed, based on its correlation with each path's length, which is the main determinant for the calculation of the traffic-induced pollutants. A macroscopic static environmental model is then used for determining the volume of each pollutant as well as fuel consumed by passenger vehicles.

The paper is structured as follows: The following section includes a detailed description on materials and methods used in the framework of this paper, a brief review on environmental modeling techniques used for estimating traffic pollutants, the relevant methodology for calculating them. Afterwards, the section of Results and Discussion includes the results and findings of the application of the proposed methodology, while the final section includes concluding remarks of the paper.

2. MATERIALS AND METHODS

2.1 Model-based calculation of traffic induced pollutants

During a vehicle's operation, its engine undergoes changes in the temperature. The chemical substances emitted during this process can be divided in two main categories: hot and cold emissions. The first category refers to the pollutants emitted when a vehicle's engine is at its "cold phase" with low temperatures ((~ -18 -7 C^o). On the contrary, hot emissions refer to the pollutants emitted when a vehicle's engine is at its "hot phase", where high temperatures (~ 80 - 95 C^o) are prevalent.

Calculation of emissions is mostly conducted with the help of modeling techniques, usually referred to as emission models. The most important feature of these models is the nature of parameters used for the calculation of pollutant emissions. Depending on the kind of parameters, models are categorized in two main categories, namely static and dynamic. Static models can be used in macro- or meso-scale level (national, regional, and city level) and refer to models, which use average values of parameters for calculating pollutants (e.g. average vehicle speed). On the other hand, dynamic models use instantaneous variables and can be used at microscopic level (street, vehicle level) [3, 4].

Static models are used to evaluate environmental pollutants based on the average speed and they are encountered in a series of research works, as their main advantage relies on their ease of use. Yet, average values are not representative in many cases, such as in urban areas, where the sequence of intersections is importantly high. In this case, average speed cannot be regarded as a significant parameter for the calculation of the environmental indexes [3]. On the other hand, dynamic emission models can prove to be an alternative approach as their calculation function is based on instantaneous values taking into consideration kinematic motions based on different traffic flow and geometrical conditions [5-9].

According to the study area in the current paper (Figure 1), the sequence of intersections is not importantly high. Given the fact that the establishing point to point detection system (§2.3) estimates the average time for each path and each path's length is also carefully selected, it is possible to calculate average speed via the primary kinematic function: average speed= length/average time. In this way, average speed is known, which means that a static model is more appropriate for use considering the fact that a static model uses average values.

Among the static macroscopic emission models lies COPERT, which is the emission model used in the current paper for evaluating emission pollutants [10, 11]

2.2 Study context

Thessaloniki is the second largest city in Greece and one of the most important industrial and commercial centers in the Balkan Peninsula. Its population is approximately 1.006.730 citizens, covering an area of 1.455,68 square kilometers with a density of 692 inhabitants per square kilometers. The city provides public transportation by the responsibility of Thessaloniki's Urban Transport Organization (OASTH) [1, 2].

The study area, where the estimation of road traffic environmental pollutants has been made, consists of ten paths (a group of links between two intersections equipped with Bluetooth detectors) in the Municipality of Thessaloniki. They are identified by the alphabet characters A-H denoting the starting and the ending intersection, which has a Bluetooth detector. Particularly, the paths are E-F [Konstantinou Karamanli Avenue (Intersection with Kleanthous Street)-Syntrivani Square], A-G [Lagkada Street (Intersection with Agion Panton Street)-Dimokratias Square], A-H [Lagkada Street (Intersection with Agion Panton Street)-Agiou Dimitriou Street (Intersection with Ethnikis Aminis Street)], F-C [Syntrivani Square-White Tower], B-D (Vasilisis Olgas Street (Intersection with Archeologikou Mouseiou Street)-YMCA Square], D-F [YMCA Square-Syntrivani Square], G-F [Dimokratias Square-Syntrivani Square], H-F [Agiou Dimitriou Street (Intersection with Ethnikis Aminis Street)-Syntrivani Square], F-H [Syntrivani Square-Agiou Dimitriou Street (Intersection with Ethnikis Aminis Street)] and F-G [Syntrivani Square-Dimokratias Square]. The reason why these paths have been selected is not only based on the implemented point to point detection system within the city's road network but also on the fact that these paths accommodate a large number of daily vehicular traffic. The latter provides the ability to have more accurate results for the average time estimation. Figure 1 depicts the location of the ten paths in the urban area of Thessaloniki.

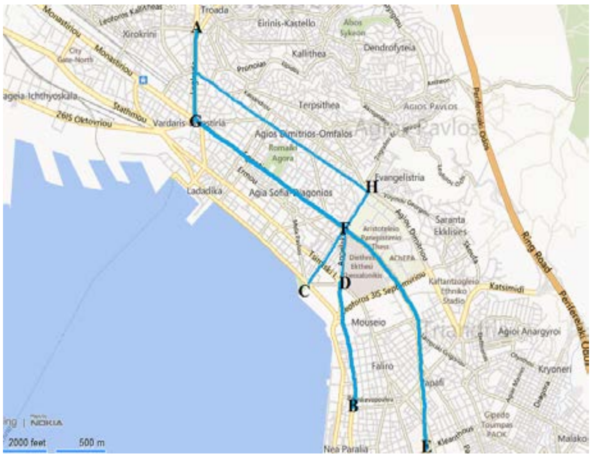

Figure 1. Study area including ten paths in which the point-to-point detection system has been established

In need of calculating emissions (CO, NO_x, HC) and fuel consumption (FC), the initial dataset was needed. This dataset consists of the characteristics related to the ten paths, including length in meters, free flow travel time in seconds, average flow in vehicles per hour and average travel time in seconds.

2.3 Average speed calculation based on a point-to-point vehicle detection system

Provided that COPERT is a static model, this means that it uses average values. The main parameters, which describe a vehicle's move, are speed, length and time. Some parameters are known by measurements at real time, whereas others occur via mathematical functions. In this paper the measured and defined parameters examined, are the average time and path's length respectively. This was achieved by a point-to-point vehicle detection system, being established in ten paths in Thessaloniki's urban area. This point-to-point detection system includes ten detectors, being able to track active Bluetooth devices (e.g. mobile phones) existing in vehicles, establishing a network. After the establishment and definition of the network, a calibration is necessary in order to give a reliable database of estimated travel times. On condition that the network is defined and calibrated, this allows collecting and analyzing data, according to a specific and proposed methodology. Therefore, the processed data can be provided as information to travelers by VMS[12].

2.3.1 Preparatory procedure

The preparatory procedure refers to several important actions, which should be made before the final estimation of travel times for each path. It includes: the selection of the location of the Bluetooth detectors, and the respective paths' length and the identification of vehicle fleets using Bluetooth devices. After the network's definition the collected data should be analyzed in real time in order to estimate the final average travel time values for each path.

2.3.2 Average speed calculation

Regarding the average speed calculation, the final output database is related to the estimated travel times in a daily basis and in hourly intervals (i.e. 1:00-2:00 am-pm), for a time period of 7 days (October-November 2012) according to the kinematic function $u = Dx/Dt$, where u is the average speed in meters per second or in kilometers per hour, Dx is the length in meters and Dt is the average time in seconds.

2.4 Pollutants estimation method

COPERT is able to conduct three major calculations: the exhaust system's emissions, fuel consumption, and non-exhaust emissions such as tire wear, brake wear and road abrasion. The model can categorize several vehicles' categories, including passenger cars, light and heavy duty vehicles, buses, motorcycles and mopeds. Furthermore, it calculates the following emissions - Carbon Monoxide (CO), Nitrogen Oxides (NO_x), Hydrocarbons (HC) and Fuel Consumption (FC) based on the following function:

$$EF = (a + c * V + e * V^2)/(1 + b * V + d * V^2) \quad (1)$$

where,
EF is the estimation of the pollutant (g/km),
V is the speed (km/h) and
a, b, c, d, e are stationary parameters - coefficients of the function.

The function coefficients are described in detail in [13].

3. RESULTS AND DISCUSSION

Utilizing the initial data and the methodology as described in the previous chapters, it was possible to produce the results related to the pollutant emissions. The examined pollutants refer to CO, NO_x, HC and Fuel Consumption (FC) for EURO I-IV emission standards, measured in grams per kilometer. According to function (1), the pollutant indexes are dependent on the average speed, calculated by the average values of time and length. The analysis consists of three steps: hourly analysis from Monday 15/10/2012 to Sunday 25/11/2012, aggregate analysis for each day (Monday to Sunday) for the same time period and speed-emission analysis based on the day with the highest emission levels for all technologies (EURO I-IV).

3.1 Hourly analysis of emissions

The hourly analysis of emissions describes pollutants' behavior in hourly intervals during a day for the examined time period. It includes the matrices, which represent a specific pollutant (CO, NO_x, and HC) or the Fuel Consumption (FC) according to EU legislation for the vehicles fleet composition. The vehicles fleet composition refers to a Light Duty vehicle's type related to its stage emission standards (EURO I-IV), which have been defined by the EU Legislation in the legal framework of directives, which amend the Directive 70/220/EEC. Furthermore, it refers to the vehicle's engine capacity in order to separate vehicles with different cylinder capacity (Light Duty Vehicles with cylinder capacity less than 1,4 liters, 1,4-2,0 liters and more than 2,0 liters).
The pollutant emission matrices (CO, NO_x, and HC) include emission levels in grams per kilometer for EURO IV Light Duty Vehicles, which cover all engine capacities [Table 3-41, 13]. Instead, the Fuel Consumption (FC) matrices represent fuel consumptions for EURO IV Light Duty vehicles according to their engine capacity. This can be explained by the fact that the function's (1) coefficients for fuel consumption are different for vehicles with engine capacity under 1,4 liters, 1,4-2,0 liters and higher than 2,0 liters [Table 3-41, 13]. Each matrix's cell includes the average emission value (grams per kilometer) related to a specific hourly interval and day. By finding all the average values for each cell it is possible to create the relative graphs, which describe pollutants' behavior in all 24 hourly intervals. Findings refer to Tuesday for all related dates (16/10, 23/10, 30/10, 6/11, 13/11 and 20/11), which are incorporated into the observed time period (15/10/2012 - 25/11/2012).Tuesday was selected because, it is not only a typical workday but also appears to have the highest emission levels compared to the rest days. Figure 2 shows the hourly emission analysis.

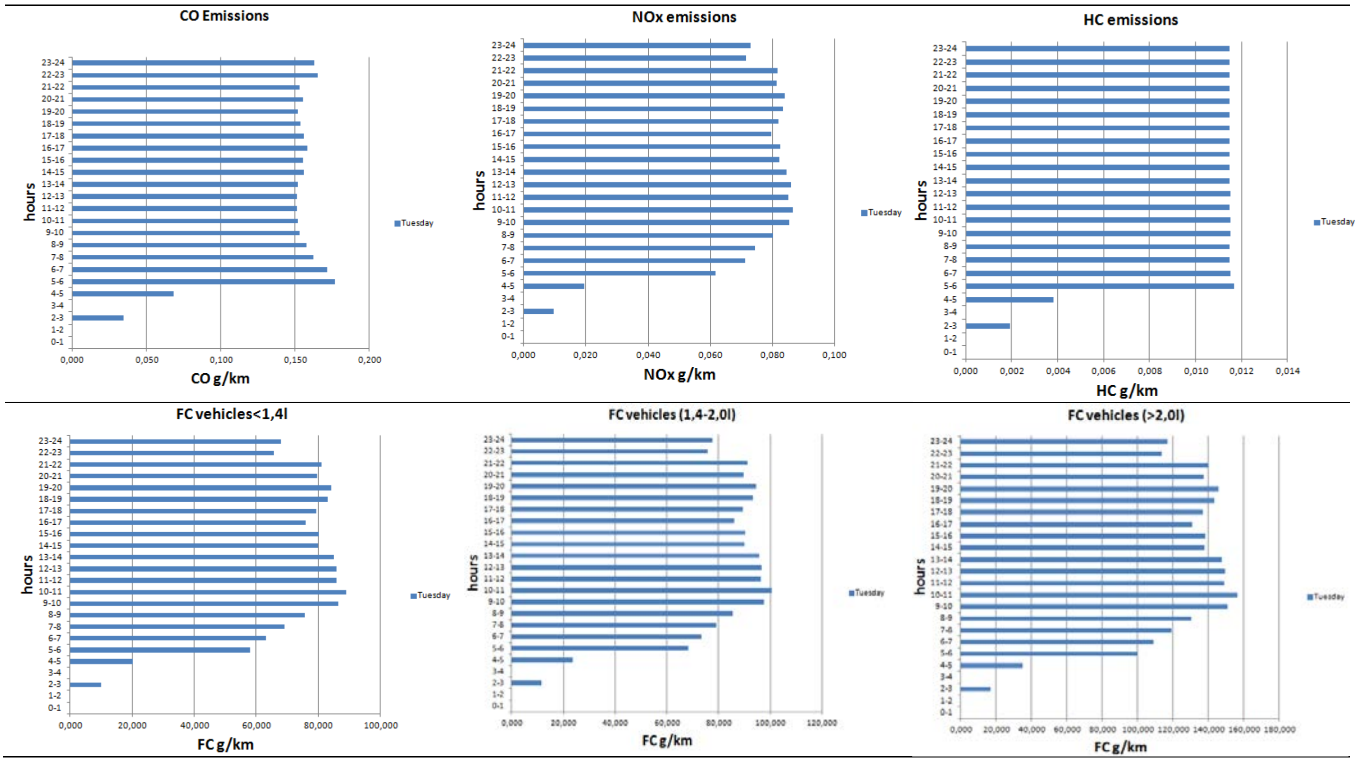

Figure 2. Pollutant analysis in hourly intervals

As observed, there are empty bars in the hourly intervals 0-1, 1-2 and 3-4. This can be attributed to a lack of primary data related to average time, which arise by the establishing point to point detection system. This means that it is not possible to estimate the average speed, which is an important factor in function (1). In addition, high levels of CO emissions appear in the early morning and before midnight (5:00-7:00 and 22:00-24:00). This can be explained by the fact that these hourly intervals let drivers accelerate and reach high speeds due to low values of traffic volume. As a result, vehicles' axes rotate more frequently, decreasing fuel economy. In this way, higher emission levels occur. Furthermore, NO_x emissions appear high levels in the morning from 9:00 to 13:00 with the highest in the hourly interval 10:00-11:00 (0,087 grams per kilometer), due to high vehicle accumulation during these hours. An increase in vehicles' number leads to travel delays with more time spending traveling. In this way vehicles' engines are often exposed to high temperatures, which are common sources of NO_x emissions. Similarly, maximum fuel consumption levels appear in the morning from 9:00-13:00 where the interval 10:00-11:00 appears the highest values. Finally, hydrocarbons show stability throughout the day.

3.2 Daily Analysis of emissions

The present aggregate analysis refers to a time period of 40 days and aims to analyze each pollutant's behavior on each day individually. Therefore, there was a need of a matrix, including all the aggregate values (grams per kilometer) of all pollutants for each working day. Each cell's value arises by the aggregate value of all emissions and fuel consumptions related to the hourly intervals for a specific day in the time period of 15/10/2012 to 25/11/2012. By summing the emission values for every single day (i.e. value 18.606 grams per kilometer arises by summing emissions CO for 15/10, 22/10, 29/10, 5/11, 12/11, 19/11 for Monday) Table 1 was created.

Table 1: Aggregate table (EURO IV) for all pollutants (g/km)

	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
CO	18.606	18.496	18.009	18.094	17.835	18.681	19.097
HC	1.345	1.345	1.310	1.310	1.300	1.334	1.345
NOX	9.253	9.357	9.168	9.027	9.075	8.965	8.800
FC<1,4	8885.687	9037.014	8744.582	8638.294	8920.699	8526.794	8239.739

FC 1,4-2,0	10092.199	10234.631	9896.162	9793.245	9957.284	9723.491	9439.656
FC >2,0	15399.452	15643.866	15114.827	14937.127	15232.464	14778.663	14272.498

By observing Table 1, it can be concluded that the highest level of CO emissions, appear on weekends (Saturday-Sunday). This can be attributed to the dates 26, 27 and 28 of October, which are Friday, Saturday and Sunday respectively. These dates include national holidays, having a lot of activities such as the army parade on 28 of October. To this reason, main central avenues are not accessible by vehicles so, there is a traffic transposition to other main roads, which results in a traffic congestion not least an increase on the CO emissions from vehicles' exhaust system. On the contrary, the HC and NO_x emissions have their highest values on the week's beginning days (Monday-Tuesday), which also have the highest traffic volumes. HC and NO_x emissions are produced when a vehicle's engine has high temperatures, which is a common phenomenon in urban areas with high traffic volumes. Similarly, the highest levels of fuel consumption are observed on the week's beginning days (Monday-Tuesday).

3.3 Speed – emission analysis depending on vehicle technology

The European emission standards, determine the emission limits, caused by vehicles in EU member states. Since 1992, they have been lowered with the EURO I-IV stages. Specifically EURO I stage refers to vehicles being introduced by Directive 91/441/EEC in July 1992 with a system of three way catalyst. EURO II vehicles constitute an enhancement application of EURO I vehicles in the catalyst system accompanied by lower emission limits, being introduced by Directive 94/12/EC in 1996. EURO III stage, being introduced in January 2000 (Directive 98/69/EC), includes vehicles with twin lambda sensors, in an EU's effort to reduce the emission limits. Finally, EURO IV stage, being introduced in January 2005 (Directive 98/69/EC), pertains reductions to emission pollutants particularly, 57% for CO, 47% for HC and NO_x in comparison with EURO III stage [13].

The speed emission analysis represents a way to describe the estimation of hot emissions, dependent on average speed and vehicle's technology system. In addition, it may provide useful elements such as technology vehicle's system and its reliability. Therefore, its results are able to provide suggestions if a technology car system should be adopted or not and alternative solutions as well.

In this paper, the speed emission analysis is conducted in accordance with the previous stage's daily emission analysis and includes a study for a specific day related to the time period of 15/10/2012 to 25/11/2012, for EURO I-IV technologies.

The speed emission analysis is related to six Tuesdays on October and November of 2012 (16/10, 23/10, 30/10, 6/11, 13/11 and 20/11). It requires the average speed for these particular dates. The average time, which refers to an hourly interval, is estimated by the establishing point to point detection system in the study area of Thessaloniki whereas the path's length is carefully defined according to the preparation procedure (§ 2.3.1). The use of the primary kinematic function (average speed=length/average time), leads to an estimation of average speed for each hourly interval within a day. In addition, the average value of the 24 hourly interval average speeds is the average day's speed (e.g. for 16/10). The same procedure is followed for the rest dates (23/10, 30/10, 6/11, 13/11, 20/11). Furthermore, the six average day speeds for each date are used to the COPERT model, particularly to the function (1) [13], in order to estimate CO, NO_x, HC emissions and Fuel consumptions, which refer to a date for a specific emission standard (e.g EURO IV). The rest emission standards (EURO I-III) are estimated in the same way, using the six average date speeds in the COPERT model on condition that the appropriate coefficients of function (1) are used. As a result, graphs can be formed where the six average day speeds represent the x variables whereas the estimated emissions represent the y variables.

Figure 3 depicts the estimation of pollutant emissions dependent on the average speed for each emission standard - EURO I (blue line), EURO II (red line), EURO III (green line), EURO IV (purple line). All the values refer to particular dates (Tuesdays 16/10, 23/10, 30/10, 6/11, 13/11 and 20/11), being incorporated into the observed time period.

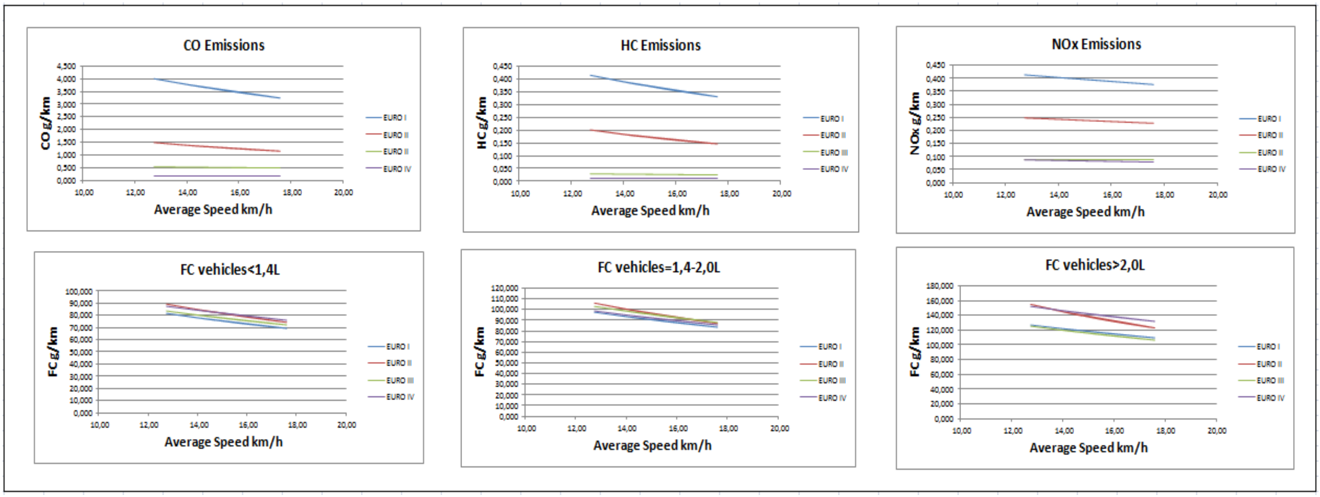

Figure 3. Correlation between emission pollutants and average speed

As observed, EURO IV technology plays an important role in order to decrease the emission pollutants values, enhancing air's quality. Figure 3 depicts that EURO III and IV technology vehicles are both similar and stable concerning low emission indexes, which decrease as speed increases. Earlier technologies do not reveal this stability and their emission indexes are higher in lower speeds. As in the emission pollutants graphs, all EURO technologies reduce the fuel consumption as speed increases. However, EURO IV technologies do not affect fuel consumption importantly. For vehicle speeds approximately equal to 18 kilometers per hour, fuel consumption oscillates from 70 to 90 grams per kilometer with EURO I and III technologies providing better results.

5. CONCLUSIONS

This paper describes an important correlation between traffic and environmental values. A point to point detection system, which is able to give traffic values (travel time, average speed) can be correlated with a mathematical model (COPERT) in order to calculate emission values.

Taking the results into consideration, it can be concluded that the week's beginning days appear the highest emission levels. On the other hand, EURO IV technologies decrease the emission levels but they do not affect fuel consumption importantly.

These paper findings may help to start environmental campaigns in order to inform and make people more conscious about the emission pollutants. Therefore, they can be a motive for participating in activities related to environmental protection. Furthermore, these findings may be taken into account for studies related to cities with similar features to Thessaloniki. Finally, further studies and innovations are needed in order to restrict fuel consumption.

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