Micro and Macro Modelling of Cold Start Emissions from Road Traffic in Athens

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Abstract

This study aims to visualize and quantify the contribution of cold start emissions on the overall road transport emissions in the road network of Athens, Greece. The developed methodology was based on the combination of PTV VISUM and COPERT Micro models, for traffic and emissions modelling respectively. The hourly and daily CO, VOC, NO_x and CO_2 emissions from passenger cars were calculated for both hot operation and cold starts, in each of the traffic links for a typical weekday (October 2010). The study focuses on passenger cars only, since they constitute the major category of the Athens vehicle fleet. The results on micro level revealed the local hot-spots and the high emitting links, which usually belong to the large boulevards of the city. The results on macro/city level showed that the cold start emissions constitute a major contributor for CO and VOC road transport emissions (45% and 44% respectively), whereas their impact on total NO_x and CO_2 emissions is relatively smaller (21% and 7%). Thus, specific cold start allocation modelling activities to road networks have to be developed in order to correctly allocate the cold start impact, in particular for local hot-spots.

Introduction

During cold start, the exhaust emissions of regulated pollutants are high, since the engine, catalyst and drive train have not reached their regular operating temperatures. Several studies have been carried out trying to identify the impact of various parameters, such as vehicle technology, average speed, ambient temperature, travelled distance and parking duration, on the cold start emissions from passenger cars (André and Joumard, 2005).

A number of models have been developed for calculating cold start emissions (Boulter and Latham, 2009). Due to lack of data, most of these models focus mainly on passenger cars. The ARTEMIS project developed a detailed approach to calculate cold-start emissions for a variety of conditions and with models of variable resolution (Joumard et al., 2007). One of the three proposed ARTEMIS models is used here in order to quantify the impact of cold start emissions on micro (per traffic link) and macro level (entire city) for the Greater Athens Area.

According to data from EC4MACS project (http://www.ec4macs.eu) the share of passenger cars in the Greek vehicle fleet was 56% in 2010. If we take into account that the last national census – conducted in 2011 – showed that out of 11 million Greeks the 4 million live in Athens (Hellenic Statistical Authority, 2014), one concludes that approximately 50% of the registered vehicles operate in Athens and are primarily passenger cars. Thus, in respect of air quality, the quantification of cold start emissions from passenger cars in Greater Athens Area is an issue of significant importance.

Methodology

The flowchart of the methodology followed in this study is presented in Figure 1. There are two distinct parts on the flowchart; the first one is the traffic modelling and the second one is the emissions modelling, which are analysed in the next sections. The main concept is to use the available traffic data measured with inductive loops in order to calculate the necessary traffic parameters (traffic volume, average speed, number of trips, trip length etc.) throughout the Athens network. Then, by using these parameters, calculate both hot and cold start emissions from every traffic link and for the entire city.

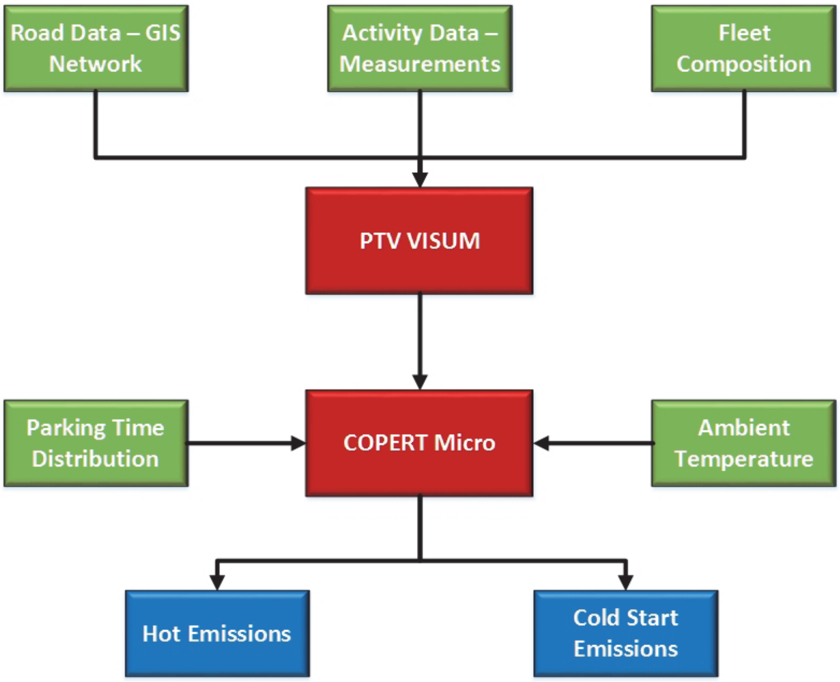


Figure 1: Flowchart of the methodology

Traffic modelling

The transportation model for Athens has been developed with the PTV VISUM software (http://vision-traffic.ptvgroup.com/en-us/products/ptv-visum), a traffic assignment tool for urban and regional operational planning analysis that has been used in several studies (Stamos et. al., 2011; Ayfadopoulou et. al., 2012). The network used for the purpose of this paper consists of a detailed representation of the urban and regional road network of the metropolitan region of Athens, based on open-source GIS, fused with traffic related parameters (Figure 2).

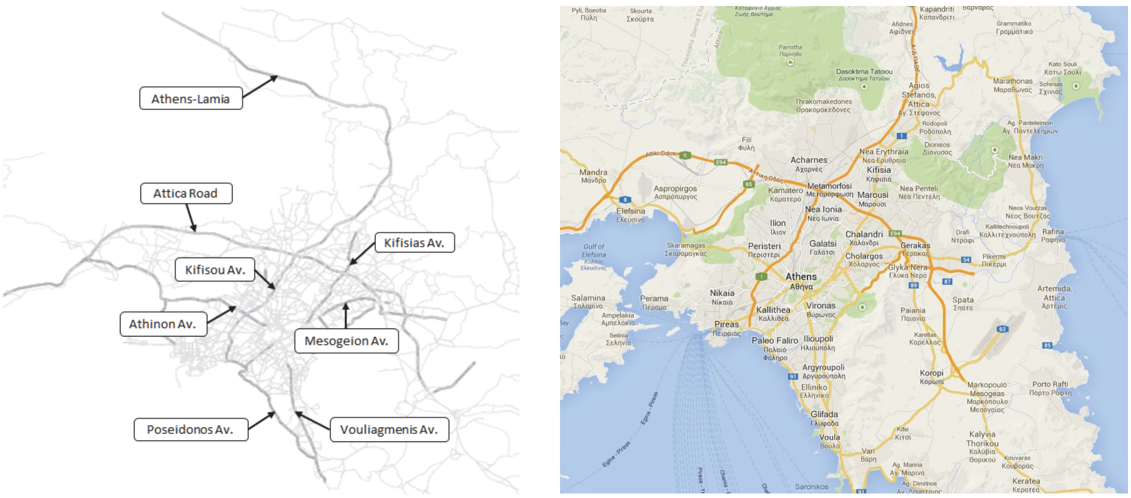


Figure 2: Map and schematic representation of the Athens network on GIS (main roads are highlighted)

The network consists of 81880 directed links and 36725 nodes. The links contain information about the number of lanes, the road type and its hierarchy in the network, width, length, free flow speed, design and effective capacity, direction, allowed transport systems. The link delays are calculated with the use of BPR functions, the parameters of which rely on previous studies and have been updated through travel time measurements for the purposes of the work presented herein. The nodes contain detailed information about the junction's geometry, allowed movements and control type of the node.

The network consists of 359 traffic analysis zones connected to physical nodes of the road network via 3468 connectors, according to their accessibility index (Friedrich and Galster, 2009), avoiding connections with nodes belonging to high hierarchy links. The demand side is comprised by 24 hourly Origin-Destination (OD) matrices and the travel demand for a typical weekday is within the range of 3.873.745 vehicle trips. The obtained OD matrices are corrected using the hourly volume data measured by inductive loop detectors installed at 557 locations across the city. The OD matrix correction is performed with a fuzzy-set based matrix correction procedure (Rosinowski, 1994).

Since traffic measurements are available only at a number of locations which is smaller than the number of trips, then the problem of determining the OD matrix which reproduces trips that result to traffic volumes equal to the ones measured is underdetermined. The matrix correction procedure described herein is of bi-level nature, where at the upper level user equilibrium traffic flows are computed, subject to the corrected OD matrices at the lower level. The upper level user equilibrium traffic flow estimation, known as the Traffic Assignment Problem, based on Wardrop's user equilibrium principle (Wardrop, 1952), is solved with an implementation of the Linear User Cost Equilibrium algorithm (Gentile and Noekel, 2009), with an average goodness-of-fit of 0.94.

Emissions modelling

The emissions calculation were performed with COPERT Micro (Samaras et al., 2014), a specially developed version of COPERT 4 (Ntziachristos et al., 2009). COPERT Micro calculates both hot and cold start emissions per traffic link following an approach that combines the methodology of COPERT 4 (for hot emissions) and ARTEMIS project (for cold start emissions) respectively.

A. Hot emissions

The equations below summarize the main calculations conducted by COPERT Micro during hot exhaust emissions calculation. First of all, based on the average speed of each traffic link the corresponding emission factors are calculated for each vehicle category and for every pollutant:

$$EF_{i,\,k}(V)= f_{EF,\,i,\,k}\,(V_j)$$

Where:
$EF_i(V)$: hot exhaust emission factor per vehicle category k, for average speed V and for pollutant i [g/km]
i: pollutant of interest (CO, NO_x, VOC and CO_2)
$f_{EF,\,i,\,k}$: polynomial function derived from measured data (as trendline); unique for every vehicle category k and for each pollutant i
V_j: average speed of the vehicles circulating on the traffic link j [km/h]

After calculating the emission factors for all pollutants, the hot exhaust emissions of the traffic link j are calculated by the formula:

$$Ehot_{i,\,j} = L_j \times N_j \times \sum(P_{j,\,k} \times EF_{i,\,k}(V))$$

Where:
$Ehot_{i,\,j}$: hot emissions of pollutant i produced by N_j vehicles that circulate on the link j [g]
L_j: length of the traffic link j [km]
N_j: number of vehicles circulating on link j
$P_{j,\,k}$: percentage of vehicles of the specific category k on the overall vehicle fleet that circulate on link j, e.g. passenger cars 0.8 – 1.4 l gasoline Euro 3 = 5% etc.

Finally, the total hot exhaust emissions of the pollutant i from the entire area ($Ehot_{i,\,area}$) are calculated by summing the emissions of individual traffic links j:

$$Ehot_{i,\,area} = \sum Ehot_{i,\,j}$$

Since the hourly activity data are available from the traffic model, the calculation is repeated for each hour of the day and the hourly and daily emissions are calculated for all pollutants and for all traffic links.

B. Cold start emissions

Under the framework of ARTEMIS project three new models were developed for calculating cold start emissions (Joumard et al., 2007). In COPERT Micro the first model was incorporated, which expresses the cold start excess emission for a start and a vehicle type k as follows:

$$EE(T, V, \delta)_k = \omega_{20^oC,\ 20\,km/h} \cdot f(T, V) \cdot h(\delta) \cdot g(t)$$

Where:
EE $(T, V, \delta)_k$: excess emission in mass per start and per vehicle type k [g/start].
T: temperature [°C]
V: average speed [km/h]
$\delta = d/dc$: dimensionless travelled distance
d: travelled distance [km]
d_c: cold distance [km]
t: parking time
$\omega_{20°C,\ 20km/h}$: excess emission at 20 °C and 20 km/h [g]
f(T, V): cycle speed and the temperature influence dimensionless function, with

$$f(T, V) = \omega(T, V) / \omega_{20°C,\ 20km/h}$$

$\omega(T, V)$: cycle speed and the temperature influence function
$h(\delta)$: distance influence function
g(t): parking-time influence function

Since the number of trips for the entire city is known from the traffic model, the number of trips for each vehicle category k is calculated by:

$$T_k = P_k \times T$$

T_k: number of starts for each vehicle category
P_k: percentage of vehicles of specific type k on the overall vehicle fleet
T: total number of trips for the entire city (either hourly, or daily – Figure 3)

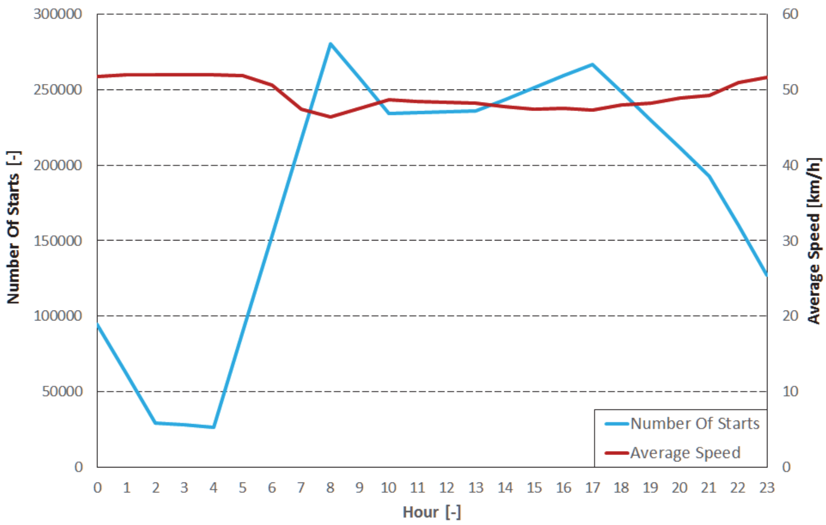


Figure 3: Number of starts and average speed per hour for the entire network of Athens

The product of the two equations gives the excess emissions for every vehicle type k (either per hour, or per day). The sum of these products will be the total cold start excess emissions for the entire city and for each pollutant i (where i = CO, NO_x, VOC and CO_2):

$$Ecold_{i,\ area} = \sum EE(T, V, \delta)_{i,\ k} \times T_k$$

The last equation is applied for every pollutant on hourly basis using “average characteristics” of the whole area. The term “average characteristics” implies that e.g. for speed, the average hourly speed of the entire network is used (Figure 3). Finally, the distribution of total cold start excess emissions on individual links is conducted with the equation:

$$Ecold_{i,j} = Ecold_{i,\,area} \times (L_j \times N_j) / \sum(L_j \times N_j)$$

Where:
$Ecold_{i,\,j}$: cold start emissions of pollutant i produced by N_j vehicles that circulate on the link j [g]
L_j: length of the traffic link j [km]
N_j: number of vehicles circulating on link j

So, the cold start emissions of each link j are proportional to the contribution of the veh-km of the link j on the overall veh-km of the network. Contrary to hot emissions calculation, which is based on a bottom-up approach, the cold start calculation uses a top-down approach; from the total emissions (of the city) we end up with the specific emissions on individual links.

C. <u>Total emissions</u>

The total emissions for each link and for every pollutant is the sum of hot and cold start emissions:

$$Etotal_{i,j} = Ehot_{i,j} + Ecold_{i,j}$$

The last equation is used also in the macro/city level.

Results

The results are divided into two sections. In the first section the emissions on micro/link level are presented upon the GIS grid, whereas on the second section the hourly and daily emissions for the entire city/macro level are given (Samaras et al., 2012).

Emissions on micro level

In Figure 4 the daily hot and cold start CO emissions are given for every link of the network. It is evident that in both emission types the main roads, such as Kifisou Avenue, Attica Road (especially its eastern part), along with Kifisias Avenue and Poseidonos Avenue (especially its northwest part), are the major emitters. This is not surprising since the number of vehicles circulating on these boulevards is quite high. Although the location of the main hot-spots in both grids is similar (those in red colour), a closer look will reveal the differences in specific roads (which i.e. in hot emissions grid are painted yellow, whereas in cold start grid are painted orange). Note that both grids share the same climax, so there is a clear indication that the contribution of cold start emissions on the overall CO emissions is high.

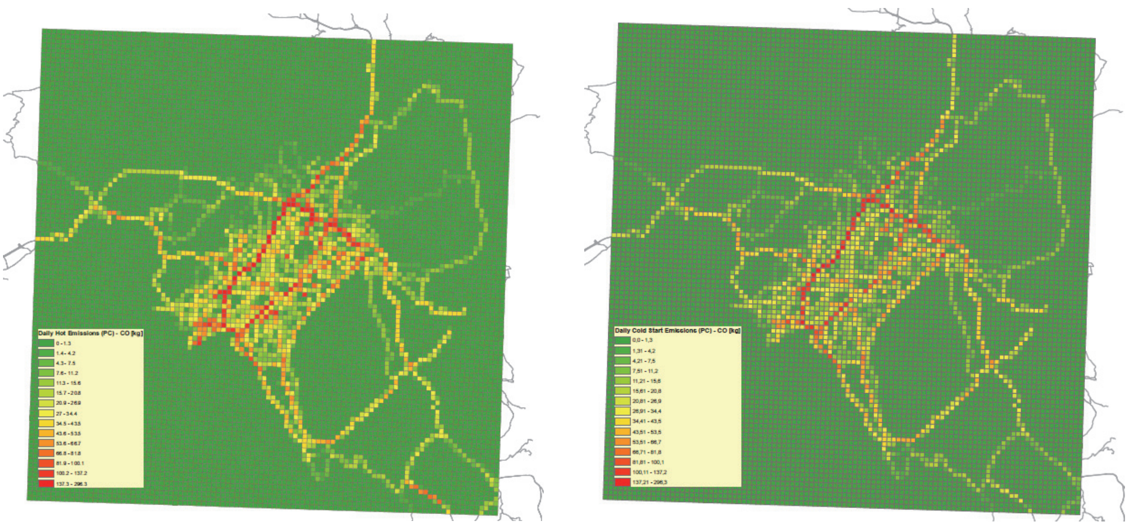


Figure 4: Daily hot (left) and daily cold start (right) CO emissions (kg) from passenger cars on a 100 x 100 (500 x 500 m^2) grid for a typical weekday of October 2010 in Greater Athens Area

When the hourly cold start emissions are plotted on the grid (Figure 5), the progressive change of hot-spots can be easily distinguished. Apart from the four main roads that aforementioned, the contribution of other roads becomes equally important. During off-peak (3 to 4 A.M.), there are no hot-spots (red colour) and it's even difficult to distinguish roads with medium contribution to emissions (yellow colour). The reason is that after 1 A.M. there is low activity on the entire city – lower number of vehicles, lower trips and higher average speed throughout the network.

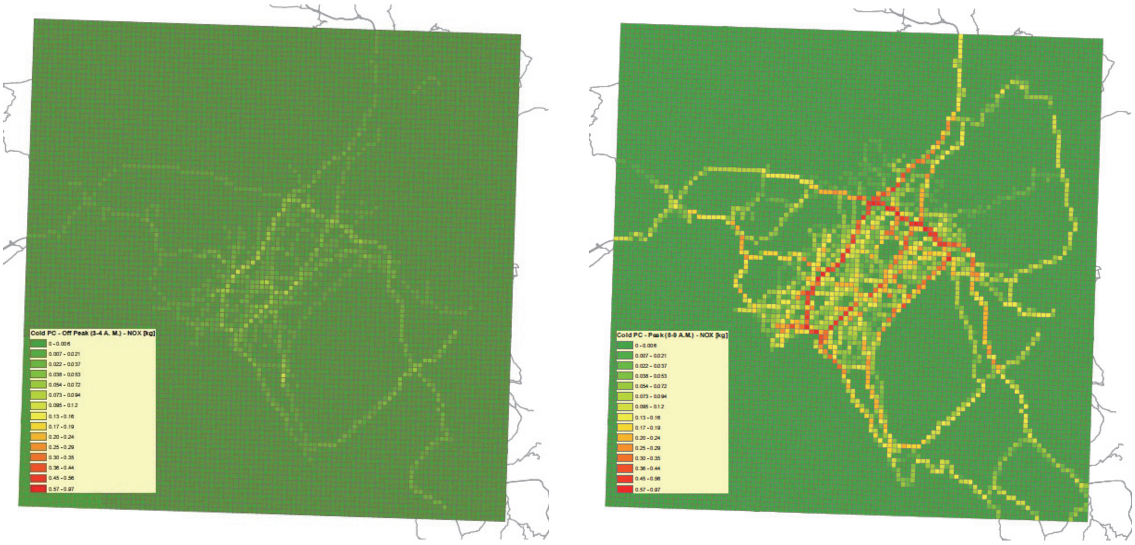


Figure 5: Off-peak – 3 to 4 A.M. – (left) and peak – 8 to 9 A.M. – (right) NO_x cold start emissions (kg) from passenger cars on a 100 x 100 (500 x 500 m^2) grid for a typical weekday of October 2010 in Greater Athens Area

On the peak hour in the morning (8 to 9 A.M.), there is high traffic activity and the majority of vehicles circulate through the main boulevards. The increasing number of vehicles over the same road capacity causes traffic jams and congestion in many roads, so the average speed of the network decreases. As a consequence, there are many hot-spots on the network, especially in junctions of the main avenues with secondary roads.

Emissions on macro level

The visual representation of cold start emissions on the grid is extremely helpful for identifying the localized hot-spots throughout the network. However, the contribution of cold start emissions on the overall emissions can be only identified if both hot and cold start emissions are calculated for the entire city. In the column charts of Figure 6 the share of CO and NO_x hot and cold start emissions on hourly basis is represented. It is evident that cold start emissions are almost equal to the hot ones for CO, whereas for NO_x are much lower.

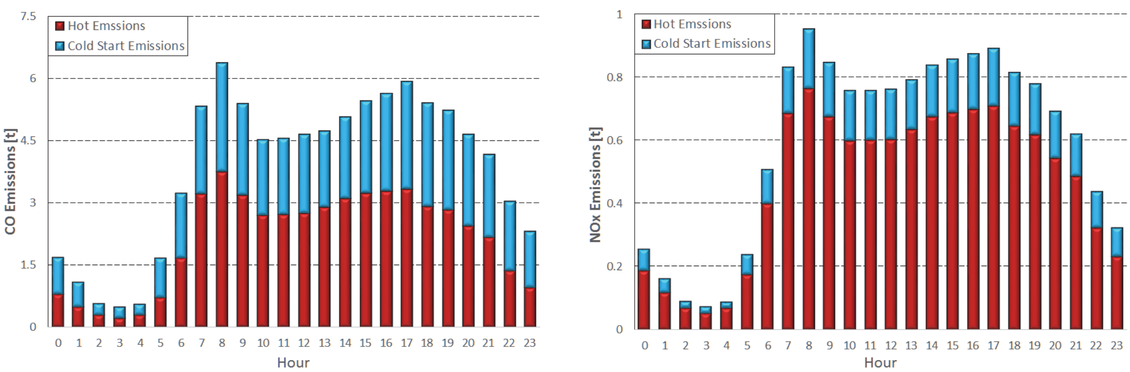
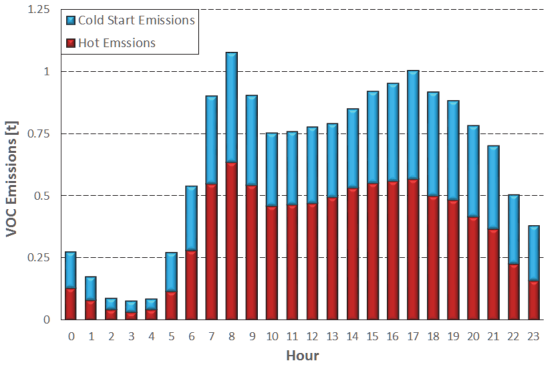


Figure 6: Hourly CO (left) and NO_x (right) hot and cold start emissions from passenger cars in the Greater Athens Area (calculated for a typical weekday of October 2010)

Similar to CO case, the VOC cold start emissions are almost the half of the total ones (Figure 7). The CO_2 cold start emissions on the other hand are quite low compared with the hot ones.



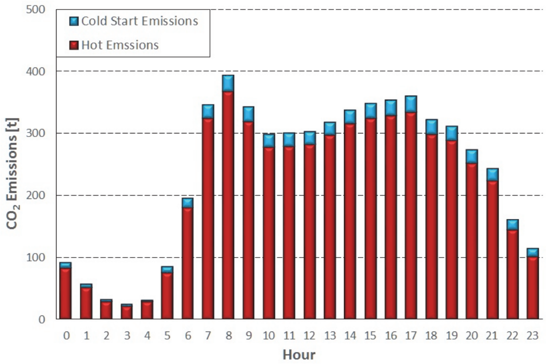


Figure 7: Hourly VOC (left) and CO_2 (right) hot and cold start emissions from passenger cars in the Greater Athens Area (calculated for a typical weekday of October 2010)

Table 1 summarizes the minimum and maximum shares of cold start emissions on overall emissions per pollutant on hourly basis. The minimum shares for all pollutants occur during rush hours, either in the morning, when people drive to their work, or in early afternoon, when they return back to their homes. On the other hand, the maximum shares appear just before midnight, with the exception of NO_x, the maximum share of which occurs on 3 A.M. The minimum and maximum shares are inversely proportional to traffic activity; during rush hours the contribution of cold start emissions – regardless of pollutant – is minimum, whereas during the night it becomes more important.

Table 1: Minimum and maximum share of cold start on total emissions per pollutant.

Pollutant	Min	Hour	Max	Hour
CO	39%	2 – 3 P.M.	59%	11 – 12 P.M.
NO_x	18%	7 – 8 A.M.	29%	3 – 4 A.M.
VOC	37%	2 – 3 P.M.	58%	11 – 12 P.M.
CO_2	6%	7 – 8 A.M.	11%	11 – 12 P.M.

On macro level it's easier to quantify the contribution of cold start on overall emissions. Table 2 contains the daily hot, cold start and total emissions for all the pollutants considered in this study. It's clear that for CO and VOC the cold start are almost the half of total emissions produced, whereas for NO_x and CO_2 the contribution of cold start is much lower.

Table 2: Daily hot, cold start and total emissions from passenger cars in Athens per pollutant

Pollutant	Cold Start [t]	Hot [t]	Total [t]	Cold/Total
CO	41	51	92	45%
NO_x	3	11	14	21%
VOC	7	9	15	44%
CO_2	415	5229	5644	7%

Conclusions

The study aimed to visualize and quantify cold start emissions on both micro and macro level for the Greater Athens Area. The results indicate that cold start emissions constitute major contributor for CO and VOC road transport emissions (45% and 44% respectively), whereas their impact on total NO_x and CO_2 emissions is relatively smaller (21% and 7%). In specific traffic links, which belong to the main boulevards of the city, the contribution of cold start emissions is dominant, thus significantly affecting local air quality.

The contribution of cold start on overall emissions is not constant, but changes during the day; in many cases – especially for CO and VOC – it's almost equally important to hot emissions. Therefore, specific cold start allocation modelling activities to road networks have to be developed to correctly allocate the cold start impact, in particular for local hot-spots.

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