Towards a comprehensive model for the impact of traffic patterns on air pollution

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Overview

The impact of vehicular traffic on society is huge and multifaceted, including economic, social, health and environmental aspects. The problems is complex and hard to model since it requires to consider traffic patterns, air pollutant emissions, the chemical reactions and dynamics of pollutants in the low atmosphere. Our research aims at exploring a simulation tool ranging from vehicular traffic to environmental impact. We describe Modules 1, 2, 3 and 5 shown on the right, leaving the study of pollutant diffusion as a future work. The analysis focuses on the nitrogen oxides and the ozone, due to their negative effect on health.

Traffic model

Traffic dynamic is described by the second order CGARZ model [2]

$$\begin{cases} \rho_t + (\rho v)_x = 0 \\ w_t + v w_x = 0, \end{cases} \quad (1)$$

where $v = V(\rho, w)$ and w is a property of vehicles which distinguishes drivers behavior. From (1) we estimate

- the density of vehicles $\rho(x,t)$,
- the speed of vehicles $v(x,t)$,
- the acceleration $a(x,t)$.

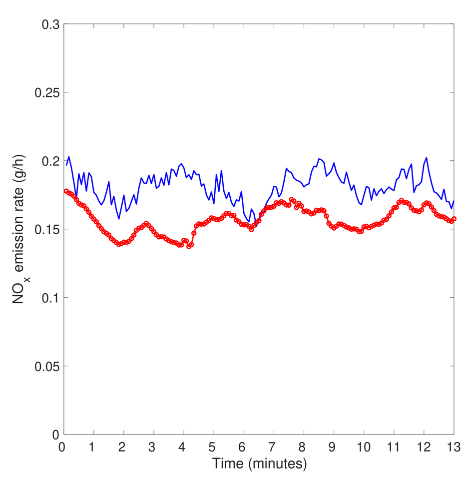
Emission model

The emission rate E is estimated from ρ, v and a as

$$E = \rho \max\{E_0, f_1 + f_2 v + f_3 v^2 + f_4 a + f_5 a^2 + f_6 v a\}, \quad (2)$$

with E_0 lower-bound and f_1-f_6 emission constants, [3].

Model validation [1]. We compare the NO_x emission values (2) computed with velocity and acceleration related to the traffic model (1) (red line) with the emission values estimated with the real velocity and acceleration of the NGSIM dataset [4] (blue line).



Chemical reactions

In polluted regions with high vehicle emissions, the production of ozone associated to the photochemical smog is due to the following reactions

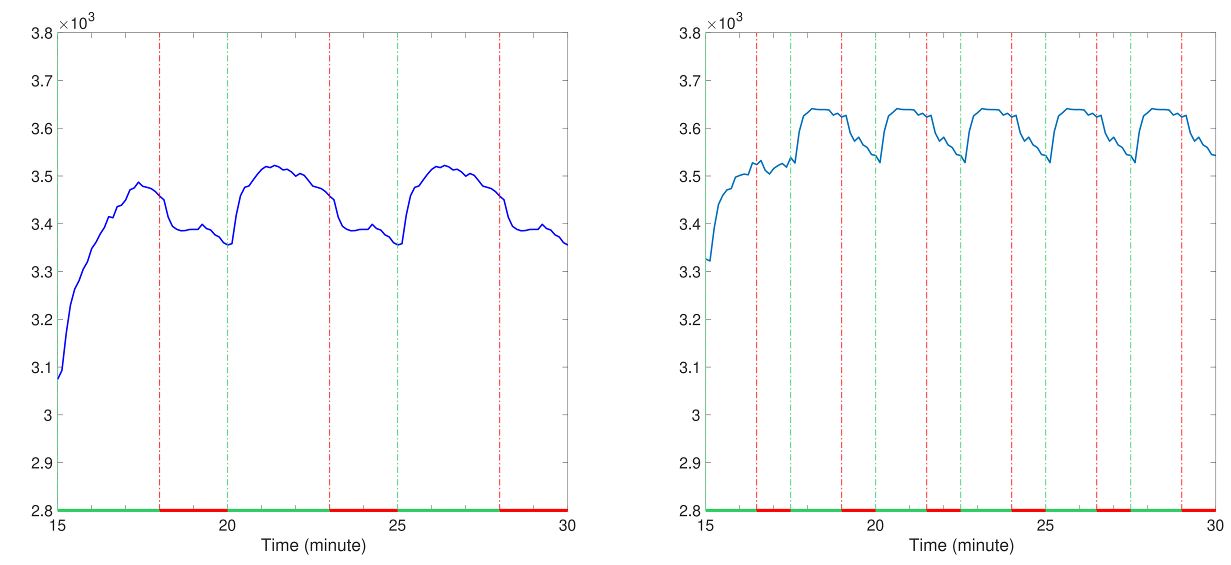
$$NO_2 \xrightarrow{k_1} O + NO$$
$$O + 2O_2 \xrightarrow{k_2} O_3 + O_2$$
$$O_3 + NO \xrightarrow{k_3} O_2 + NO_2.$$

with O atomic oxygen, O_2 oxygen, O_3 ozone, NO nitrogen oxide and NO_2 nitrogen dioxide. We treat the reactions with an ODEs system with source term for NO and NO_2 given by $S_{NO} = pE/V$ and $S_{NO_2} = (1-p)E/V$, $p = 0.15$ and V air volume.

Environmental impact

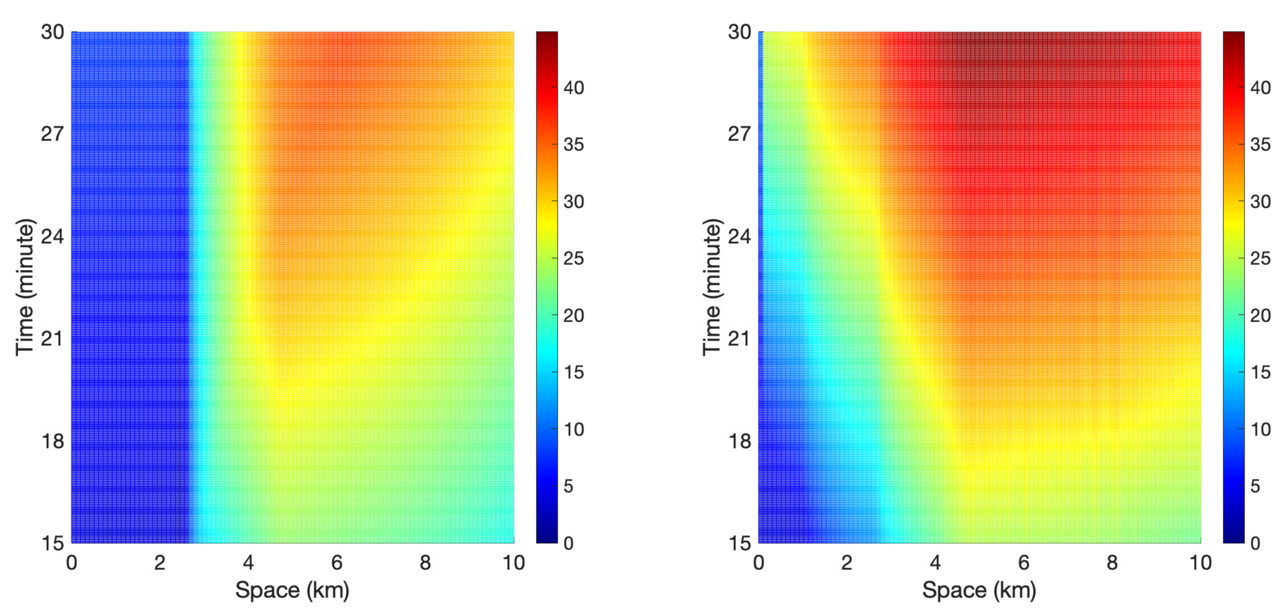
Effect of traffic lights on NO_x emissions (● → ●)

We test the impact on NO_x emissions of a traffic light placed at the end of a road, modeling traffic dynamic with (1) and the emissions with (2). The total NO_x emission rates grow when the traffic light time is shorter (5 minutes on left and 2.5 minute on right) and there are more vehicles restarts.



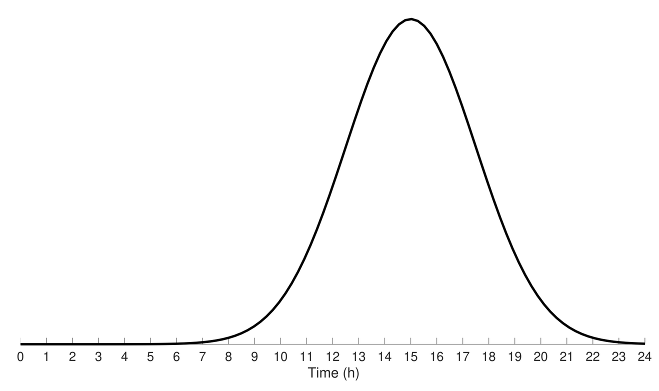
Effect of traffic lights on O_3 production (● → ● → ●)

We test the ozone production on a road with traffic modeled by (1), where the NO_x emissions estimated by (2) are used as source term of the ODEs system associated to the chemical reactions. We show the ozone production without (left plot) and with (right plot) traffic lights in space and time.

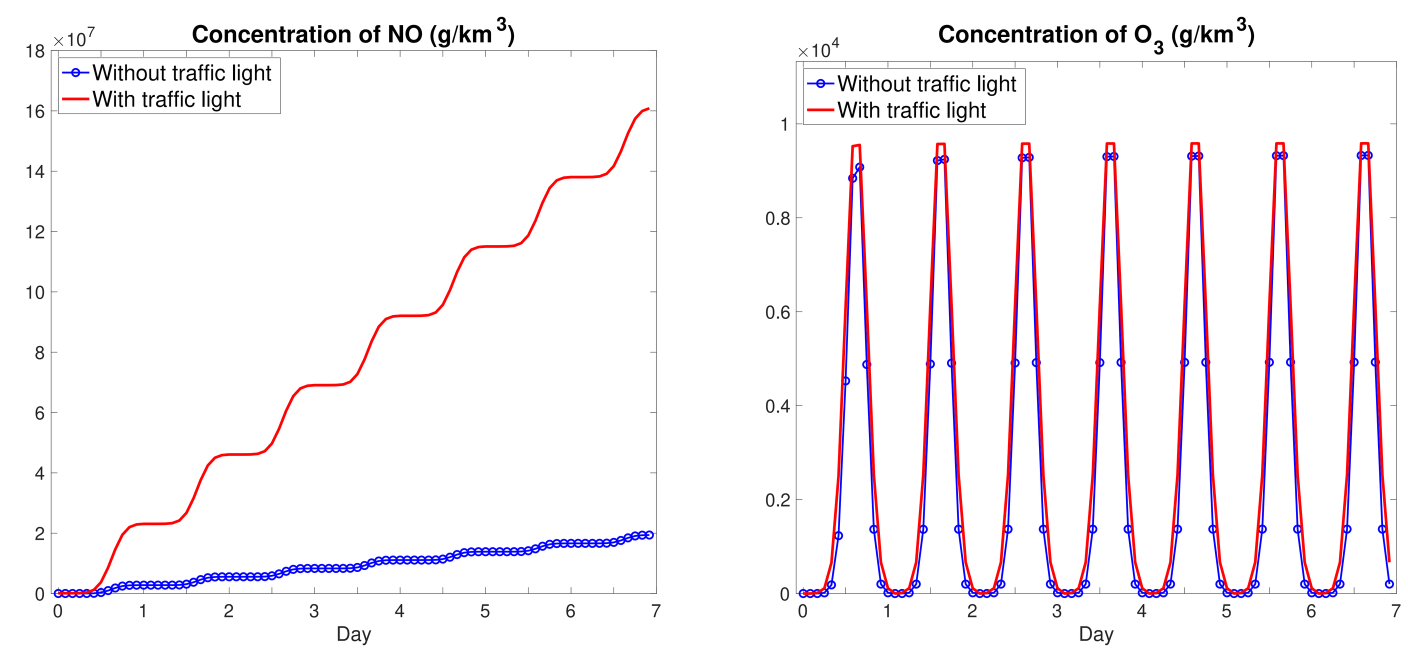


Weekly trend (● → ● → ●)

Day and night are simulated by varying the kinetic constant k_1 associated to the first reaction and to the source terms S_{NO} and S_{NO_2} due to traffic as in the figure on the right.



In the figures below we compare the concentration of NO and O_3 along the whole road in presence of the traffic light (red line) with respect to the one obtained in the case without traffic light (blue line). NO productions (left plot) are highly amplified by the presence of the traffic light while the dynamic of O_3 (right plot) reaches its saturation value each day at 3 p.m. regardless the presence or not of the traffic light.



Future perspectives

- Extend the tool to road networks to better capture environmental effects.
- Analyze other chemical reactions.
- Exploit the dependence on time of emissions to compare pollution levels between weekends and working days.

References

[1] C. Balzotti, M. Briani, B. De Filippo, B. Piccoli, *Evaluation of* NO_x *emissions and ozone production due to vehicular traffic via second-order models.*, arXiv preprint arXiv:1912.05956, (2019).

[2] S. Fan, Y. Sun, B. Piccoli, B. Seibold, and D. B. Work, *A Collapsed Generalized Aw-Rascle-Zhang Model and its Model Accuracy*, arXiv preprint arXiv:1702.03624, (2017).

[3] L. I. Panis, S. Broekx, and R. Liu, *Modelling instantaneous traffic emission and the influence of traffic speed limits*, Sci. Total Environ., 371 (2006), pp. 270–285.

[4] US Department of Transportation and Federal Highway Administration, *Next Generation Simulation* (NGSIM), http://ops.fhwa.dot.gov/trafficanalysistools/ngsim.htm.