Traffic emission estimation based on quasi-dynamic network loading

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Introduction

Highly congested urban areas is a side effect of our modern society. Traffic congestion increases travel times, but also implies increased energy usage and vehicular emissions, having a negative impact on both air quality and climate change. According to the European Environment Agency, transportation, and especially exhaust emissions from road traffic, remains a significant contributor to the main air pollutants affecting substantially the urban air quality [EEA, 2016]. Specifically, NO_x, CO and $PM_{2.5}$ make up 32%, 23% and 8% of the total emissions, respectively. Considering the high rates of road traffic emissions and the negative effects on air pollution, one can clearly conclude that this type of emissions significantly affects human health. In order to evaluate this effect, the estimation of the magnitude, location and the duration of the exposure to the pollutant is necessary.

The modelling components, which are necessary to move from road emissions to the estimation of the socio-economic impact of health effects, are described in Figure 1. Initially, the amount of a pollutant emitted at a street level in grams per space and time unit is estimated by emission modelling. Next, a dispersion model can be used to provide the concentration of a pollutant in grams per m^3 at a specific location and time period. Dispersion models describe the chemical and physical processes within a plume combining the emission rates estimated by the emission model, with some geographical, meteorological and background pollution information. Then, exposure modelling, considering the spatio-temporal information on the pollutant's concentrations as well as demographics and land use data, estimates the final number of people inhaling the pollutant per time unit. The magnitude of the combined effects on health and environment, determine the economic effects of air pollution [Smit et al., 2010].

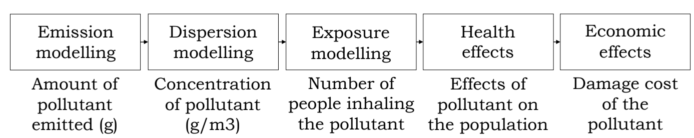

Figure 1: Steps required to link source emissions to health effects.

An important step of the modelling process is the estimation of road emissions at a street level. Traffic emission models are used for the road emission estimation, employing *traffic data* (speed and flow), information on vehicle fleet and other local conditions (e.g. road type and gradient, ambient temperature). The basic aim of these models is to estimate the appropriate amount of a pollutant emitted in grams per vehicle and kilometre. In large urban areas, macroscopic or aggregated emission models are commonly applied, with COPERT

[Ntziachristos et al., 2009] and HBEFA [Keller, 2010] being the two leading emission models in Europe. Macroscopic emission models provide *emission factors* in grams/vehkm as a function of the traffic conditions.

Motivation

In large urban areas, traffic data used for exhaust emission and air pollution analysis is usually derived by transportation planning traffic models, based on *Static Traffic Assignment* (STA). STA models are commonly used for the strategic assessment of the current or future state of a transportation network and they can efficiently be applied to larger areas with relatively low computational cost. However, by using static models, many important dynamic traffic flow phenomena, such as the formation and the propagation of queues and *spill-back*, cannot be taken into account. This can result in an inaccurate estimation of dynamic variables, such as the *location of congestion*. Congestion is strongly correlated with increased emission rates since it is associated with low speeds and stop and go conditions.

More specifically, in the case of a bottleneck, all the time delays, and consequently the high emission rates, are assigned by STA models at the bottleneck link. The links upstream the bottleneck remain unaffected. In reality, increased delays and emissions are observed upstream the bottleneck due to the queue spill-back. However, the spatial allocation of congestion is a significant factor with respect to emission modelling, as emissions have *local effects*.

Many applications of emission modelling, such as dispersion and exposure modelling, are sensitive to the spatial distribution of emission rates. Dispersion models consider location specific background pollution and meteorology data. In addition, different network links are associated with different number of pedestrians, cyclists and people living or working by the road side and are affected by the emissions. This could have a direct effect during an economic analysis, such as a *cost-benefit analysis*, where the monetary cost of a gram of pollutant emitted is analogous to the number of people exposed and affected [Eliasson, 2009]. Accordingly, in such an analysis, the travel time costs are associated with route, from origin to the destination, travel times and the use of STA may be sufficient. In most of the cases, though, STA consists the basis for both travel times and emissions estimation.

In contrast to STA, dynamic modelling approaches, such as *Dynamic Traffic Assignment* (DTA) can model spill-back of the queues as traffic demand exceeds capacity, and dispersion of the queues when demand is below the capacity. However, complexity issues make dynamic modelling computationally expensive and time consuming to calibrate, discouraging their application in larger areas. Also, dynamic models do not possess the property of unique link flows, which is an important feature when using model output for policy or project evaluations. A middle-ground solution between static and dynamic modelling could be the *post-processing* of static models using *quasi-dynamic* network loading approaches, such the ones described in [Bliemer et al., 2012] and [Bundschuh et al., 2006].

Tsanakas et al. [2017] attempted to reduce the emission estimation errors which are related to STA, by applying a quasi-dynamic network loading model, Static Traffic Assignment with Queuing [Bliemer et al., 2012, STAQ]. They estimated emissions for a road stretch in Stockholm considering two cases of deriving the traffic data. Regarding the first case, traffic data was based on a simple STA model, while for the second case, traffic data relied on the post-processing of STA results using the STAQ loading approach. A comparison, then, was performed for both cases with emissions which were based on traffic counts. They concluded that such post-processing of STA can lead to more realistic emission estimates, since the propagation of the queues can be accurately captured. However, their findings were based on experiments performed for a simple corridor network including one only bottleneck. In this study we evaluate the use of STAQ model considering a larger network with actual intersections where traffic is merged or diverged. The evaluation is performed by comparing the total network emissions as well as the spatial distribution of emissions that arise from the simple STA with the corresponding emissions derived from the STAQ approach. Our main aim is to quantify the effect that spill-back of the queues imply in terms of emission estimation and evaluate their significance with respect to the applications of emission modelling.

Emission estimation based on static traffic assignment

Consider the traffic network as a directed graph, $\mathcal{G} = (\mathcal{N}, \mathcal{A})$, which includes a set of *nodes* $\mathcal{N}$ and a set of *links* $\mathcal{A}$, where each link is associated with different attributes, such as capacity, C_a and length L_a. Let $\mathcal{R}$ be the set of origin nodes associated with the origin zones, $\mathcal{R} \subseteq \mathcal{N}$, and $\mathcal{S}$ the set of destination nodes concerning the destination zones, $\mathcal{S} \subseteq \mathcal{N}$. Furthermore, let $\mathcal{K}^{rs}$ be the set of different alternative link sequences, called *routes* or *paths* that connect each node $r \in \mathcal{R}$ with a destination node $s \in \mathcal{S}$. The problem of traffic assignment, then, concerns how the demand, q^{rs}, between each origin-destination pair, rs, will be distributed among the possible paths k, $k \in \mathcal{K}^{rs}$, given that link travel time, t_a, is a function of link flow, x_a, for each $a \in \mathcal{A}$ [Sheffi, 1985].

The assignment usually relies on behavioural principles, such as the User Equilibrium [Wardrop, 1952, UE]. UE is a stable condition where all the available paths k, $k \in \mathcal{K}^{rs}$, have the same travel time and no traveller can improve his or her travel time by unilaterally changing routes. To find the equilibrium solution in a network, STA problem was mathematically formulated as an optimisation problem by Beckmann et al. [1956].

Solving the STA problem will lead to optimal link flows, x_a, for each $a \in \mathcal{A}$, such that the travel time between each O-D pair, rs, is the minimum possible and equal for every $k \in \mathcal{K}^{rs}$ with positive flow. Having information on link flows and travel times, the amount of emitted pollutant can be estimated using the HBEFA model. The emission factors are given as a function $e_a^p[V_a]$ of average speed, V_a, for each link a and for each pollutant, p (HC, CO, NO_x, CO_2 and PM). Then, the emission factor multiplied by the traffic activity expressed in *vehicle kilometre travelled*, $x_a \cdot L_a$, gives the total grams of each pollutant p, emitted at link a,

$$E_a^p = e_a^p[V_a] \cdot x_a \cdot L_a. \tag{1}$$

An important assumption considered in Beckmann's formulation is that travel time, t_a, on a given link, $a \in \mathcal{A}$, is a function of flow on that link only, and it doesn't depend on other links' flow. In this way, link interactions are explicitly not considered and spill-back is neglected. The later could lead to an inaccurate location of congestion having a direct effect in emission estimation analyses. One more significant assumption considered in Beckmann's formulation is that link flow, x_a, can exceed capacity, C_a, resulting in unrealistic high emission rates at the corresponding locations.

Quasi-dynamic network loading as a post-processing approach

In STA models, due to the lack of any time variable, demand is loaded instantaneously into the network, leading to the drawbacks described above. However, by applying STAQ as a post-processing method, the network loading could instead be quasi-dynamic. STAQ is a dynamic model considering two important static assumptions: demand is stationary, and part of the demand is loaded instantaneously. The model consists of two phases, the *squeezing* and the *queuing* phase. During the squeezing phase, in which there is no time variable, the optimal demand share, f_k^{rs}, of each path $k \in \mathcal{K}^{rs}$, is loaded into the network through an incremental assignment which ensures that no link flow, x_a, exceeds capacity, C_a. When the capacity of a link is reached, the remaining demand forms a vertical queue at the upstream end of link a.

Next, during the queuing phase these vertical queues propagate to the upstream links. The propagation is based on the *kinematic wave theory* and the LWR first order traffic flow model [Lighthill and Whitham, 1955, Richards, 1956]. In LWR-model, traffic flow is treated as a one-dimensional compressible fluid. The basic dynamic variables, in correspondence to fluid-dynamics, are the density $\rho(x,t)$, the flow $Q(x,t)$ and the mean speed $V(x,t)$, with the independent variables being the location x and the time instant t. The conservation law defines the basic relationship between flow and density

$$\frac{\partial \rho}{\partial t} + \frac{\partial Q}{\partial x} = 0, \tag{2}$$

describing how a change in density over time relates to a change in flow over space. The relation between flow and density is assumed to be static, with the flow expressed as a function of density, $Q = Q_f(\rho)$, known as the *fundamental diagram* of traffic flow.

The space-mean speed, V, is computed by the *hydrodynamic flow relation*, $V = Q_f(\rho)/\rho$ considering that traffic conditions at location x and time t are in steady-state. Solving Equation 2 with the method of *characteristics curves* [Leutzbach, 1988, Newell, 1993], implies that traffic state remains constant along a characteristic curve or wave. At the boundary between two different traffic states a kinematic wave is formed, propagating with a velocity of

$$w = \frac{dQ_f(\rho)}{d\rho}. \tag{3}$$

The queuing phase of STAQ relies on the event-based solution algorithm [Raadsen et al., 2016, eLTM] for the Link Transmission Model [Yperman, 2007, LTM]. LTM is a dynamic network loading model that adopts the Newell's simplified wave theory [Newell, 1993] for solving Equation 2. The algorithm ends when all traffic demand has reached its destination. The main output of the STAQ is average link travel times, calculated by the cumulative number of vehicles [Bliemer et al., 2012, Brederode et al., 2018, Leeuwen, 2011]. However, by applying an event-based algorithm it is also possible to keep track of the spatial position of the shock-wave whenever an event occurs.

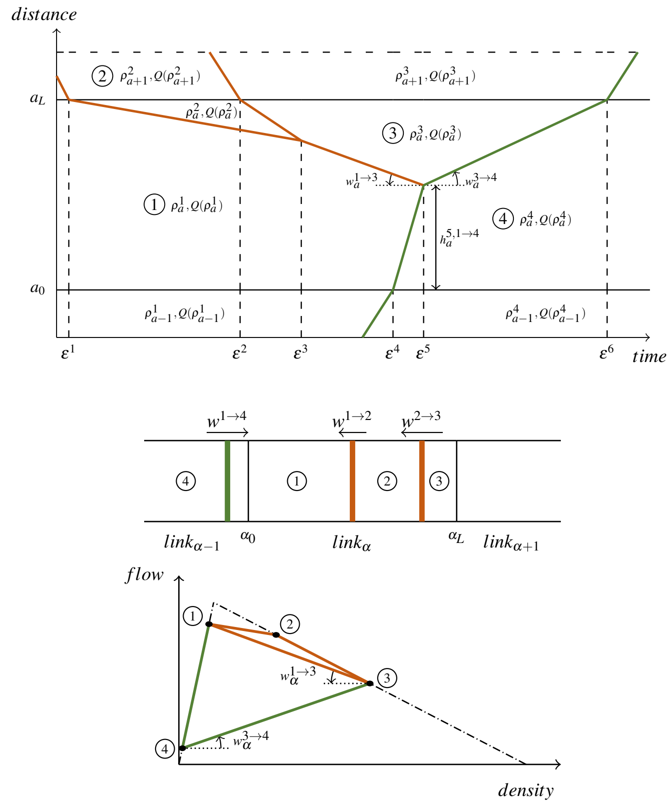

Figure 2: Spatial and temporal evolution of shock-waves.

Figure 2 illustrates the spatio-temporal evolution of shock-waves defining the transition between four different traffic states, for a network link, a. From the time-distance plot we can notice that the shock-waves divide a link into different smaller areas. Each one of them is associated with a different traffic state, $[\rho,\ Q(\rho),\ V(\rho)]$, and emission factor $e^p[V(\rho)]$.

Let $\mathcal{M} = \{1, 2, ..., N-1\}$, where N is the total number of events during the simulation period. Every link of the network, $a \in \mathcal{A}$, at each step $n \in \mathcal{M}$, is divided into P_a^n parts depending on the number of shock-waves, W_p^n, traversing the link at the time of the nth event, ε^n. Let $\mathcal{P}_a^n = \{1, 2, ..., P_a^n\}$ and $\mathcal{W}_a^n = \{1, 2, ..., W_a^n\}$. The algorithm keeps track of the position, namely the distance from the downstream end of the link, $h_{a,j}^n$, and the shock-wave speed $w_{a,j}^n$ of every shock-wave $j \in \mathcal{W}_a^n$ as well as of the traffic conditions, $\rho_{a,i}^n$, $Q_{a,i}^n$ and $V_{a,i}^n$ for each part of the link, $i \in \mathcal{P}_a^n$. Since in steady state conditions shock-wave speeds are constant along the characteristic curves, the transitions between the different traffic states are linear in the space-time domain, and they can be expressed through linear equations of the form $y_1 = m \cdot y_2 + b$. The slope m is by definition equal to the shock-wave speed $w_{a,j}^n$, $j \in \mathcal{W}_a^n$, while the constant b equals to $h_{a,j}^n - w_{a,j}^n \varepsilon^n$, $j \in \mathcal{W}_a^n$. Hence, the area in the space-time domain $R_{a,i}^n$ of its part $i \in \mathcal{P}_a^n$, which is defined between two shock-waves $j,\ j+1$ and between two time steps $n,\ n+1$, can be computed as

$$\begin{aligned} R_{a,i}^n = & \int_{\varepsilon^n}^{\varepsilon^{n+1}} \left(w_{a,j+1}^n \omega + h_{a,j+1}^n - w_{a,j+1}^n \varepsilon^n \right) d\omega \\ & - \int_{\varepsilon^n}^{\varepsilon^{n+1}} \left(w_{a,j}^n \omega + h_{a,j}^n - w_{a,j}^n \varepsilon^n \right) d\omega, \\ & \forall\ i \in \mathcal{P}_a^n,\ \forall\ j \in \mathcal{W}_a^n. \end{aligned} \tag{4}$$

The area multiplied by the flow rate at step n, $Q_{a,i}^n$, gives the vehicle kilometres travelled for the specific state. Finally, for each link a the grams of each pollutant, p, emitted can be estimated as

$$\tilde{E}_a^p = \sum_{n \in \mathcal{M}} \sum_{i \in \mathcal{P}_a^n} R_{a,i}^n \cdot Q_{a,i}^n \cdot e_a^p \left[V_{a,i}^n \right]. \tag{5}$$

(a) (b)

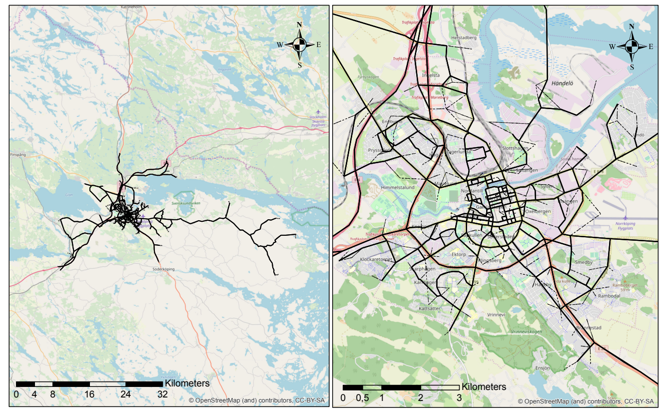

Figure 3: (a) Norrköping greater area network, (b) Norrköping's city centre. The real network's links are denoted by the black solid line while the pseudo-links connecting the zones' centroids with the network are depicted by the grey dashed line.

Case study network

Norrköping is a city in the province of Östergötland in eastern Sweden with a population of 137.000 inhabitants. Figure 3(a), illustrates the Norrköping's network which is represented by 155 zones, forming $155 \times 155 = 24025$ O-D pairs, 513 nodes and 1344 links. The city centre, where the main congestion problems can be identified, is depicted in Figure 3 (b). The demand between each O-D pair regards the number of trips made from private traffic during the peak hour for a typical day.

Solving the STA problem for the Norrköping's network results in the equilibrated path flows f_k^{rs} and link flows x_a. Figure 4 (a) presents those flows in terms of flow to capacity ratio which is a significant attribute determining the emission factors. The width of the bars is associated with the assigned flow. We can observe several links where flow exceeds capacity. The STA emissions, E_a^p, for each link a and pollutant p, can be computed by Equation 1.

Next, the path flows, f_k^{rs}, are loaded into the

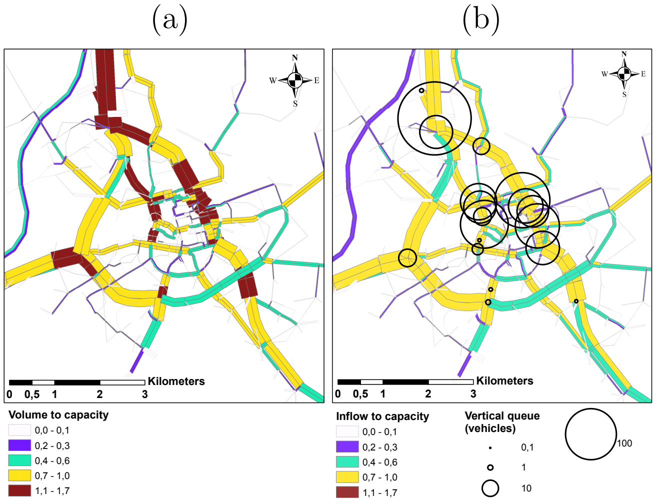

Figure 4: (a) Equilibrated traffic flows based on STA (b) STAQ squeezing phase.

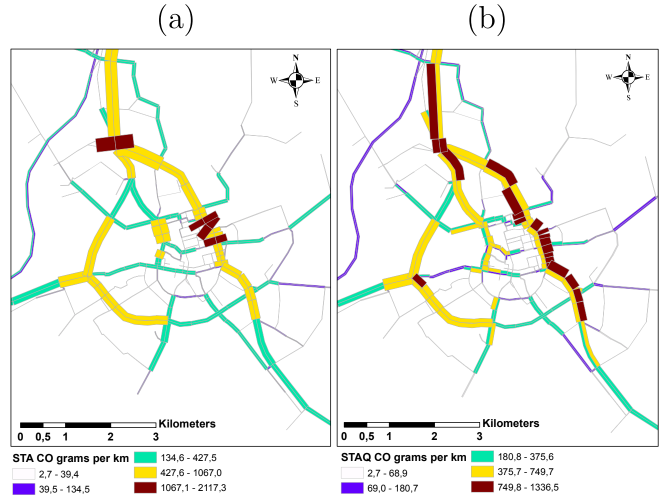

Figure 5: Emissions in grams per km for CO based on (a) STA (b) STAQ.

network according to the STAQ approach. The squeezing phase of STAQ, given the path flows f_k^{rs}, blocks the paths containing a link where flow exceeds capacity through an incremental assignment. When a link flow reaches the capacity, every path containing this link is blocked at this point and all the downstream path links cannot accept any flow during the assignment of any next increment. In this way, when some additional flow is to be assigned over a path that contain a blocked link, vertical queues are formed at the upstream end of the blocked link. For the Norrköping's network, the demand is assigned through 24 increments and the results are illustrated in Figure 4. The radius represents the length of the vertical queues in vehicles.

During the queuing phase, the vertical queues are propagated through the network. The algorithm terminates when every vehicle has reached its destination. Applying the algorithm for the Norrköping's network 437 events are occurred. Finally, the STAQ emissions, $\tilde{E}_a^p$, are calculated according to Equation 5.

Results

Figure 5(a) illustrates the estimated, CO emissions in grams per km, based on STA, for each link of the network. We can notice that the highest values of emitted CO are concentrated at specific locations. The links corresponding to these locations become activated bottlenecks during the peak hour, being the exclusive entrances to the city centre. STA assigns almost all the delays in to those bottlenecks, ignoring the queues that may be formed at the upstream links.

Figure 5(b) illustrates the resulting grams of CO emitted per km based on STAQ. We can notice a different pattern now, the excess due to congestion emissions are not concentrated at the bottleneck links. In contrast to STA, they are observed at the links upstream the bottlenecks due to queue spill-back.

Regarding the total network emissions, the relative difference between STA and STAQ, for each pollutant p, is calculated as

$$\frac{\sum_{a\in\mathcal{A}}\left(E_a^p-\tilde{E}_a^p\right)}{\sum_{a\in\mathcal{A}}\tilde{E}_a^p}100, \qquad (6)$$

and the results are presented in Table 1.

Table 1: Relative difference of total network emission rates between the two different methods of deriving the traffic data.

Pollutant	HC	CO	NO_x	CO_2	PM
STA-STAQ %	-2.45	1.45	-0.53	-1.36	-0.41

Conclusions and future research

The simplified nature of STA models can lead to an inaccurate location of traffic queues, influencing the estimation of emissions. As it is depicted in Figure 5(a), STA assign all the delays and consequently the increased emission rates at the bottleneck links, while the links upstream the bottleneck remain unaffected. Considering the above inabilities of STA, we suggest the post-processing of STA results based on the STAQ approach. STAQ is quasi-dynamic post-processing approach that takes into account queue spill-back. By comparing the emission estimates which rely on STA with the corresponding ones which are based on STAQ, we notice that although the differences in terms of total emissions are not so high, the spatial distribution of the emitted pollutants is significantly changed. Congestion and consequently higher emission rates are now observed at the links upstream the bottlenecks.

For large-scale or long-term emission analyses, STA can sufficiently be used to provide the input traffic data. Those analyses can either regard emission inventories or CO_2 based studies, since CO_2 has global effects. Contrary, for more sensitive to the spatio-temporal variations of traffic conditions applications of emission modelling, such as dispersion and exposure modelling, the accurate estimation of congestion's location becomes an important aspect. In such cases, STA may lead to unreliable results and post-processing becomes a crucial step during the emission estimation process.

The emission estimation methodology proposed in the study can be used in future studies to generate inputs for dispersion modelling. In this way, the actual differences between static and quasi-dynamic modelling in terms of pollutants concentrations can be investigated. Future studies could also investigate the association between the differences in the spatial distribution of emissions due to post-processing with the damage cost of each pollutant.

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