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Environmental Traffic Management: Technology Scenarios and Outlook

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Abstract

With traffic being one of the main factors of air quality in urban regions, effective management instruments are required to curb its impact with measures that control and mitigate its effects in highly dynamic environments. Environmental Traffic Management (ETM) systems have demonstrated to reduce emissions in urban areas and traffic corridors, while remaining a regulating, non-restrictive instrument. This paper describes the current state-of-the-art of ETM in terms of existing technology setups, their use cases and benefits, and provides an outlook of the future of such systems based on current developments.

Keywords:

Environmental Traffic Management, emissions, pollution, model, simulation, forecast

Introduction

Cities are constantly seeking to manage their transportation networks with the aim of sustainable traffic operations that reduce the environmental impacts of individual car traffic. Beside the long-term strategies that aim to avoid and reduce traffic by shifting individual trips to environmentally friendly traffic modes, mid-term and, especially, short-term real-time traffic management tools can help minimize the impact of trips where mode choice has already been made or the trip is already ongoing. Combining traffic control center capabilities enhanced with environmental detection and traffic forecasting capabilities provides a solid framework for environmentally oriented traffic management.

Road transport accounts for a significant amount of air pollutant emissions. According to the European Environment Agency (EEA), road transport is responsible for to up to 9.9% of all $PM_{2.5}$ emissions in the European Union, 7.7% of PM_{10}, 28.1% of NO_X, 7.6 of NMVOC[1], and 18% of CO. Road transport also accounts for up to 16% of the total greenhouse gas (GHG) emissions in the EU, amounting for 73% of all transport contributions [1]. Although monitoring and regulations have produced a downward trend in total pollutant emissions, a significant part of the population is still exposed to air pollutant concentrations above the air quality standards set by the EU and the World Health Organization (WHO). This effect is magnified in urban centers, where higher traffic volumes and

1 Non-Methane Volatile Organic Compounds

congestion produce a concentration of pollutants in short time peaks, therefore exposing areas with high population densities to high pollution levels.

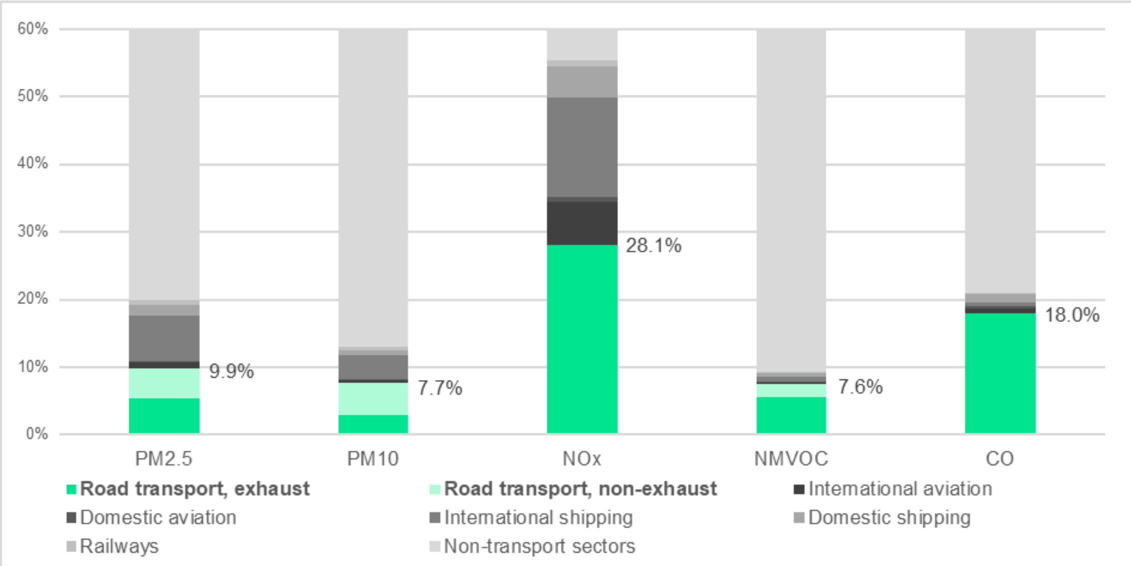

Figure 1 – Contribution of the transport sector to total emissions of the main air pollutants[2]

In urban contexts, Environmental Traffic Management has been an important approach to tackle air quality. With traffic management, the traffic flow in the cities can be optimized and controlled, leading to more efficient fuel consumption, route navigation and avoiding time loses, which all together induce less traffic related emissions [2]. Following this direction, air quality, which was before treated as a consequence of traffic management, has become one of the driving goals of urban transportation management systems in recent years. Within ETM, a systemic evaluation and approach of air quality as an aftereffect of urban traffic motivates a framework for modelling processes, which enclose emission measurements and forecasts and converts them into responsive traffic control measures.

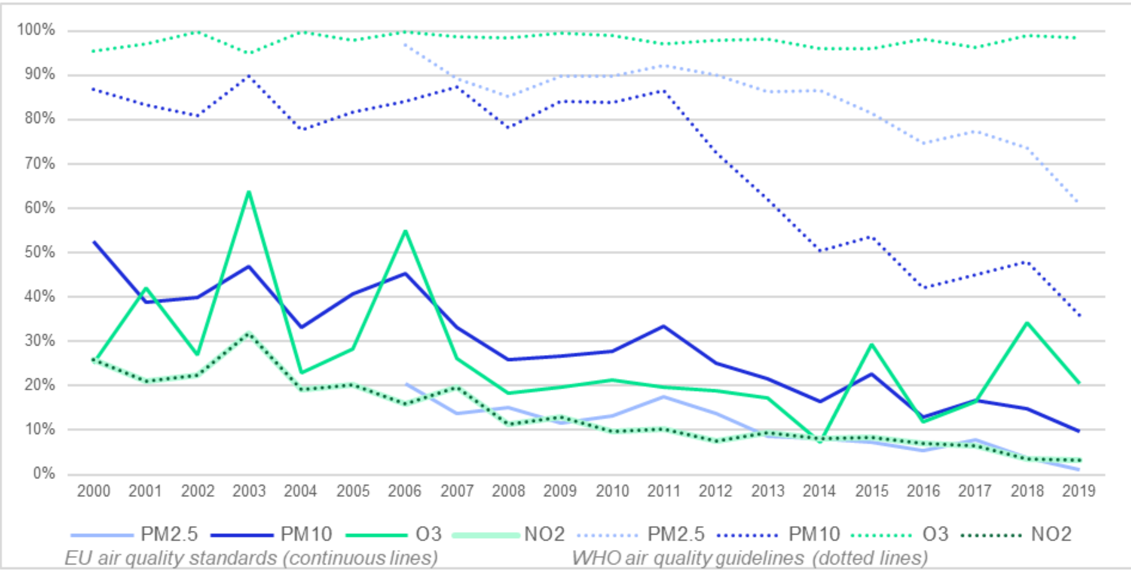

Figure 2 – Urban population exposed to air pollutant concentrations above selected EU & WHO (2005) air quality standards, EU-27 and the UK (Source: EEA)

Technology Setup and ETM Scenarios

ETM systems are not standardized solutions, as all cities have different geographic contexts, technological infrastructure, motivation, policies, data resources, etc., that ultimately determine the specific setup required for an effective emission reduction in traffic. ETM systems have also developed and evolved in the past 10 years as better and faster data acquisition and analysis becomes possible, as well as real-time model-based simulation.

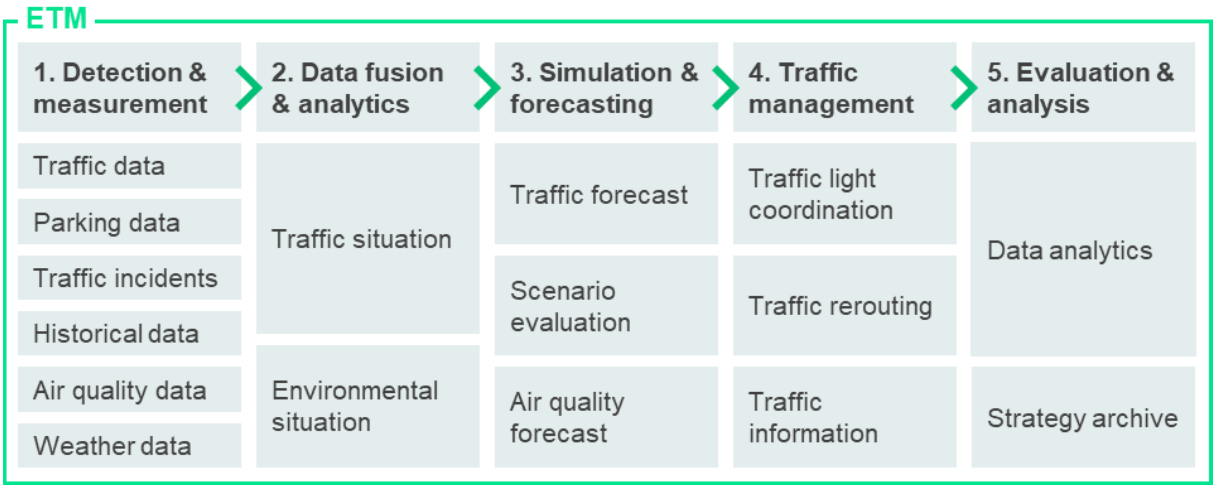

Figure 3 – ETM technology stack overview

Figure 3 above shows a general overview of the modules that compose the technology stack behind an advanced ETM system, and which could be described as:

1. Detection and measurement: data is collected from several sources, such as field devices for the real-time measurement of traffic (traffic counts, density and speed from loop detectors, traffic cameras, FCD[2], etc.), air quality (immission values for PM_1, $PM_{2.5}$, PM_{10}, NO_2, O_3, CO, and SO_2 from environmental monitoring stations), and weather (temperature, humidity, precipitation, wind, etc.). Additionally, information on traffic incidents and parking occupation may also be collected. All data is then transmitted to and integrated in the Traffic Management Center (TMC).
2. Data fusion and analytics: data from the "Detection and measurement module" is filtered, aggregated, and analyzed to obtain KPIs and specialized metrics, such as the traffic density and Level of Service (LoS) of network links, and the wide-area pollutant immission levels. Thus, data fused from multiple sources create a comprehensive and consistent image of the traffic and environmental situation. A central part of this module is the emission model. This model uses traffic state data from a so-called Traffic Situation Engine (TSE) and calculates the emissions for the modelled network links. Data is then visualized in dynamic maps, graphs and dashboards, and is matched to pre-established thresholds.

[2] Floating Car Data

3. Simulation and forecasting: an advanced feature of state-of-the-art ETM systems, this module allows operators and authorities to evaluate and proactively trigger strategies to reduce traffic-related emissions. Forecasting is usually based on two methodologies: model-based simulation, and daily distribution curve analysis. While the former provides a reliable methodological base and is most appropriate for large and complex urban systems, the latter can provide valuable predictions for all system scales. Advanced data analytics and Artificial Intelligence (AI) is also able to match the observed real-time data with historical patterns, identifying trends and forecasting, e.g., air quality levels [3].
4. Traffic management: the core of the system intelligently connects to and coordinates ITS devices (traffic lights, DMS[3], etc.) to directly influence traffic and effectively reduce emissions. Traffic management may be classified into soft measures and hard measures [4]. Soft measures include the dissemination of information, traffic flow improvement at traffic lights, dynamic inflow metering, dynamic speed limits, modal shift and dynamic traffic re-routing. Hard measures on the other hand, apply restrictions to traffic, such as dynamic closure through environmental zones, dynamic city toll and enforcement systems. The traffic management module is also responsible for gathering, integrating and monitoring information from the ITS network, alerting operators on critical trends in the data, and enabling them to implement strategies via automated response plans, as well as decision support systems (DSS). Further, advanced management systems are able to recommend, calculate, simulate and evaluate parallel scenarios to derive the best and most effective course of action, based on traffic and KPI forecasting.
5. Evaluation and analysis: this module closes the ETM process and interlaces back to the detection and measurement of traffic and environmental data to close the loop and enable immediate and future iterations. By means of real-time data and advanced analytics, the results of the triggered traffic management actions are assessed and monitored. AI algorithms can then be trained to grade the effectivity and timeliness of individual response plans and allow operators to refine and improve their strategy.

ETM systems that have successfully been deployed throughout the last decade predominantly follow the above structure to some degree. Effective systems have been implemented in European cities on both ends of the complexity scale, where configurations range from the most basic to the most comprehensive. Four levels of ETM setup complexity are described below, from the simplest to the most complex.

Minimal ETM setup

At a minimum, an ETM system must be able to monitor traffic and air quality in real time, and to activate traffic control strategies to avoid or react upon the exceeding of pollutant immission thresholds. While many cities worldwide have TMCs in place, continuous monitoring of urban air

[3] Dynamic Message Signs, such as digital information boards or dynamic speed limit signs

quality is an important action that is increasingly being adopted by European cities in an attempt of containing pollution concentration within recommended or mandated thresholds.

Minimal setup systems are relatively simple to implement and highly effective in small or sparse networks, including highway networks at a regional scale. This setup is horizontally and vertically scalable. The horizontal dimension here relates to the area covered by the sensor network within the study area, and the vertical dimension to the additional modules that may be integrated.

An example for this setup is the immission-critical section Märkische Strasse in Hagen, Germany. Here, a dynamic truck driving ban is triggered whenever a critical NO_2 level is reached, effectively blocking the city center for truck transit, offering an alternative route instead.

Data-driven Emission Model

As an enhancement to the above-described setup, TMCs may integrate a TSE or similar data fusion module that gives the operator a comprehensive view of the traffic situation in the network. This can be achieved by using FCD and sensor data, with the output being the aggregated real-time LoS values for all monitored network links. The advantage of achieving such overview is the ability to calculate traffic emissions for each of these links based on the traffic data generated.

An example of such a system can be found in the city of Würzburg, Germany. The city uses a Sitraffic Concert TMC from Yunex that integrates field device data plus FCD from HERE and a TSE built by VMZ Berlin to feed the emission model developed by IVU Umwelt. This setup allows Würzburg to not only optimize traffic in the city to reduce emissions, but also to inform users about more environmentally friendly route and mode alternatives via a Mobility App.

Baseline Emission Forecasting

A simplified approach to forecasting and the prediction of emission peaks uses historical traffic data to compare the current traffic situation to similar instances in the past, taking into consideration the current and forecasted weather conditions. This allows for situations that lead to emission to be identified, and preemptive action to be triggered. This approach can be further enhanced by AI and advanced analytics to identify complex patterns between traffic and climatic conditions and increase the system's reliability.

A similar system has been implemented in the city of Bolzano, where the A22 highway, one of the busiest transalpine corridors uses Variable Speed Limits (VSL) to reduce the immission of pollutants in the urban area, as well as congestion as part of the BrennerLEC project [5]. The system runs on the A22's own traffic management central, with support from NOI.

Simulation-based Forecasting and Scenario Evaluation

The most complex setup in this scale incorporates macro-, meso- or even microscopic modelling capabilities on top of the above to generate short-term forecasts (up to 60 minutes in the future) not only of the current traffic simulations, but of a series of scenarios in order to evaluate the impact of different response plans and assist in the selection of the optimal strategy.

The spatial-temporal character of the empirically collected and AI-analyzed data sets predetermines traffic management based on purely data-driven estimations and predictions to be limited to the location of the data sources, indicators that they observe or derive, and to the conditions observed (typical/recurring conditions). Traffic models and simulations fill any gaps by estimating the network state for the entire study area, providing full coverage of the road network by fusing data from various sources and using mathematical algorithms to create and propagate traffic flows, thus consolidating the traffic state information for both recurring and non-recurring conditions. They also estimate the impact of predicted traffic states and demonstrate the effectiveness of environmentally oriented traffic management strategies by simulating their impacts. Finally, they enable combined AI methods to extract valuable indicators from large data sets and combine these with expert knowledge when defining, scoring, and optimizing environmentally oriented strategies. With a direct feed to linked air-quality models, this framework forms a crucial decision-support tool for road operators and city administration.

The city of Wiesbaden, Germany, arguably the paragon of ETM systems today is an example of this setup. As part of the "Digitalization of Traffic" project (DIGI-V) the city aims to lower traffic-related nitrogen oxide emissions with an extensive air-pollution-control package that covers all areas of mobility. Here, a combination of data analytics reinforced by artificial intelligence and traffic-flow simulation supports traffic management decisions. The system incorporates a Sitraffic Concert TMC from Yunex, which manages the real-time data exchange, a mesoscopic model-based traffic simulator and predictor from Aimsun (Aimsun Live), and IVU Umwelt's emission model provides the modeling framework with current network data and the operator's choice of traffic mitigation strategies. A continuous quality assurance system runs in the background to provide the traffic management system with up-to-the-minute information about the system's performance.

In the Wiesbaden use case, Aimsun incorporates a data-driven demand preparation tool to estimate origin–destination (OD) flow patterns based on historical and current traffic data. Next, OD demand patterns are fed into a dynamic traffic assignment to compute traffic states in real time every 5 minutes. This time-dependent demand is matched to the digital representation of Wiesbaden's road network, covering all the characteristics of a dynamic traffic system: 152 signalized intersections, timetables for all relevant public transportation lanes in the study area, road capacities calibrated by the parameters of vehicle-based behavioral models, and emulation of the traffic management controllers and strategies in the network.

On the side of traffic assignment, a fast vehicle-based simulation represented by mesoscopic network loading ensures that the model's time and space granularity capture the traffic dynamics appropriately while keeping the required simulation time beneath the required threshold. This involves a road lane-fine, event-based mesoscopic simulation that can model different types of driving behavior. This level of detail when simulating the dynamics of a traffic state is crucial to capture the impacts of traffic management strategies like road-network speed changes, signal-control coordination, or alternative routing have on traffic flow and, ultimately, on vehicles' tailpipe emissions. Yet the event-based mesoscopic simulation and parallelization of simulation runs guarantee that simulation outputs and the evaluation of alternative response plans are delivered within 2–3 minutes.

The above-described simulation-based DSS constitutes the only true digital twin: a system continuously fed by sensor data updating its state in real time, a system capable of predicting its future state and finally a system raising alarms when a KPI-based threshold is exceeded.

Outlook

As ETM systems continue to evolve, they increasingly incorporate current trends in mobility and benefit from the promising features upcoming technologies have to offer. The following selection showcases some of these opportunities.

Connected (Autonomous) Vehicles

The arrival of connected vehicles on urban roads opens a new field of opportunities for data-based models and traffic control. On one hand, field traffic data is enhanced by enriched and more granular data from the connected vehicles themselves, allowing for better and more precise traffic estimations. On the other, environmentally friendly behavior may be suggested to drivers in the form of speed recommendations that apart from producing less emissions, reduce the number of stops at traffic lights thanks to SPaT (Signal Phase and Timing) messages. Thus, more efficient energy consumption through vehicle platooning development and optimized driving behavior can be achieved. In addition, connected (autonomous) vehicles (CAV) can dynamically recalculate routes to avoid emission heavy areas or mandated (U)LEZ, improving air quality via prediction and immediate vehicle response [6].

Mobility Management

A holistic approach to reducing overall emissions must go beyond traffic and consider all urban transportation modes in an overarching strategy. As such, mobility management should allow users to choose the best alternative for their trips with full transparency on the environmental implications. Mobility Apps (see the example of Würzburg above) are a way for authorities and mobility operators to present these alternatives to users, and to promote environmentally friendlier choices, such as public transport, or non-motorized transport (NMT, i.e., cycling and walking). For authorities to do so, traffic management tools may be used to improve the conditions for these modes. Public transport on the roads (buses and tramways, e.g.) can be prioritized at intersections, thus reducing their overall journey times and increasing their attractivity. Similarly, so-called “green waves”, or green-light coordination for cyclists may be enabled by use of advanced sensors (cameras, radars, or even Wi-Fi and Bluetooth beacons), providing a safer and more attractive environment for cyclists and pedestrians. While public transport vehicle prioritization is already commonplace in many European cities, solutions like SiBike from Yunex, which provides traffic signal prioritization for bicycles, are being pioneered in cities like Marburg or Reutlingen, both in Germany.

Dispersion Modelling

Dispersion simulation takes into consideration measured and forecasted weather conditions (e.g., satellite and statistical data), as well as land and building topology to model the spreading of pollutants in a given period of time. Such models can track pollutant immission in time and space and provide a view of the short-term future of how pollutants will behave given a certain scenario. Dispersion modelling could further provide value in rapidly changing and dynamic environments where wind and precipitation – or the lack thereof – play an important role in the effects of ETM in urban areas /for residents. Strong winds and upcoming rain could, e.g., help dissipate pollutants in a complementary way to traffic measures or on the other hand even concentrate them in an unexpected pocket of the city. Additionally, phenomena such as thermal inversion may exacerbate the need for emission reduction during specific periods of the day.

Advanced Data Models

A promising application of FCD is the microscopic calculation of emissions that results from converting driving behavior from individual vehicles (acceleration, speed and braking) to precisely determine their exhaust emissions based on their vehicle dynamics and engine characteristics [7]. This approach could give cities a more granular view of emissions within their network, allowing for factors such as topography (i.e., slopes) or intersection turns to be more closely evaluated in their contribution with pollution. Further, a closer look on the braking behavior of vehicles could have a large impact on a large part of PM pollution, which has a non-exhaust origin in the abrasion of brake pads and vehicle tires. In a future where significant portions of the vehicle fleets consist of electric vehicles, non-exhaust pollution (already amounting for half of $PM_{2.5}$ and most of PM_{10} road transport emissions) could be as effectively tackled as exhaust emissions today. As a whole, this approach additionally provides useful input for less-polluting connected, as well as autonomous vehicles.

Conclusions

Environmental Traffic Management has already proven its effectivity in reducing traffic emissions. In a study from the German Federal Highway Research Institute (BASt), ETM systems were found to be able to reduce up to 22.4% of $PM_{2.5}$ emissions, 7.1% of PM_{10}, 17.3% of NO_2, and 15.2% of CO_2 [8]. The number of cities incorporating this technology has been steadily growing in the last 10 years, and agencies on both national and European levels are encouraging more operators to follow suit. It is worth noting that although CO_2 is not considered as a (health-threatening) pollutant, but rather a GHG, some policies and metrics do not set a binding limit or threshold for its emissions in e.g. traffic. It is however possible that, through the same methodologies that ETM incorporates, a precise estimation and consequent reduction of CO2 can be achieved for the benefit of climate change actions and other related policies.

While the complexity scale of ETM systems broadens by integrating more, and more elaborate elements, the implementation of effective instruments remains flexible and scalable. In this sense, systems may start small and build on complexity and size as operators gain expertise and understanding of the cause-and-effect relations for their own system's emissions. Finally, it is expected that the technological evolution of ETM systems continues to develop, providing improvements and additional capabilities to the process with each new feature. It is through this constant evolution of the system, that its overall effectivity will increase, and traffic emissions will be further avoided.

City/Street	PM_{10} emission reduction (days w/ overruns	$PM_{2.5}$ emission reduction (t/a)	NO_2 emission reduction (t/a)	CO_2 emissions reduction (t/a)	PM2.5 immission reduction (µg/m³)	NO_2 immission reduction (µg/m³)
Brunswick Altewiekring	not calculated	0.177 -1.2%	0.558 -1.3%	1.032 -0.2%	12.3 -0.9%	39.9 -3.7%
Erfurt Leipziger Str. & Talstr./Bergstr.	not calculated	0.134 -22.4%	0.300 -17.3%	545 -15.2%	18.7 -3.9%	38.0 -2.6%
Potsdam Behlerstr.	not calculated	0.081 -3.2%	0.270 -5.1%	591 -5.1%	20.0 -0.4%	36.8 -2.5%
Wittenberg Dessauerstr.	28 -7.1%	0.123 0%	0.417 -0.7%	720 -0.7%	18.3 0%	34.8 -0.6%

Table 1 - Results of the BASt study of different ETM systems

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