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Methods for assessing the role of traffic management in mitigating the environmental impacts of urban road transport: an overview

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Abstract

The role of transport is significant in the environmental sustainability challenge of European cities. In this framework, traffic congestion in modern cities is considered a major contributor to the problems of air quality and greenhouse gas emissions. Intelligent Transport Systems (ITS) for urban traffic management can reduce traffic congestion and decrease the environmental impacts of the transport systems. This paper reviewed several scientific articles evaluating the ITS technology examined, the impact analyzed, and the methodology applied to assess potential environmental benefits. Microscopic traffic simulation and qualitative approaches are the most commonly chosen methods. The impacts analyzed are equally distributed through air quality, GHG emissions, and congestion. Finally, the collected results are discussed, highlighting different approaches' potentials and limitations (for example, typical scenarios, required input data, and achieved outputs).

Keywords: Traffic management; ITS; GHG emissions; air pollution.

1. Introduction

European cities can contribute to the Green Deal target of reducing emissions by 55% by 2030 and being climate neutral by 2050 by providing cleaner air, safer transport, and less congestion and noise to their citizens. Indeed, cities consume over 65% of the world's energy and account for more than 70% of global CO_2 emissions. The transport sector is responsible for nearly a quarter of Europe's greenhouse gas emissions, of which about 77% are caused by

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road transport (European Commission. Directorate General for Mobility and Transport., 2022). Whereas CO_2 and GHG contribute to the greenhouse effect and the now well-known climate change, on the other hand, road transport also causes air pollution with emissions of oxides of nitrogen (NOx), carbon monoxide (CO), and particulates (PMx). The European Public Health Alliance estimated that the health costs of air pollution caused by road transport in Europe are €67 billion to €80 billion annually.

In this framework, traffic congestion in modern cities is considered a major contributor to the problem of air quality. In particular, intersections play a critical role, as locations where traffic flows from multiple directions cross with limited capacity can create road bottlenecks (Alobaidi et al., 2020; Wei and He, 2022). In these areas, vehicle slowing and stopping operations increase the concentration of pollutants due to exhaust emissions (Alobaidi et al., 2020; Wang et al., 2023). Traffic and vehicle dynamics have a significant influence on air quality. On the other hand, greenhouse gas emissions are relatively less sensitive to local congestion problems.

In recent years, in the transport sector, various approaches to planning and policy-making, technologies, or transport demand have been studied to reduce environmental impacts (Aminzadegan et al., 2022). Intelligent Transport Systems (ITS) can support the transport system by collecting and processing data from infrastructure and vehicles and managing traffic flows and mobility. These technologies hold the potential to reduce traffic congestion and improve driving behavior to decrease the environmental impacts of the transport systems (Barth et al., 2015; de Souza et al., 2017; Kolosz and Grant-Muller, 2015; Nasir et al., 2014; Tang et al., 2020).

This work provides an overview of the role of selected ITS solutions in reducing the environmental impacts of transportation systems. Section 2 introduces urban traffic management strategies (TMS) and their classification. Section 3 investigates the main methodological approaches used in the scientific literature to quantify the effect of selected ITS on the environment. Finally, the method ology-related aspects are discussed in the closing section.

2. Urban traffic management solutions

Urban traffic management solutions (TMS) aim to get road users to their destinations quickly and safely. At the same time, as mentioned above, traffic management is also used to reduce the negative effects of mobility on the environment. According to Bigazzi and Rouleau (2017), TMS influences travel activity (the number of trips generated and their distribution in space and time), travel mode choices (principally single-occupant vehicles versus multi-occupant vehicles, public transit or non-motorized modes), vehicle speeds (including speed dynamics such as accelerations and idling, influenced through traffic conditions and driver behavior), and vehicle types (including engine and fuel characteristics, influenced through vehicle ownership, usage and maintenance decisions).

Several classifications of TMS are proposed in the scientific literature. Table 1 shows the one proposed and used in this work (based on Bigazzi and Rouleau, 2017; Charlie Wallace et al., n.d.; de Souza et al., 2017; Institute for Transport Studies, n.d.; Othman et al., 2019; Pandazis, Jean-Charles and Winder, Andrew, 2015). Traffic signal control systems are the most common traffic management instruments and are one of the most targeted solutions for optimizing traffic flows at road intersections. As described above, signalized intersections are often critical points regarding environmental emissions from road transport. Indeed, optimizing the operation at signalized intersections can help reduce fuel consumption and greenhouse gas emissions on the urban road network by reducing idling, the number of stops, and unnecessary acceleration and deceleration at signposted intersections. As detailed in Table 1, traffic signal management at intersections has evolved from traditional fixed-time signal control to adaptive signal control (Wei and He, 2022):

- Fixed plans systems select traffic light plans by time of day and do not allow for adaptation to the real situation of the intersection. These systems cannot respond dynamically as they use pre-calculated timing plans.
- Plan generation systems use fixed-time plans but select which plan to use based on information provided by detectors strategically placed in the network rather than by time of day.
- Actuated signal systems enable the micro-regulation of traffic lights to manage situations with high variability in demand. Some systems incorporate local adaptation at the controllers to adjust the action of centrally imposed fixed-time plans.
- Adaptive signal systems are traffic management techniques that adjust the timing of traffic signals based on real-time traffic demand. This is achieved using a control system comprising hardware and software. The

hardware includes sensors for real-time traffic density estimation, while the software analyzes captured data to understand the city's current traffic flow.

The adaptive signal system dynamically adjusts signal timing plans in real-time based on the traffic conditions, demand, and system capacity to maximize throughput and reduce traffic jams (Ahmed and Hawas, 2015; Kühnel et al., 2018). This system reduces fuel consumption and emissions by minimizing idling, the number of stops, and unnecessary accelerations and decelerations at signalized intersections (Barth et al., 2015; Kühnel et al., 2018). Adaptive signal systems operate through a central computer communicating with individual traffic controllers. The system gathers basic information from intersection sensors and integrates it with decisions, data from surrounding intersections, and inputs from the mobility management center.

Table 1. Classification of main urban traffic management applications

Application	Example
Access control and operating restrictions	Access restrictions by zone, time of day, or route
	Low/zero emission zones and eco-zones
	Ramp metering
Lane management	Lane capacity changes
	Shared lanes
	Eco-lanes
	Dynamic lanes
Traffic signal management	Adaptive signal systems
	Coordinated traffic light
	Actuated signal systems
	Fixed plans
	Transit signal priority
Parking management	Real-time Occupancy monitoring
Speed management	Variable speed limits
	Speed enforcement
	Urban intelligent speed adaptation
	Eco-driving
Pricing strategies	Road, congestion, and cordon pricing
	Electronic toll collection
Dynamic routing	Route suggestion
	Re-routing and speed adjustment

3. Method and approach to assess environmental impacts of TMS

Once the context of the analysis and the specific type of ITS were defined, articles of interest were searched in major scientific databases. The databases used in this study were "Web of Science," "IEEE Xplore," "ScienceDirect," and "Google Scholar." Only English-language contributions were selected. Papers on related ITS technologies or broader approaches were included to cover various methodologies. A preliminary selection of the most relevant articles resulted in 21 papers being included in the study. Articles published up to December 2023 were included.

The collected papers are categorized into specific fields. First, the type of ITS solution is analyzed according to our classification (see Table 1), including a sub-classification for the traffic signal category (TSM_fixed, TSM_plan generation, TSM_actuated, TSM_Adaptive, TSM_without specification). Next, the environmental impacts considered in this paper—namely air quality, GHG emissions, and congestion—are examined. The methodology used to assess these impacts is likely the most critical aspect. Table 2 presents the main features extracted from the selected papers. The analyzed articles span from 2009 to 2023, with a peak in publications around 2017. Regarding methodology, most papers (62%) propose quantitative approaches, particularly through microscopic and macroscopic traffic simulation models or mathematical models, while others employ qualitative methods, i.e., literature research. Most of the papers, likely because of the chosen keywords and the focus of the search, analyze traffic signal management solutions and speed management technologies. Quantitative methods, especially traffic microsimulation, are used when researching a specific technology. If, on the other hand, a broad category of ITS is being treated, descriptive approaches are preferred.

Table 2. Collected papers and main features

Paper	Access control	Lane management	TSM_fixed	TSM_plan generation	TSM_actuated	TSM_Adaptive	TSM_without specification	Parking management	Speed management	Pricing strategies	ITS no specified	Impact_air quality	Impact_GHG emissions	Impact_congestion	Quantitative method	Qualitative method	Method
(Ahmed and Hawas, 2015)						x								x	x		Microsimulation traffic model
(Alobaidi et al., 2020)			x									x	x	x	x		Microsimulation traffic model
(Barth et al., 2015)		x				x	x		x			x	x	x		x	Literature research
(Bigazzi and Rouleau, 2017)	x	x					x	x	x	x		x	x			x	Literature research
(De Coensel et al., 2012)				x								x	x	x	x		Microsimulation traffic model
(de Souza et al., 2017)							x		x					x		x	Literature research
(Grote et al., 2021)							x					x	x	x		x	Survey (Delphi technique)
(Hamilton et al., 2013)							x									x	Literature research
(Khan and Ghodmare, 2017)											x	x		x	x		Mathematical Modelling
(Mangiaracina et al., 2017)							x	x				x	x	x		x	Literature research
(Mascia et al., 2014)			x									x	x	x	x		Microsimulation traffic model
(Mascia et al., 2017)			x									x	x	x	x		Microsimulation traffic model
(Nasir et al., 2014)							x			x		x	x	x	x		Mathematical Modelling
(Othman et al., 2019)							x		x			x	x	x		x	Literature research
(Salzillo-Arriaga et al., 2022)							x				x		x	x	x		Mesosimulation traffic model
(Smith et al., 2013)						x						x	x	x	x		Test Pilot
(Tang et al., 2017)	x											x	x		x		Macroscopic traffic model
(Tang et al., 2020)	x								x			x	x				Macroscopic traffic model
(Vilcan et al., 2022)							x						x	x	x		Macroscopic traffic model
(Wang et al., 2023)												x		x	x		Air quality model
(Zito, 2009)				x								x			x		Microsimulation traffic model

The role of ITS in supporting urban smart mobility was investigated by Mangiaracina et al. (2017) through an extensive *literature review*. They divided the collected papers into two main groups: freight and people transport. The ITS described in the papers in this second group are then classified into traffic management, public transport, and parking management. The authors do not detail the technologies described; however, they state that most papers considered using smart traffic lights as road intersections are perceived as critical points for urban traffic flow. In terms of methodology, the authors noted a lack of quantitative models to measure the overall impact of ITS technologies in the urban context. It was stated that simulation is needed to quantify the environmental impacts. A specific ITS category, i.e., TMS, was analyzed by Bigazzi and Rouleau (2017) to assess its effects on air quality and, thus, on the impact on road users' health. The authors included the following technologies in this category: operating restrictions and pricing, lane and speed management, traffic flow control (including adaptive signal systems), and trip reduction strategies. Bigazzi and Rouleau (2017) analyzed papers from different scientific fields in their review by evaluating the data types used for impact analyses. As might be expected, it emerges that in the transportation sector, the exposure data are unused, whereas the measured traffic data are the first choice, followed by modeled emission data. Finally, the authors propose a weight-of-evidence approach to evaluate if the information gathered in the analysis is sufficient to assess the benefits of TMS on air quality. There is limited evidence of emission effects for some strategies, including road pricing and low-emission zones on air quality. This does not mean that the other management strategies in traffic are not effective, but they are not sufficiently studied and evaluated. Traffic management solutions were also classified, reviewed, and analyzed by de Souza et al. (2017). This review is quite different as it focuses directly on technologies and not on scientific papers. The authors did not analyze the environmental impact of the selected technological solutions in detail. The reduced environmental impact is considered an end goal that can be achieved through traffic control by reducing congestion, suggesting alternative routes, and regulating vehicle speed. The same technological focus is proposed by Hamilton et al. (2013), which presents an interesting temporal (and technological) evolution of Urban Traffic Controls (UTC). The desired characteristics of future UTC systems from the policy implementation perspective were collected by Grote et al. (2021) through a two-stage survey conducted among local government policymakers and implementers. "A UTC system that prioritizes improvement of air quality and the reduction of adverse climate effects through reducing vehicle emissions" is one of the characteristics chosen by respondents. Barth et al. (2015) outlined how the different areas of ITS can impact GHG and pollutant emissions by reducing energy consumption. They proposed an environmentally friendly state-of-the-art ITS program in the U.S. and Europe. The solutions are classified into three areas: vehicle systems, traffic management systems, and travel information systems. Regarding the second area, TMS, the authors collected results of projects that used "eco-signal operations," i.e., the use of ITS technologies to decrease fuel consumption and GHG emissions by reducing idling, the number of stops, and unnecessary accelerations and decelerations at signalized intersections. The other selected paper presenting a literature review is by Othman et al. (2019). They aimed to review the existing modeling approaches to represent traffic behavior and the associated energy consumption and pollutant emissions. The energy consumption and emission models were divided into single vehicles and traffic vehicular flow. According to this classification, the investigated control strategies included eco-driving for vehicle-related solutions, traffic lights control, and speed limit control for traffic flow management. Developing energy consumption and emission macroscopic models that use aggregate network or link-based data is necessary if the evaluation level is the traffic flow. These models are more coarse but simpler and faster to use based on traffic variables such as average speed, vehicle density, or traffic flow (Othman et al., 2019). Many articles focus on traffic control projects that do not directly aim to reduce emissions and energy consumption but for more classic outputs such as distance traveled, delays, or total time spent in networks. However, improving traffic flow can positively impact environmental metrics, as they reduce, for instance, the number of stops and accelerations.

Vehicle emissions are influenced by traffic flow and emission rate. Wang et al. (2023) applied a Community Multiscale *Air Quality* (CMAQ) *model* and real-time traffic congestion data from TomTom to investigate the air quality and health impacts of traffic congestion. The congestion data are used to generate the hourly diurnal temporal profile of the vehicle emissions. Corrections are applied to qualify the emission rate changes, which depend on driving speed and traffic congestion. Their simulations show that traffic congestion increases pollutant concentration. Using aggregate formulations, Khan and Ghodmare (2017) propose analytical formulas for calculating annual congestion cost, time benefit value, emission savings value, and safety savings value to compare different ITS strategies using data from urban mobility reports.

A common approach in the literature is using a traffic simulation tool (micro- or macroscopic) as input for emission models to compare scenarios that may also include traffic management strategies. For example, De Coensel et al. (2012) combined a *microscopic traffic simulation model* (Paramics) with a model for air pollutants (VERSIT) to study the influence of traffic intensity, signal coordination schemes, and signal parameters on CO_2, NOx, and PM emissions. They included noise emission levels in their analysis. Their study area is an arterial road with five traffic signals spaced 200 meters apart. Vehicle behavior parameters, such as the driver's aggressive driving and reaction time distributions, were not varied in this study. While these are important parameters, the authors stated that the primary goal was to test different optimized and synchronized traffic light cycles. A traffic microsimulation model using the Paramics tool was also proposed by Mascia et al. (2017, 2014) with a specific emission model called AIRE (Analysis of Instantaneous Road Emissions) to assess the environmental impact of combined VMS routing and traffic signal coordination measures. This methodology enables estimating the effects of ITS actions on CO_2 and Black Carbon emissions per link. The output of the traffic microsimulation model includes speed and trajectory data for each vehicle every second, which serves as input for the emission model. Like De Coensel et al. (2012), the driver's driving behavior parameters are the default ones, while five scenarios are defined by varying the traffic demand. The methodology was tested on a part of the urban road network consisting of two corridors in Glasgow, Scotland. Simulation results have demonstrated the effectiveness of traffic signal control systems in reducing emissions and improving traffic conditions, even though these benefits depend on several factors, such as the level of demand and its traffic composition (percentage of buses, HDV) (Mascia et al., 2017). A corridor in the urban area of Palermo in Southern Italy composed of a sequence of 4 coordinated traffic lights (range 80–150 m) was the test site chosen by Zito (2009). Traffic loop detectors and one pollution-monitoring are used to collect data on the model built using DRACULA traffic micro simulator software to quantify CO and C_6H_6 roadside concentrations. In this approach, each vehicle is associated with a set of characteristics of the vehicle and driver behavior. The author uses queue length as a traffic parameter correlated with the change in pollutant concentrations over time. The traffic parameters quantified by DRACULA software and average weather features were used to calibrate a neural network to estimate pollutant concentrations. Ahmed and Hawas (2015) proposed an integrated traffic signal control system to handle various boundary conditions of recurrent and non-recurrent congestion, transit signal priority, and downstream blockage conditions, tested with a microsimulation traffic model named "CORSIM" (CORridor SIMulation). The network used is a grid of 49 intersections with 7 horizontal arterials and 7 vertical arterials, where each intersection of each pair of arterials represents a signalized intersection. In this case, the network does not reproduce any real site, and different levels of traffic demand were configured, including cars and buses. The performance indicators to compare different traffic control strategies in this methodology were only related to transportation performance (travel time, delay) without environmental impact assessments. Conversely, the core of the work presented by Alobaidi et al. (2020) is to estimate the negative impact of traffic congestion by calculating the amounts of gas emitted during traffic congestion at a signalized intersection in Baghdad. A three-leg signalized intersection was modeled using SIDRA software (Signalized and Un-signalized Intersection Design and Research Aid), and traffic data was obtained using the videotaping method. Optimization of traffic light cycles (obtained with microsimulation software) was compared with classic indicators such as LOS and delay and those related to environmental impacts (CO_2, CO, HC, and NO_X emissions). A pilot implementation and *field test* of a real-time adaptive traffic signal control called SURTRAC (Scalable Urban Traffic Control) is presented by Smith et al. (2013). The pilot site, in Pittsburgh's East Liberty neighborhood, consists of nine intersections between 30 to 150 meters apart, averaging 83 m. In this case, the GPS app collected travel time, speed, number of stops, wait time, and fuel consumption, while emissions were derived from fuel consumption.

An alternative to the microsimulation of traffic may be the more aggregated approach, namely the *traffic macrosimulation model*. Nicolae et al. (2019) and Vilcan et al. (2022), for instance, analyzed the impact of the Traffic Management System in the city of Pitesti by combining a transport macro-simulation (VISUM) with detailed junction modeling (ICA-Intersection Capacity Analysis). The authors compared the volume/capacity ratio, LOS, and GHG emissions in the base scenario (without any TMS) and future scenario (with TMS) during two daily peak hours. However, the papers do not detail how the control strategy will be implemented and simulated. Tang et al. (2017) used the same macrosimulation tool, but the emissions were quantified using COPERT 4. The main goal of their work was measuring the impacts, in terms of emissions, infrastructural (new tunnel construction), and regulatory (access restriction for heavy trucks) changes. The macrosimulation approach estimates the effects on total emissions in a wider area (the Dublin city region). The same approach with some evolutions is presented by the same authors a few years later (Tang et al., 2020). They studied the change in air pollution levels, focusing on $PM_{2.5}$ and NO_2 emissions, based on comparing the impacts of 4 types of TMSs: a shift in road infrastructure, regulation of heavy goods vehicles, speed limit changes, and fleet composition changes. Compared with the methodology used by Tang et al. (2017), the modeling chain proposed by the same author in 2020 contains not only the traffic and emission model but also the dispersion model and the health impact assessment model. Apart from microscopic and macroscopic models, mesoscopic models can also be used for similar analyses, as reported in the examples of Environmental Traffic Management described by Salzillo-Arriaga et al. (2022). To enable the selection of the correct mitigation strategy, the authors propose for the city of Wiesbaden a model using real-time traffic data in a system consisting of a mesoscopic traffic model (Aimsun) and an emissions model (IVU Umvelt's). Furthermore, Nasir et al. (2014) propose *mathematical models* to evaluate the environmental effects of a "green navigation technology" to help the driver save fuel and reduce environmental pollution.

4. Discussion and conclusions

The simulation scale is mainly influenced by the type of ITS solutions to be analyzed. For instance, traffic restriction strategies are most efficiently evaluated with a macro simulation approach, while representing the impact of traffic light control solutions requires microscopic simulation. All of this is closely related to the study area. The most frequently used scenario for TMS is the urban "corridor," described according to the number of intersections and their spacing (De Coensel et al., 2012; Mascia et al., 2017, 2014; Zito, 2009). For macroscopic analysis, the area can be extended to the entire or a portion of the city (Tang et al., 2020, 2017). Choosing temporal and spatial discretization is crucial (Othman et al., 2019). The kinematics of vehicles is an essential point for estimating energy consumption and emissions. Traffic microsimulation models allow consideration of factors such as the number of accelerations, decelerations, and individual vehicle dynamics. Macrosimulation models are generally simpler and quicker to use but also coarser. These models are based on aggregated traffic variables such as traffic flow, density, and average speed. Therefore, the combined associated emission models must be consistent and receive input from traffic models considering aggregated and disaggregated variables per vehicle. Moreover, measurement indicators collected, such as travel time, speed, delay, NOx, and CO, can be estimated at the network, intersection, and corridor levels, while the impact of ITS differs based on the spatial reference of the indicators (Mascia et al., 2014). The most commonly used indicators to assess the impact on air quality in the analyzed papers are NOx emissions, followed by CO. As for climate change impacts, CO_2 is the predominant indicator. Moreover, travel time and speed are often used to quantify congestion. As demonstrated by the scientific research presented in this paper, quantifying the benefits of TMS solutions regarding environmental sustainability is usually aggregated and qualitative. Among the identified shortcomings is the lack of detail in describing the contexts in which the effects are assessed (number of lanes, traffic demand) and the simulated technological solutions. For instance, the traffic light control strategy and its simulation methods in the model are often not explained sufficiently.

In conclusion, the methodologies used to assess the environmental impacts of ITS solutions are not contradictory and could also be integrated. The choice of a methodological approach for such a study depends on the analyzed TMS strategy, the study area (size and level of detail), the type of impact, the final objective, and the available data and models. The extension of this initial research will detail the definition of the performance indicators and obtained results from the analyzed studies. Future research will focus on applying a microscopic traffic model to evaluate traffic control strategies' environmental benefits and aspects that may influence the results, such as traffic composition or the geometry of the intersection (and corridor).

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