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Review article

Traffic control for freeway networks with sustainability-related objectives: Review and future challenges

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ABSTRACT

Sustainability is a key point in the design and management of mobility and traffic systems, which affects also the development of traffic control strategies for freeway networks. According to sustainability-related concepts, freeway traffic controllers should be devised not only for maximally exploiting the road capacity and decreasing vehicles travel delays, but also for reducing pollutant emissions, fuel consumptions, accidents, noise, and so on. This paper analyses the state of the art of freeway traffic control strategies characterised by sustainability-related objectives, in particular referred to traffic emissions and traffic safety, by providing a classification of the research papers in this area. The final part of the paper highlights the main research challenges for modelling and control techniques brought by the introduction of emerging information and communication technologies, that are becoming more and more widespread and are transforming the concept of vehicles in intelligent and connected agents, able to measure the traffic state and to implement specific traffic control policies.

Contents

1. Introduction

Nowadays, the greater awareness about the dangerous effects produced by myopic policies aimed only at pursuing short-term benefits has brought the issue of *sustainable development* to the

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centre of the political agenda of many countries worldwide. In recent years, in fact, the theme of sustainability has been addressed considering various fields of the human activity and proposing several definitions and targets (as those proposed in Kates, Parris, & Leiserowitz, 2005 and Giovannoni & Fabietti, 2014). Although concerning different aspects, such definitions agree that only the actions aimed at achieving the optimal relation between the humans and the environment can ensure a fair development of contemporary and future society. Yet, the concept of sustainability is extremely complex, since it requires the fulfilment of a mix of often conflicting objectives. The creation of sustainable cities, the promotion of a more equitable economic growth and the environmental safeguard represent just some of the objectives identified in United Nations (2017) to accomplish the 2030 Agenda for Sustainable Development (United Nations General Assembly, 2015).

The implementation of the 2030 Program requires a rethinking of *transportation systems* in a more open-minded and environment-friendly perspective. In this sustainable vision, the transport system should enhance the social equity and ensure a safer mobility by increasing the access to services and to the most disadvantaged areas, without damaging the environment and people's health. This ambitious journey towards *sustainable mobility* starts from the awareness that the transport system, in particular the road sector, is today one of the leading sources of greenhouse gases and pollution, involving serious consequences both for human health and for the environment (Hoek, Brunekreef, Goldbohm, Fischer, & Brandt, 2002). A survey developed by the World Health Organization, on the basis of 2012 data, revealed that 3.7 millions of premature deaths may be attributed to environmental pollution. Most of these deaths and diseases are caused by the prolonged exposure to substances resulting from the use of fossil fuels.

The need to urgently address these sustainability-related issues calls for a new political approach. Referring to the European context, the European Commission has promoted several studies focused on the quantification of the impacts of transport, outlined for instance in Maibach et al. (2007), Martino, Maffii, Sitran, and Giglio (2009) and MOVE (2014), and has drawn up the White Paper on Transport (European Commission, 2011) reporting the main guidelines to face the future mobility in the European area. Despite the great efforts in this direction, *road traffic emissions* are still far from the challenging limits imposed to safeguard the human health, since the growing number of vehicles has caused an increase of pollution, compensating the positive effects obtained by the progress achieved in the automotive sector (European Commission, 2011; Johansson, Pearce, & Maddison, 2014).

Another significant problem, that cannot be absolutely neglected, regards the need to improve *traffic safety* in order to reduce accidents and the related deaths, injuries and material damage. World Health Organization (2018) estimates that road crashes are the eighth leading cause of death for people of all ages and the first cause of death for children and young adults. The same report indicates that, despite the growth of motorised transport, a 50% reduction in road accident deaths has been observed in the last fifteen years. However, the number of fatal accidents occurred in the same period corresponds to a rate of 18 deaths per 100,000 inhabitants that, compared to the target value of 3.6 defined in United Nations General Assembly (2015) for 2020, shows that the path towards a safer mobility is still very long.

The increasing number of vehicles has also led to an intensification of *traffic congestion*, implying an increase of travel times as well as a loss of confidence on the reliability of traffic systems by the drivers. Nevertheless, it is evident that in many cases it is not possible to modify the existing infrastructures to meet the ever increasing traffic demand, both for physical and economic constraints. In this scenario, the development of *managing and control tools* for traffic systems becomes crucial to efficiently exploit the existing road network, without requiring substantial interventions on the infrastructures (a very deep analysis on the impacts and challenges of systems and control methodologies on most application domains, including transportation and traffic systems, can be found in Lamnabhi-Lagarrigue et al., 2017).

Since a large part of the freeway systems is not able to meet the current mobility needs, thus affecting the road users in the form of congestion, increased air pollution and reduced safety, in the last decades numerous studies have been carried out by researchers to develop planning and control algorithms for freeway traffic networks. If the former works, dating back to the Nineties, were basically devoted to mitigate congestion phenomena, the present global roadmaps in terms of eco-innovation of transport systems require the achievement of even more ambitious targets. This implies a revision of the traditional control strategies towards a more sustainable perspective vision, so that the control objectives, besides the efficient use of the road network capacity, also include the minimisation of emissions, fuel consumptions, accidents, and so on.

This survey paper aims at classifying the works in the literature which propose freeway traffic control schemes and explicitly include environment-friendly and safety-related control objectives. In particular, in Section 2 the most relevant sustainable control objectives in freeway traffic control are analysed. A brief survey on models for traffic flow, emissions/consumptions/dispersions and safety, useful for the definition of sustainable traffic control strategies for freeways, is reported in Section 3. A review and classification of the main sustainable control approaches for freeway networks is given in Section 4, while Section 5 provides some comments and remarks about the control strategies analysed in the paper. Finally, future perspectives and trends of freeway traffic control towards sustainability are discussed in Section 6.

2. Sustainable control objectives in freeway traffic control

The concept of sustainable mobility embraces a wide range of aspects, from the environmental safeguard to the social and economic development. In this context, the road transport plays a crucial role for the economic growth and the population well-being, since it still represents the most widespread means to move passengers and to supply goods. In this sense, the goal of sustainable transport is to preserve the social and economic needs and, at the same time, to offer a reliable and inclusive service, improving access and connections to all users. Given the complexity of the topic, the problem of sustainability in transport has been investigated by the research community for several decades (Banister, 2008; Castillo & Pitfield, 2010; Santos, Behrendt, & Teytelboym, 2010). Certainly, changing the people attitudes towards sustainable issues is a long process, requiring a reinforcement of laws and a great educational effort to increase the people awareness about the consequence of their actions. Nevertheless, these latter aspects are out of the scope of this paper, in which an overview of the control methodologies developed to mitigate the negative effects caused by freeway traffic is provided. Specifically, in this paper we will focus our attention on traffic emissions (and the related aspects of dispersion of pollutants and fuel consumptions) and road safety, which are the main problems generated by freeway traffic, together with congestion phenomena.

Let us start by introducing the issue of *traffic congestion*, since its reduction is the typical goal of traditional freeway traffic control strategies. As mentioned above, the development of mobility systems, both of freight and of passengers, has contributed to the social and economic growth of the society, but on the other hand it has resulted in the spreading of congestion and the consequent worsening of the current mobility offer. Such congestion phenomena may occur with different levels of magnitude, simply

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causing the formation of queues and the consequent increase in travel times, or even provoking a system deterioration leading to a standstill of vehicular traffic. Moreover, as recognised by the studies developed in Hennessy and Wiesenthal (1999) and Lajunen, Parker, and Summala (1999), the frequent exposure to congestion phenomena also involves an increase of the frustration of drivers who consider the greater time spent to reach their destination as wasted time, which could be used for other activities.

Recurrent and non-recurrent congestion events represent just some of the drawbacks resulting from the rise in traffic volumes. The almost exclusive use of fossil fuels and the increase in the number of vehicles have seen the sector of road transport as a major source of *emission of harmful substances*. It is widely recognised that vehicular traffic is responsible for a significant part of emissions, among which carbon monoxide, carbon dioxide, nitrogen oxides, particulate matter, methane and non-methane hydrocarbons. Some of these substances released into the environment contribute to the chemical reactions which take place in the air, leading to phenomena such as photochemical smog and greenhouse effect. In other cases, the aforementioned types of pollutants, besides producing significant damages to the quality of air and water, involve serious repercussions on human health such as cancer or respiratory and cardiovascular diseases (Hoek et al., 2002). Despite the technological progress achieved in recent years, the global pollutant emissions deriving from the use of fossil fuels are still increasing, e.g. the carbon dioxide produced by road transport has grown of 64% from 1990 to 2012 (IEA, 2014). For this reason, the standards limiting vehicle emissions have been progressively strengthened. Nonetheless, the level of some of these substances is still far from the normative limits and further actions are required to improve air quality. The clean technologies already available or under development offer a high potential for reducing pollutants in the long term, yet the *decarbonisation of road transport* is still a long way to go, since the penetration of such technologies in the automotive market is rather limited.

Achieving sustainable transport also means reducing the number of *road accidents*. Road accidents are certainly recognised as one of the main causes of non-recurrent congestion, but above all they are cause of *life losses and serious injuries*. The World Health Organization in the Global status report on road safety 2018 (World Health Organization, 2018) indicates that all over the world 1.35 million people die in road accidents each year, while millions of people are seriously injured and suffer the consequences of traffic accidents for the rest of their lives. The same study reveals that road accidents are a major cause of death for people aged 15–29 years. Therefore, besides being a serious public health problem, road accidents are a significative burden for the economic sector, as they mainly afflict the most active age group, causing serious economic damage to families and to the workforce in general. A possibility of reducing most of these fatal accidents is represented by suitable safety measures adopted both on vehicles and on roads.

3. The modelling framework for sustainable freeway traffic control

As aforementioned, the identification of adequate traffic control measures represent a viable solution to accelerate the process towards achieving a more sustainable mobility. Different types of control actions can be used to regulate the traffic flow in a freeway network. The main possibilities refer to ramp management (in particular ramp metering, applied with traffic lights at the on-ramps), mainstream control (including variable speed limits, lane control, congestion warning, keep-lane instructions, and so on), and route guidance (normally displaying specific indications at intersections).

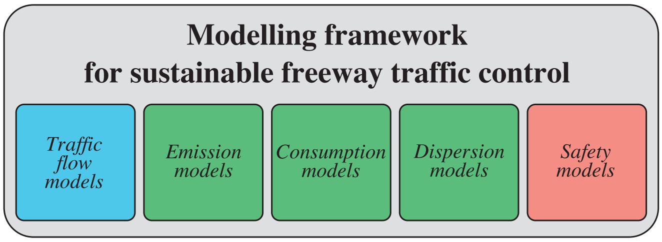

Fig. 1. Modelling framework for sustainable freeway traffic control methods.

In order to develop these control measures, an adequate *modeling framework* has to be defined, both for the description of traffic flow behaviors and for the evaluation of all the sustainability-related issues. Fig. 1 shows the main modelling aspects for sustainable freeway traffic control tools, further analysed in the paper, i.e. traffic flow models, emission models, consumption models, dispersion models and safety models. In order to be adopted within traffic control frameworks, especially if working in real time, these models have to provide a rather accurate estimation of the traffic system dynamics and of the sustainable objective, on the one hand, and they must be computationally treatable, on the other hand. In this respect, it should be noted that the evaluation of environmental impacts and traffic safety not only depends on the evolution of some traffic characteristics, which can be provided by the traffic flow models, but also on some additional inputs. For instance, several emission/consumption/dispersion models base their estimations also on the knowledge of some atmospheric aspects and the physical processes underlying the phenomenon they intend to quantify, while some safety models evaluates the crash risk also on the basis of the layout of the road, the weather and lighting conditions and so forth. Another aspect that cannot be overlooked concerns the calibration of the adopted models which must be able to reproduce, as accurately as possible, the real behaviour of the system. In particular, the validation and calibration of a safety relation may prove to be a very demanding issue, since it requires the acquisition of a large amount of data over a long time period, because the occurrence of road accidents is a rather rare event. Therefore, the task of the researchers is to choose the modeling framework that better reconciles the practical and computational requirements mentioned above with the availability of the input data required by the models. The following subsections report a brief review of the state of the art of these models, with specific attention to the models mostly adopted in the freeway traffic control schemes for sustainable mobility described in Section 4.

3.1. State of the art of traffic flow models

Traffic flow models derive from the need to describe the dynamic behaviour of real traffic systems through mathematical relations. Besides the applications of the system analysis and prediction, traffic flow models may be adopted for the definition of planning actions, the evaluation of the effects produced by the introduction of new infrastructures or the modification of the existing road layout, and to define, simulate and evaluate specific control measures.

Starting from the paper by Lighthill and Whitham (1955) in the Fifties, a wide range of traffic flow models with different features and for different fields of application has been developed. Traffic models can be classified according to different criteria (Ferrara, Sacone, & Siri, 2018c; Hoogendoorn & Bovy, 2001; van Wageningen-Kessels, van Lint, Vuik, & Hoogendoorn, 2015). In Fig. 2, the classification followed in this paper is presented, and the coloured boxes indicate the classes of models which are examined in detail in this section, since they are the most used for

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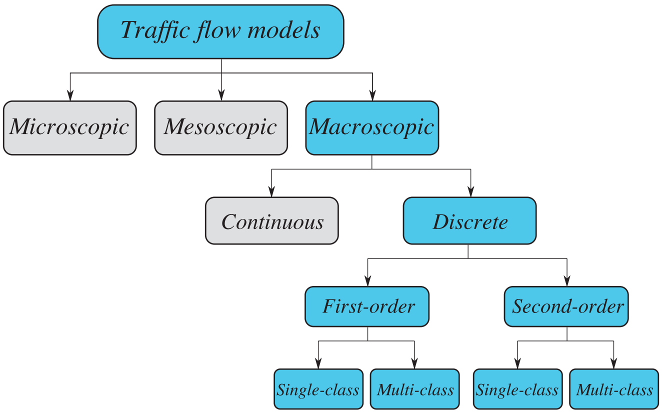

Fig. 2. Classification of traffic flow models.

freeway traffic control with sustainable purposes. The most common classification of traffic flow models is related to their level of detail, distinguishing among microscopic, mesoscopic and macroscopic models.

- *Microscopic traffic models* represent the dynamics of all vehicles and their interactions at a high level of detail. Each vehicle is normally described with a dynamic model, with specific parameters to represent the desired speed or acceleration capabilities of the vehicle, the aggressiveness and reaction times of the driver, and so on. Microscopic models are very accurate and are often used in simulation software tools; on the other hand, due to their complexity, they can be computationally intensive, especially for control purposes.
- *Macroscopic traffic models* represent the traffic dynamics at an aggregate level. The behaviour of vehicles is modelled as a whole, considering the flow of vehicles in analogy with the flow of fluids or gases, and its dynamics is described by means of aggregate variables, specifically density, mean speed and flow. Macroscopic models are less computationally intensive than microscopic ones, and easier to be calibrated, due to the lower number of parameters.
- *Mesoscopic traffic models* show an intermediate level of detail, by representing the heterogeneity of the drivers and vehicles in probabilistic terms.

Another relevant distinction among traffic models is associated with the continuous or discrete nature of the variables representing space and time. *Continuous models* adopt continuous variables for space and time, and the dynamics of the system is represented with differential equations. In *discrete models*, space and time are instead discretised (a road is divided into a set of portions with finite length, while the time horizon is divided into a given number of time intervals), and difference equations are used to model the system dynamics.

Referring specifically to freeway traffic control strategies, that are the main subject of this paper, *macroscopic models of discrete type* are surely the most common choice. The low level of detail and the discretisation allow in fact a small computational complexity, which makes macroscopic discrete models particularly suitable for control schemes acting in real time for large freeway traffic networks. Nevertheless, it is worth noting that the use of continuous macroscopic models for controlling purposes is receiving increasing attention from researchers in this field. Also microscopic simulation software tools are used in some cases, especially for testing and validating new control schemes in a simulated traffic environment. However, the class of macroscopic and discrete traffic models remains the most used in freeway traffic control with sustainable objectives, hence a more detailed analysis on them is provided in the following.

Macroscopic models of discrete type can be further divided according to the number of state variables adopted. *First-order macroscopic traffic flow models* are the simplest ones and capture the dynamics of one aggregate variable, which is the traffic density (see Ferrara, Sacone, & Siri, 2018b for an overview on this class of models). A widely adopted discrete first-order model is the so-called *Cell Transmission Model* (CTM) (Daganzo, 1993; 1994; 1995), developed in the Nineties as a discretisation of the continuous Lighthill-Whitham-Richards model (Lighthill & Whitham, 1955; Richards, 1956). The CTM is a nonlinear model often used for control purposes, especially in its mixed-integer linear reformulation (Ferrara, Sacone, & Siri, 2015a) or in its switched interpretation (Ferrara, Sacone, & Siri, 2015b; Muñoz, Sun, Horowitz, & Alvarez, 2003).

Second-order macroscopic traffic flow models are characterised by two dynamic equations, one for the density and the other one for the mean speed of vehicles (see Ferrara, Sacone, & Siri, 2018d for an overview). The most famous discrete second-order model was developed in the late Eighties (Papageorgiou, 1990; Papageorgiou, Blosseville, & Hadj-Salem, 1989) and is called *METANET*. METANET is a nonlinear model, with a higher complexity compared with the CTM, very widespread in the engineering field and used for control purposes as well.

Both first-order and second-order models have been extended to represent the heterogeneous features of traffic flow, leading to *multi-class traffic models*. They distinguish the user classes according to the type of vehicle (e.g. cars, trucks, public transport, and so on), allowing the description of some relevant phenomena that cannot be captured by models with a single class of vehicles. In other words, multi-class traffic flow models allow to carry out a more realistic and reliable analysis of the real system thanks to the distinction of different categories of vehicles with different features (vehicle length, free speed, and so on). Such models are particularly suitable in case they are associated with emission models, as it is discussed in this paper, because they allow to accurately compute the pollutant emissions for each class of vehicles and then to define appropriate control actions for each of them.

Some multi-class discrete first-order models have been developed so far, such as in Tuerprasert and Aswakul (2010), where a multi-class CTM is proposed. Other multi-class versions of the CTM can be found in Levin and Boyles (2016) and in Roncoli, Papageorgiou, and Papamichail (2015), where the presence of autonomous or intelligent vehicles is explicitly modelled as a class of vehicles. Another version of first-order multi-class models is the Fastlane model, presented for the first time in Lint, Hoogendoorn, and Schreuder (2008). The presence of buses in the traffic flow is considered in the multi-class CTM model presented in Liu, Wang, Wijayaratna, Dixit, and Waller (2015), while a unified framework to model heterogeneous traffic flows for large-scale networks is proposed in Qian, Li, I., Zhang, and Wang (2017).

Other studies, instead, propose multi-class versions of discrete second-order models. Among them, the work in Deo, De Schutter, and Hegyi (2009) extends METANET to represent heterogeneous traffic flows by interpolating the fundamental diagrams defined for each vehicle class. Further multi-class versions of METANET have been proposed in Caligaris, Sacone, and Siri (2010) and then in Pasquale, Sacone, Siri, and De Schutter (2017), where different categories of vehicles are modelled by means of specific fundamental diagrams and where the flow of each class depends on the total density. Finally, being inspired by Logghe and Immers (2008), a further version of the multi-class METANET model has been developed in Liu, De Schutter, and Hellendoorn (2014).

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3.2. State of the art of traffic emission, fuel consumption and dispersion models

As previously introduced, the production of pollutants and their consequent dispersion in the surrounding environment is one of the main externalities of vehicular traffic. In order to estimate and predict the environmental impact caused by traffic flows, specific models have been developed.

Let us start with *traffic emission* and *fuel consumption* models that, having a similar form, can be discussed together. In general, these models allow to quantify the quantities of pollutants released into the air and the consumption rates through the knowledge of the traffic state (i.e. traffic volume, traffic composition, vehicle speed, and vehicle acceleration), which is estimated through detectors located in the network or simulated via traffic flow models (see Treiber & Kesting, 2013 and Ferrara, Sacone, & Siri, 2018a for a detailed discussion on these aspects).

Vehicular emissions and fuel consumptions strongly depend on the operating conditions of the vehicle and the driving style of the driver; in fact, the duration and the sequence of acceleration, deceleration and cruise mode phases have a particular influence on the production of pollutants. Traffic emissions do not depend only on the dynamics of vehicles, but also on the type of adopted fuel, the mechanical characteristics of the vehicle and on environmental factors such as temperature and air humidity. Another relevant aspect is represented by the morphology of the road, for example slopes or intersections increase fuel consumption and the production of polluting substances.

Depending on the level of detail with which the emissions and consumptions are estimated, these models can be distinguished in microscopic, mesoscopic and macroscopic models.

- *Microscopic models* allow to quantify the fuel consumptions and the emissions of a type of pollutant starting from an accurate description of the physical and chemical processes underlying this phenomenon, requiring detailed information not only on the motion of vehicles but also on the surrounding environment. Examples of microscopic emission models are CMEM (An, Barth, Norbeck, & Ross, 1997), MEASURE (Bachman, Sarasua, Hallmark, & Guensler, 2000), VT-micro (Ahn, Rakha, Trani, & Aerde, 2002) and VERSIT+ (Ligterink & De Lange, 2009; Smit, Smokers, & Schoen, 2005). Among them, CMEM and VT-micro models also estimate fuel consumptions.
- *Macroscopic models* evaluate the consumptions and the emissions of pollutants using less detailed data than those required by microscopic models. Such information is generally based on the average speed and acceleration of the vehicles. Some widespread macroscopic emission models are MOBILE (U.S. Environmental Protection Agency, 2002), COPERT (Ntziachristos & Kouridis, 2007; Ntziachristos & Samaras, 2000), VT-macro (Zegeye, De Schutter, Hellendoorn, Breunesse, & Hegyi, 2013) (this latter including also a fuel consumption model) and the macroscopic VERSIT+ (Pasquale, Liu, Siri, Sacone, & De Schutter, 2015).
- *Mesoscopic models* bridge the gap between microscopic and macroscopic ones (as e.g. in Richardson & Akcelik, 1981 and Wallace, Courage, Reaves, Schoene, & Euler, 1984).

These models estimate the quantities of pollutants and fuel consumptions, which may be referred to time units or space units. As indicated in Treiber and Kesting (2013), an emission model (or fuel consumption model) produces a *local emission factor* when the emission (or consumption) is quantified in kilograms per meter (or in litres per meter), while it outputs an *instantaneous emission factor* when the emission (or fuel consumption) is expressed in kilograms per second per vehicle (or in litre per second per vehicle). Given the wide range of traffic emission and fuel consumption models, the researchers have to choose the model with the descriptive power appropriate for the purposes of their applications. For instance, microscopic models are mostly used for off-line evaluations, while macroscopic models are more suitable for controlling purposes, since they allow to analyse the entire transport system with a generally acceptable computational effort.

Among macroscopic emission models, one of the most used in the field of freeway traffic control is the *COPERT* model (Ntziachristos & Kouridis, 2007; Ntziachristos & Samaras, 2000). It allows to compute the local emission factors for several types of pollutants and for a broad range of vehicles. It belongs to the class of average-speed emission models, since it provides the average values of the emissions factors of each harmful substance as a function of average speed values. This model allows also to distinguish the emissions on the basis of the control technologies installed on board of the vehicle. Although coarse, COPERT provides a rather realistic estimation with a low computational burden and therefore it is one of the most suitable models to be adopted in online control schemes.

In order to overcome the limits of COPERT, other traffic control approaches adopt the macroscopic version of microscopic emission models. This is the case of the VT-micro model and the VERSIT+ model, which have been extended to the macroscopic case and called *VT-macro* (Zegeye et al., 2013) and *macroscopic VERSIT+* (Pasquale, Sacone, Siri & De Schutter, 2015; Pasquale et al., 2017a), respectively. Both models are regression-based models, which, in the microscopic versions, use the instantaneous speed and the acceleration relations obtained on the basis of linear regressions. The motivation for the use of these models is that, differently from COPERT, they consider the effects of acceleration, providing a more accurate estimate of emissions. Both VT-macro and the macroscopic VERSIT+ can be adopted as single-class or multi-class models, depending on the considered control purposes and the available traffic models.

In Zegeye et al. (2013), the error introduced by VT-macro compared with the original microscopic version is analytically quantified and empirically evaluated referring to the Dutch A12 freeway. On the other hand, the main peculiarity of the VERSIT+ macroscopic model is that it is characterized by a limited number of parameters and a rather simple formulation, so that it may be suitable for implementation in online control schemes. The VERSIT+ macroscopic model, in the multi-class version, computes the emission factors related to the mainstream flow and to the flow entering from the on-ramp on the basis of the average speeds and accelerations of the traffic flows aggregated by class of vehicle. The evaluation of the operating conditions of the vehicles at the on-ramps and the related emissions represent a key element in the design of freeway control strategies based on ramp metering, since the emissions of vehicles present at the on-ramps can not be neglected in the total calculation of traffic emissions (Pasquale, Liu, et al., 2015).

The polluting emissions released by vehicular traffic do not remain confined to the freeway perimeter, but seriously damage the surrounding environment in which they are spread. Therefore, *dispersion models* can be very relevant to evaluate the impacts of vehicular traffic on air quality. Several dispersion models have been developed in the literature to describe the accumulation of pollutants. Examples of dispersion models can be found in Buckland and Middleton (1999) and He, Qi, Hang, King, and Zhao (2011). However, these models are characterised by a high level of complexity as they have to take into account different environmental aspects such as the presence of obstacles or the effects of air turbulences. In order to develop freeway traffic control strategies, specific dispersion models should be devised, such as the one described in Csikós, Varga, and Hangos (2015), which has been

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properly conceived for the control of freeway traffic systems. Specifically, in Csikós et al. (2015), the partial differential equations used to model the dispersion process, which is a distributed parameter system, are converted in a set of ordinary differential equations, then transformed in a model which is discrete both in space and time. This discrete model can be used with a low computational effort and seems particularly suitable for control schemes with the objective of maintaining pollutant concentrations in the proximity of a freeway under legislation limits. Another dispersion model suitable to be adopted in freeway control algorithms has been developed in Zegeye, De Schutter, Hellendoorn, and Breunesse (2011): it is a discrete-time model which allows to quantify the variation of the emission dispersion level for a reference area by considering the direction and speed of the wind.

3.3. State of the art of traffic safety models

Another very relevant issue for designing sustainable freeway traffic systems is *road safety*. This aspect has been investigated in many research works, since the road accidents affecting many drivers every day represent a relevant criticality of freeway systems. Accidents are one of the major causes of congestion, both for the capacity reduction due to the interruption of one or more lanes and because of slowdowns caused by drivers that observe the accident or are involved in the rescue operations (Potts et al., 2013). The reasons for traffic accident occurrences have been examined and are still under investigation by researchers. Many studies rely on statistical analyses of real historical data about crashes, in order to correlate accidents with specific traffic states or conditions, as well as on other factors, such as road geometry, drivers' behaviors and environmental factors (see Marchesini & Weijermars, 2010 for an extensive overview on the relation between road safety and congestion in freeways).

Among the works investigating the correlation between the safety level in a freeway and the corresponding traffic conditions, it is worth citing the study in Lord, Manar, and Vizioli (2005), based on traffic and crash data from a Canadian case, in which a relation between crashes and traffic data, such as flow and density, has been defined for both rural and urban freeway segments. Other studies analyse the crash likelihood as a function of traffic flow (Chang & Xiang, 2003; Golob, Recker, & Pavlis, 2008), propose a density-versus-safety relationship (Potts, Harwood, Fees, Bauer, & Kinzel, 2015), investigate the relation between traffic states and crash involvements (Yeo, Jang, Skabardonis, & Kang, 2013), or identify specific traffic conditions as crash precursors (Christoforou, Cohen, & Karlaftis, 2011; Lee, Saccomanno, & Hellinga, 2002).

Based on the safety-density relation developed in Potts et al. (2015), the authors of Pasquale, Sacone, Siri, and Papageorgiou (2018) derive a risk indicator, specifically devised for control purposes, to estimate the expected number of crashes in a freeway system and in a given time horizon. As shown in Pasquale, Sacone, Siri, and Papageorgiou (2018), this index can be one of the objectives to be included in the cost function of an optimal control problem. Note that the total number of expected crashes is obtained as a sum of two terms, respectively related to the mainstream and the on-ramps, this latter term resulting particularly relevant when applying ramp metering control, which may lead to long on-ramp queues and thereby to an increased crash risk at the on-ramps.

4. Sustainable freeway control strategies

The literature on traffic control strategies for freeways taking into account sustainability-related aspects is quite recent and mostly refers to the last decade. The existing works can be classified according to different aspects. In this section, three different factors are considered, i.e.

- The type of sustainable control strategy;
- The modelling framework;
- The control methodology.

since they represent very relevant aspects in the design of a freeway traffic controller relying on sustainability-related objectives. All the works analysed in this paper are reported in Table 1, in which they are classified according the three aspects listed above.

4.1. Classification according to the type of sustainable control strategy

First of all, the scientific works on sustainable control approaches for freeway systems can be categorised according to the type of control strategy they consider (e.g. ramp metering, variable speed limits, route guidance) and to the sustainable issues (vehicle emissions, consumptions, accidents, and so on) they refer to. The first part of Table 1 reports the classification of papers on the basis of this aspect.

In Zegeye, De Schutter, Hellendoorn, Breunesse, and Hegyi (2012), a control strategy for ramp metering and variable speed limits is derived to jointly minimise travel times and emissions in the freeway system. The same integrated control strategies are considered in Groot, De Schutter, and Hellendoorn (2013), for reducing congestion and emissions in a freeway system via Model Predictive Control (MPC). In Zegeye et al. (2011), ramp metering and variable speed limits are applied to jointly minimise travel times, traffic emissions and dispersions. Unlike the previous approaches, in Csikós, Varga, and Hangos (2018) ramp metering and variable speed limits are still used to minimise the dispersion of pollutants, but within a hybrid control scheme where, in presence of stable traffic conditions, the control actions are implemented via ramp metering, whereas both ramp metering and variable speed limits are used under unstable traffic conditions.

A supervisory event-triggered framework is proposed in Ferrara, Pasquale, Sacone, and Siri (2017) to reduce travel times and emissions, in which a supervisor communicates to local ramp metering controllers the control law to be applied and its main parameters.

Traffic control schemes to reduce emissions have been developed also in the direction of multi-class traffic control. This means that the traffic flow dynamics and the emission computation is distinguished for different classes of vehicles, as well as specific control laws are computed for each vehicle class. Among these multi-class works, local control strategies of ramp metering type are studied in Pasquale, Sacone, and Siri (2014), in order to reduce the pollutant emissions in the freeway. Coordinated multi-class ramp metering is studied in Pasquale, Papamichail, et al. (2015) for optimally reducing the total time spent by the drivers and the total emissions experienced by them in freeway systems. A supervisory coordinated ramp metering framework, extending to the multi-class case the one proposed in Ferrara et al. (2017), is investigated in Pasquale, Sacone, Siri, and Ferrara (2017), then also treated in a decentralized version in Pasquale, Sacone, Siri, and Ferrara (2018a). Different multi-class traffic and emission models are compared in Liu, Hellendoorn, and De Schutter (2017) for MPC schemes applying integrated ramp metering and variable speed limits.

Besides ramp metering and variable speed limits, also route guidance control has been investigated to reduce emissions in freeways, corresponding to the so-called eco-routing strategies. For instance, the environmental and energetic impacts produced by the route choice decisions of drivers are evaluated in Ahn and Rakha (2008). In Ahn and Rakha (2013), the system-wide impacts

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Table 1
Classification of papers on sustainable freeway control strategies.

	Zegeye et al. (2012)	Groot et al. (2013)	Zegeye et al. (2011)	Csikós et al. (2018)	Ferrara et al. (2017)	Pasquale et al. (2014)	Pasquale et al. (2015b)	Pasquale et al. (2017b)	Pasquale et al. (2018a)	Liu et al. (2017)	Ahn and Rakha (2008)	Ahn and Rakha (2013)	Groot et al. (2015)	Luo et al. (2016)	Pasquale et al. (2017a)	Abdel-Aty et al. (2006)	Lee et al. (2006b)	Lee et al. (2006a)	Yu and Abdel-Aty (2014)	Li et al. (2014)	Pasquale et al. (2018c)
STRATEGY																					
Control strategy																					
Ramp metering	×	×	×	×	×													×			×
Variable speed limits	×	×	×	×												×	×		×	×	
Route guidance											×	×	×	×							
Multi-class ramp metering						×	×	×	×	×					×						
Multi-class variable speed limits										×											
Multi-class route guidance															×						
Sustainable issue																					
Emission	×	×	×		×	×	×	×	×	×	×	×	×	×	×						
Consumption											×	×		×							
Dispersion			×	×																	
Safety																×	×	×	×	×	×
MODELLING FRAMEWORK																					
Traffic model																					
CTM																				×	
METANET	×		×	×	×								×	×					×		×
Linearised METANET		×																			
Multi-class METANET						×	×	×	×	×					×						
Fastlane										×											
Microscopic simulation											×	×				×	×	×			
Emission model																					
VT-macro	×	×	×											×							
Macroscopic VERSIT+					×																
Multi-class VT-macro										×											
Multi-class macroscopic VERSIT+								×	×	×					×						
COPERT						×	×														
VT-micro											×	×	×								
CMEM											×										
MOBILE6											×										
Fuel consumption model																					
VT-macro														×							
VT-micro											×	×									
CMEM											×										
Dispersion model																					
Csikós et al. model				×																	
Zegeye et al. model			×																		
Safety model																					
Crash likelihood																×					
Crash prediction																	×	×			
Crash risk evaluation																			×		
Rear-end crash risk prediction																				×	
Total expected number of crashes																					×
METHOD																					
Control method																					
Feedback control						×												×			
Feedback predictive control															×						
Supervisory event-triggered control					×			×													
Decentralised event-triggered control									×												
Optimal control							×												×		×
Genetic algorithm																				×	
MPC		×	×	×						×				×							
Receding-horizon parametrised control	×																				
Game theory													×								
Impact analysis											×	×				×	×	×			

of implementing dynamic eco-routing systems are investigated, considering different levels of penetration and congestion and being based on the real cases of Cleveland and Columbus, Ohio, USA. Such work concludes that eco-routing systems can reduce fuel consumption and emission levels, and this is normally achieved by reducing travel distances and not necessarily travel times.

The traffic routing problem for urban and freeway traffic networks is addressed in Groot, De Schutter, and Hellendoorn (2015) by applying Game Theory, in order to find routes which minimise the total time spent by drivers and to reduce the total traffic emissions. In Luo, Ge, Zhang, and Ban (2016), a real-time route guidance control scheme is proposed, not only to minimise the total time spent by the drivers, but also to reduce the total amount of emissions and fuel consumptions for all the vehicles. The integration of ramp metering with route guidance control strategies, for a multi-class case, has been exploited in Pasquale, Sacone, Siri and De Schutter (2017) to reduce the total time spent and the total emissions in a freeway network.

Another relevant aspect dealing with sustainable freeway traffic control strategies is related to safety. Some researchers have focused their attention to analyse the impact on safety of the adoption of specific traffic control strategies in freeways. For instance, the benefits of variable speed limits are investigated in Abdel-Aty, Dilmore, and Dhindsa (2006) and Lee, Hellinga, and Saccomanno (2006) in terms of crash likelihood reduction. Analogously, the effects of the implementation of ramp metering strategies on safety are assessed in Lee, Hellinga, and Ozbay (2006).

Other research works are devoted to explicitly consider safety in the controller design. In Yu and Abdel-Aty (2014), a control scheme for variable speed limits is studied to improve safety in freeway systems, in Li, Liu, Wang, and Xu (2014) variable speed limits are applied specifically to reduce rear-end collision risks, in Pasquale, Sacone, Siri, and Papageorgiou (2018) a coordinated ramp metering scheme is proposed jointly considering the reduction of travel times for the drivers and the improvement of safety in the freeway system.

4.2. Classification according to the modelling framework

The papers on sustainable freeway traffic control analysed in Section 4.1 can also be classified according to the adopted models. As clarified in Section 3, different types of models may be used for studying sustainable freeway traffic control strategies, regarding the representation of the traffic flow dynamics, the computation of traffic emissions and fuel consumptions, the evaluation of the dispersion of pollutants in the environment, the estimation of traffic accidents, and so on. These models can be used within model-based control schemes, or for simulation and validation purposes. The second part of Table 1 classifies the previously cited works according to the adopted models.

METANET is used as traffic flow model and VT-macro as emission model in Zegeye et al. (2011), Zegeye et al. (2012) and Luo et al. (2016). In Zegeye et al. (2011) the evaluation of the pollutant dispersions is carried out with the dispersion model developed in the same study. METANET and VT-macro are exploited also in Groot et al. (2013), where the non linear METANET model is approximated through a piecewise-affine formulation, in order to address the computational complexity of the real-time implementation of MPC schemes. METANET and VT-micro are instead used in Groot et al. (2015), while METANET and the macroscopic VERSIT+ model are considered in Ferrara et al. (2017). The METANET model is also used in Csikós et al. (2018), where the dispersion process is evaluated with the model presented in Csikós et al. (2015).

The multi-class METANET is exploited, together with COPERT to compute the traffic emissions, in Pasquale et al. (2014) and Pasquale, Papamichail, et al. (2015). The multi-class METANET is instead combined with the macroscopic multi-class VERSIT+ model in Pasquale, Sacone, Siri and De Schutter (2017), Pasquale, Sacone, Siri and Ferrara (2017) and Pasquale et al. (2018a), while different models are compared in Liu et al. (2017), specifically the multi-class METANET and FASTLANE for the traffic dynamics, the multi-class VT-macro and the multi-class macroscopic VERSIT+ for the emissions. To estimate emissions and fuel consumptions starting from probe vehicle data collected in the Northern Virginia area, different emission models are utilised in Ahn and Rakha (2008), i.e. VT-micro, CMEM and MOBILE6. In Ahn and Rakha (2013), VT-micro is considered to compute the emissions, together with microscopic simulation to evaluate the traffic dynamics.

Microscopic traffic simulation is also used in Abdel-Aty et al. (2006), Lee, Hellinga and Saccomanno (2006) and Lee, Hellinga and Ozbay (2006) to test different variable speed limit strategies, respectively combined with an index of crash likelihood (Abdel-Aty et al., 2006) and a real-time crash prediction model for the safety evaluations (Lee, Hellinga & Ozbay, 2006; Lee, Hellinga & Saccomanno, 2006). METANET is combined with a real-time crash risk evaluation model in Yu and Abdel-Aty (2014), CTM is adopted with a rear-end crash risk prediction model in Li et al. (2014), while METANET is associated with an indicator of the total expected number of crashes in Pasquale, Sacone, Siri, and Papageorgiou (2018).

4.3. Classification according to the control methodology

Another possible classification of these works regard the adopted methodology, as reported in the third part of Table 1. Most of the papers propose a control scheme for freeway traffic and can be categorised according to the control methodology, while other papers analyse the traffic control strategies and their impacts in terms of sustainability.

Analysing the papers on control approaches, it is possible to find a wide range of control schemes, from simple control rules to very sophisticated control algorithms. Simple feedback control strategies are investigated in Pasquale et al. (2014) and Lee, Hellinga and Ozbay (2006), while the authors of Pasquale, Sacone, Siri and De Schutter (2017) propose feedback predictive controllers which compute the control actions not only on the basis of the measured system state, but also on the basis of the prediction of the system evolution.

Again based on prediction and feedback controllers, more complicated frameworks can be found in Ferrara et al. (2017) and Pasquale, Sacone, Siri and Ferrara (2017) where supervisory event-triggered control is exploited, or in Pasquale et al. (2018a) where the decentralised version of the same framework is proposed and compared with the centralised scheme.

Other research works are based on optimisation approaches. Optimal control techniques are adopted in Pasquale, Papamichail, et al. (2015), Yu and Abdel-Aty (2014) and Pasquale, Sacone, Siri, and Papageorgiou (2018), while a genetic algorithm is used in Li et al. (2014) for solving the resulting optimisation problem. The application of optimisation-based techniques in real time often leads to the definition of MPC schemes, as in Zegeye et al. (2011), Groot et al. (2013), Csikós et al. (2018) and Luo et al. (2016). MPC schemes are generally computationally intensive for real-time implementations, hence some extensions are studied in the literature, such as the receding-horizon parametrised traffic controller proposed in Zegeye et al. (2012) or the consideration of end-point penalties suggested in Liu et al. (2017). Other methodologies can be adopted for freeway traffic control, such as Game Theory in route guidance problems, as proposed in Groot et al. (2015).

Finally, some of the previously cited papers do not propose any control approach but try to investigate, via simulation, the impacts of specific traffic control actions in terms of sustainability

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issues. Among them, Ahn and Rakha (2008) and Ahn and Rakha (2013) analyse the impacts of eco-routing systems, while Abdel-Aty et al. (2006), Lee, Hellinga and Saccomanno (2006) and Lee, Hellinga and Ozbay (2006) investigate the effects on safety of variable speed limits and ramp metering, respectively.

5. Remarks on sustainable freeway traffic control

On the basis of the classification provided in Section 4, it is possible to make some general remarks on the different approaches found in the literature on sustainable freeway traffic control, highlighting that there are several aspects that the interested reader should consider, to deal with one or more of the sustainable issues previously analysed. The discussion provided in this section follows the three aspects chosen to classify the control strategies with sustainable objectives in Section 4, i.e the type of sustainable control strategy, the modelling framework and the control methodology.

Having said that, it is worth specifying that the objective of this section is to provide some insights on the aforementioned approaches and not to directly compare them. Indeed, a quantitative comparison of the results provided by the previously cited papers is rather impossible, since they adopt different models, they consider different objectives (in terms of pollutant emission and safety indices) and they test their results on different traffic scenarios. This consideration suggests that what is lacking in the literature on freeway traffic control is a benchmark scenario specifically defined to address these issues, which could be used by researchers to test and compare their control strategies.

5.1. Considerations on the type of sustainable control strategy

The choice of the type of control strategy represents the first fundamental step to face one or more of the sustainable objectives discussed in this paper. Analysing the literature, it is possible to observe that some control strategies are more suitable than others in addressing specific control objectives. For instance, ramp metering, alone or combined with other control measures, allows to achieve satisfactory improvements for all the considered sustainable goals. However, it is worth noting that this application may lead to the creation of long queues at the on-ramps, producing a concentration of emissions and an increase of the crash likelihood in correspondence of the queues themselves. For this reason, in some approaches (Csikós et al., 2018; Ferrara et al., 2017; Liu et al., 2017; Pasquale, Papamichail, et al., 2015; Pasquale et al., 2014; Pasquale, Sacone, Siri and De Schutter, 2017; Pasquale, Sacone, Siri & Ferrara 2017; 2018a; Pasquale, Sacone, Siri, & Papageorgiou, 2018) the pollutant emissions, their dispersion in the environment and the crash risk at the on-ramps are explicitly considered in the definition of the ramp metering control strategies. As for the route guidance strategies, to the best of our knowledge, these approaches have been developed and successfully applied only considering environmental and fuel-saving issues. In some of these applications (see for instance the works presented in Pasquale, Sacone, Siri and De Schutter, 2017, Ahn & Rakha, 2008, Ahn & Rakha, 2013 and Luo et al., 2016), the proposed emissions (and/or energy) traffic assignment models have proven to be more effective in reducing emissions (and/or fuel consumptions) than standard assignment methodologies. Finally, variable speed limits are used in combination with ramp metering to mitigate traffic emissions and dispersion in Zegeye et al. (2011), Zegeye et al. (2012), Groot et al. (2013), Csikós et al. (2018) and Liu et al. (2017), while their use alone is mainly recommended to improve the safety level of freeway stretches. Indeed, these strategies act by seeking to homogenise traffic conditions limiting risky interactions among vehicles and thereby increasing safety. Note that, as it is underlined in Lee, Hellinga and Saccomanno (2006) and Yu and Abdel-Aty (2014), the effectiveness of variable speed limits in reducing crash risk depends on the level of acceptance of the recommended speed. Although, as previously mentioned, it is not possible to directly compare the results stemming from different simulation setups, we have observed that in general the control problems aimed at minimising the environmental impacts entail higher reductions of the performance indicators than the control problems in which the safety issue is taken into account. However, since these works generally aim at minimising the expected number of traffic accidents and not the real number of traffic crashes that may occur in a freeway stretch, even a relatively lower improvement of the safety indicators represents a good result.

All the aforementioned approaches can be extended to *multi-class frameworks* that, compared with standard control schemes, allow to define specific control actions for the most impactful classes of vehicles. For instance, some interesting results can be found in Pasquale, Papamichail, et al. (2015), proposing the application of a multi-class ramp metering strategy to face an emission reduction problem. In that work, if the traffic emissions are explicitly minimised, the controller allows trucks enter the freeway without waiting at the on-ramps. This behaviour is motivated by the fact that trucks present high emissions for low speeds and therefore their stop at the on-ramps could have a detrimental effect. Moreover, the adoption of multi-class control strategies allow to define focused policies and control options. For example, in Pasquale, Sacone, Siri and De Schutter (2017), the multi-class routing control approach is formulated in order to give priorities to the presence of a specific class of vehicles in a predefined path (or, alternatively, to discourage it). Obviously, multi-class control strategies require a more precise modelling context than single-class strategies. Besides, the development of multi-class approaches with safety-related objectives would also require safety models capable of quantifying the impact of each class on the total expected number of accidents. As far as we know, these types of models are not yet available in the literature, probably due to the large number of data that should be needed to calibrate them.

Some of the approaches included in this survey propose *multi-objective methods*, aiming at the simultaneous achievement of one or more sustainable objectives and the reduction of congestion. One of the advantages of using multi-objective approaches is to assess whether the considered objectives are in conflict and, then, to choose the appropriate cost function parameters in order to favour one or more objectives against the other. By referring to the eco-friendly objectives, it is possible to observe that some of the ramp metering control strategies with multi-objective approaches have shown different findings. In Pasquale, Papamichail, et al. (2015), it has been found that the reduction of travel times and the reduction of traffic emissions are largely non conflicting objectives since both are reduced if the control strategy aims to eliminate the traffic congestion. In Zegeye et al. (2012), instead, a great reduction of traffic emissions can be found only by directly minimising this term. In that work, the simple minimisation of the total time spent entails a small benefit in reducing traffic emissions and, in some cases, even provokes a deterioration of them, revealing a potential conflicting behaviour. Also in Zegeye et al. (2011) the minimisation of total travel times involves a worsening of the traffic emission and dispersion processes. For the sake of completeness, it should be noted that in these last two approaches the emissions produced at the on-ramps are not considered. The existence of a conflict between traffic emissions (and/or energy consumptions) and travel times is also raised in Ahn and Rakha (2008), Ahn and Rakha (2013) and Luo et al. (2016), where eco-routing control strategies are proposed. Specifically, the works (Ahn & Rakha, 2008; 2013) show that the paths which optimise energy consumptions and minimise the pollutants emissions are not necessarily the shortest or the fastest. In Luo et al. (2016), the resolution of multi-objective routing problems for different traffic scenarios shows that the reduction of emissions is often in conflict with the improvement of traffic efficiency, while traffic efficiency and fuel consumptions are not conflicting in presence of congestion and vice versa for the off-peak hours. An analogous trend has been observed also in Lee, Hellinga and Saccomanno (2006), where the improvement of the traffic safety via variable speed limits may lead to a degradation of the travel times. On the contrary, in Pasquale, Sacone, Siri, and Papageorgiou (2018) the results stemming from the multi-objective ramp metering control problem indicate that the mitigation of congestion implies an improvement of both travel times and traffic safety conditions. However, since the minima of the two objectives are obtained for different solutions, a potential competitive behavior is observed.

5.2. Considerations on the modelling framework

Another relevant aspect concerns *the choice of the modelling framework*, which must be suited to address the objective of the considered control problem. For instance, the estimation of the pollutant emissions or the fuel consumptions is strictly influenced by the capability of the model to estimate the traffic flow speed. In light of this consideration, the first-order macroscopic traffic flow models do not seem to be the most suitable choice for control schemes devised to minimise traffic emissions or fuel consumptions. This is also shown in Table 1, where only one of the considered eco-friendly control strategies is based on first-order traffic models (see Luo et al., 2016). Even though the role of speed is very important in determining the severity of road accidents, traffic safety models often correlate the occurrence of traffic accidents with variables such as flow or density and often neglect the impact of speed. Therefore, for applications to reduce safety, first-order macroscopic traffic models can be adopted to estimate the crash risk indices.

Second-order macroscopic traffic flow models, providing the dynamic evolution of the traffic speed, are instead often used both to reduce emissions and to improve safety. Yet, in order to further increase the precision of the emission estimation, average accelerations have been deduced from traffic models in Pasquale, Sacone, Siri and De Schutter (2017), Zegeye et al. (2012), Groot et al. (2013), Ferrara et al. (2017), Pasquale, Sacone, Siri and Ferrara (2017), Pasquale et al. (2018a) and Liu et al. (2017). An alternative to enhance the assessment of the air pollution is to improve the descriptive power of traffic flow models using, for instance, macroscopic multi-class traffic flow models. Thanks to these models, it is possible to explicitly consider the emissive contribution of the less-sustainable classes of vehicles (for example trucks), without unduly complicating the modelling framework which can still be used for optimisation purposes. Finally, among all the possible representations of traffic flows, microscopic simulators allow a very accurate evaluation of traffic emissions and safety, but on the other hand they are hardly usable to formulate model-based control strategies.

With regard to the sustainable-related models, the most appropriate choice should take into account not only the level of detail of the traffic model adopted (or the real traffic measurements), but also the availability of the additional information required by these models. For instance, microscopic emission and consumption models often require the setting of parameters related to the type of vehicles (e.g. passenger or commercial vehicles, type of used fuel), the road geometry and the environmental features (such as temperature and air humidity). Dispersion models, besides the knowledge of traffic evolution, need as inputs the quantity of pollutants produced by the vehicular traffic and other information such as wind direction, air temperature, the presence of obstacles and so forth. Traffic safety models, instead, are generally based on statistical processing of data and not on the description of the individual events which may be hard to predict, being often influenced by exogenous causes. For these reasons the safety relationships correlate the occurrence of crashes with the evolution of macroscopic traffic variables (such as flows and density) and with some general characteristics such as those related to road geometry, weather conditions and driver behavior.

5.3. Considerations on the control methodology

The last aspect to consider in order to define an appropriate sustainable control strategy for freeway traffic systems regards *the choice of the control methodology*. Actually, the control problems explicitly addressing environmental objectives and safety issues, besides the improvement of traffic operations, turn out to be complex control problems for the regulation of complex physical processes. Then, the considerations about the control methodology to be adopted refer to the analysis of how much it can be achieved by using sophisticated control schemes with respect to very simple ones, as it is common in all cases in which both the process and the control objective present several complex issues.

In the existing works, already presented in this survey, it is proven that feedback control strategies are very effective both in reducing emissions and improving road safety (see for instance the works in Pasquale et al., 2014 and Lee, Hellinga & Ozbay, 2006). These methodologies are simple to be applied, they generally require local measurements, and they can also be easily combined with traffic simulators in order to evaluate their effectiveness and to calibrate the control parameters.

On the other hand, optimal control strategies, both based on the solution of finite-horizon problems and based on the adoption of receding-horizon schemes (Pasquale, Papamichail, et al., 2015; Pasquale, Sacone, Siri, & Papageorgiou, 2018; Yu & Abdel-Aty, 2014), as well as MPC strategies (Csikós et al., 2018; Groot et al., 2013; Liu et al., 2017; Luo et al., 2016; Zegeye et al., 2011), allow to obtain higher improvements of the different control objectives, as reported for instance in Pasquale, Papamichail, et al. (2015), where a comparison between a PI-feedback regulator and a finite-horizon optimal control approach has been performed.

Of course, the main drawback of optimisation-based approaches, especially in centralised control schemes, regards the computational effort required for real (possibly large-scale) applications. In fact, on the one hand, these methodologies need to be based on models with adequate descriptive power, but, on the other hand, this often increases the complexity of the optimisation problem to be solved, thus affecting and reducing the practical applicability of such approaches.

Moreover, centralised and model-based control schemes generally use extensive measurements of the traffic state on the overall network, which is a crucial issue in the practical implementation of the control scheme, not only for the costs induced for realising and maintaining the necessary sensors and transmission equipments, but also for the communication efforts and for the drawbacks of possible interruptions of measurement transmissions. An alternative to optimal control approaches is the use of predictive decentralised control schemes (as the ones proposed in Pasquale, Sacone, Siri and Ferrara (2017) and Pasquale et al. (2018a) for ramp metering), which do not require the computational burden of classical optimal control schemes and, at the same time, seek to overcome the limitations of simple feedback approaches.

6. Future steps towards a greener mobility

If sustainable control strategies can significantly reduce the environmental impact and the crash risk potential in freeway

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traffic systems, the recent technological advances, regarding both the vehicles and the communication systems, allow to be even more optimistic about the possibility of improving sustainability in the traffic systems of the next future.

The automotive sector has undergone considerable changes recently and existing commercial vehicles are much more efficient than those of the past, since they are provided with engines specifically optimised to limit fuel consumptions or even equipped with electric or hybrid electric propulsion systems. Furthermore, the modern vehicles are designed with lighter and more resistant materials able to comply with higher and higher safety standards.

Other technological developments concern sensors and communication devices, that can be installed on board of vehicles or within the infrastructure. These technologies, i.e. Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication systems, give rise to a connected environment in which the vehicles themselves may become moving sensors or even actuators of suitable control actions, positively affecting the entire traffic system. Examples of collaborative control strategies have been successfully applied in the field of freight transport, where truck platooning policies are actuated in order to reduce the fuel consumptions (see e.g. Besselink & Johansson, 2017; Liang, rtensson, & Johansson, 2013; Pasquale, Sacone, Siri, & Ferrara, 2018b).

Even more ambitious technologies provide vehicles with semi-autonomous or autonomous capabilities, whose penetration in the automotive market could really change the concept of mobility as it is now commonly perceived. As a matter of fact, intelligent vehicles, with self-driving abilities and able to communicate with each other and with the infrastructure, will surely influence the traffic dynamics, possibly reducing travel times, improving safety and reducing the energy consumptions and the related environmental effects. Indeed, autonomous or semi-autonomous vehicles are designed with the aim of limiting the negative aspects of the human driving, which is often characterized by long reaction times and inefficient behaviors. For these reasons, the introduction of automated vehicles, being intrinsically safer and more efficient than traditional vehicles, is expected to considerably reduce the crash risk potential (Fagnant & Kockelman, 2015) and the environmental impacts (Greenblatt & Shaheen, 2015).

Several studies in the literature have been conducted to quantify the effects due to the presence of such vehicles, as for instance in Talebpour and Mahmassani (2016), Piacentini, Goatin, and Ferrara (2018) and Stern et al. (2018) (the interested reader may refer to Taiebat, Brown, Safford, Qu, and Xu (2018) for a complete overview on the works considering the environmental implications of automated vehicles). In many cases, it is shown that autonomous and connected vehicles act by homogenising the traffic flows according to their penetration rate, thus reducing the formation of instabilities that cause the propagation of shockwaves and the consequent increase in travel times. Besides, through field experiments conducted on a circular road, the work in Stern et al. (2018) demonstrates that few autonomous vehicles, which behave as mobile actuators, are able to influence the dynamics of the whole traffic stream by regularising the traffic speed and consequently reducing the fuel consumption by 40%.

Obviously, the real effects of the introduction of a high level of automation in the vehicles of the future is not easy to be estimated, and the debate is still open about the possible opportunities and threads, for the whole traffic flow efficiency (Cassandras, 2017; Diakaki, Papageorgiou, Papamichail, & Nikolos, 2015; Mahmassani, 2016; van Arem, Driel, & Visser, 2006). Also, there are several technological, ethical and legislative implications about the use of automated vehicles which need to be solved before making such technologies really effective on the market (see for instance the challenging issues underlined in Shladover, 2005).

If the future scenario is likely to be a traffic environment in which connected self-driving vehicles will travel in smart road networks, the closest future will be characterized by a mixed traffic in which traditional vehicles and intelligent vehicles will coexist. Both for the mixed scenario and for the completely automated case, it will be crucial to develop modelling and control frameworks, not only to improve the efficiency of individual vehicles, but also to take into account the performance of the traffic flow at a system level, in order to pursue global benefits.

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