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Traffic control for the improvement of sustainability in freeway networks: a bibliometric analysis

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Abstract: Sustainability is becoming a key factor in the design and control of traffic systems. In the field of traffic control for freeway networks, the performance criteria explicitly included in traffic control schemes to address sustainability are mainly referred to the reduction of the environmental impact and the decrease of accidents. These control objectives are generally considered together with the conventional goal of traffic control, i.e. the minimization of the total traveling times for drivers. This paper reports a bibliometric study based on keyword counting regarding the research works on freeway traffic control developed to improve sustainability. The main goal of such analysis is to evaluate how the interest of researchers on sustainability-related freeway traffic control has evolved over the last decades and which traffic control measures have been mostly used to address such issues.

1. INTRODUCTION

In recent years, the concept of sustainable development has been addressed by most of the countries worldwide, proposing several definitions and targets [1]. The concept of sustainability is extremely complex and involves the fulfillment of many objectives, such as the creation of sustainable cities, the promotion of a more equitable economic growth and the environmental safeguard [2]. Among the different fields, also transportation systems should be designed and managed according to a sustainable and environment-friendly perspective, in order to ensure a safer mobility to an increasing number of people without damaging the environment and people's health.

As well known, traffic congestion is one of the main drawbacks associated with the development of mobility systems, both for freight and for passengers. Some of the main consequences are long commuting times for drivers, that are translated, more in general, in losses of productivity for the countries [3]. In addition, 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 [4, 5]. For these reasons, decarbonization can be seen as a fast-moving trend [3], involving the use of alternative fuels like electricity, hydrogen, biofuels and natural gas, in order to reduce the dependence on fossil fuels and to decrease greenhouse gas emissions. Another very relevant problem regarding mobility systems is the unacceptable number of accidents, with the related deaths, injuries and material damages caused by the increasing number of vehicles traveling in road networks [6].

In this scenario, it is necessary to rethink transport systems in a more sustainable way. This can be achieved by designing the new mobility systems (both at the vehicle and at the infrastructure level) according to a sustainable vision, but also by managing and controlling the present systems in order to make the mobility context more environment-friendly. In this sense, the development of control methods for traffic systems is crucial to efficiently exploit the existing road networks. Among the very wide scientific literature on freeway traffic control of the last decades, it is easy to highlight, in the last years, an increasing interest by researchers towards sustainability-related objectives, such as the minimization of emissions, fuel consumptions, accidents, and so on. Two recent surveys on these topics can be found in [7, 8], where both models and control methods for sustainable traffic management are reviewed and categorized, focused respectively on freeway and urban networks. Differently from those survey papers, the scientific works on freeway traffic control aimed at the improvement of sustainability are analyzed by applying bibliometric methodologies mainly based on keyword counting.

This paper is organized as follows. Section 2 introduces the main concepts relevant to sustainable traffic control in freeway systems. The bibliometric analysis of papers dealing with sustainable freeway traffic control is developed in Section 3, while some conclusions are drawn in Section 4.

2. SUSTAINABLE FREEWAY TRAFFIC CONTROL

The traffic in freeway systems can be controlled in many ways, at a macroscopic level (road-based traffic control) or at the vehicle-level. In this work we focus on the most conventional and consolidated way to control traffic, that is through road-based control measures, i.e.:

- *ramp management*, in particular ramp metering, applied to regulate the entrance of vehicles in the free-

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way mainstream via traffic lights present at the on-ramps;
- *mainstream control*, applied to vehicles traveling in the mainstream (with variable speed limits, lane control, keep-lane instructions, and so on);
- *route guidance*, applied to route vehicles along specific paths in freeway networks (this is normally achieved by displaying indications/restrictions at intersections).

These control measures have been studied and implemented in real freeways starting from the nineties, with the main goal of reducing congestion, i.e. to reduce the total time spent by drivers in the road network. In the last years, the interest of researchers have changed to include, among the control objectives, also sustainability-related issues. In particular, the most relevant aspects that have been addressed so far are associated with environmental impact ad safety. Since most of the traffic controllers are model-based, it is worth mentioning the main models adopted by researchers in this context in order to clarify which are the most relevant issues that have been addressed by them. Of course, since we are dealing with freeway traffic control for sustainability, it is useful to mention both the traffic models adopted for the description of the traffic dynamics and the models adopted for the evaluation of the involved sustainability-related issues.

The *traffic dynamic behavior* is represented through traffic models, which can be classified according to different criteria [9]. The most common classification of traffic flow models is related to their level of detail, distinguishing among microscopic, mesoscopic and macroscopic models. The traffic flow models more suitable to be included in model-based control approaches belong to the macroscopic category. They represent the traffic dynamics at an aggregate level, by means of aggregate variables, i.e. density, mean speed and flow, considering the flow of vehicles in analogy with the flow of fluids or gases. Macroscopic traffic flow models can be further classified according to the continuous or discrete nature of the variables representing space and time. In continuous models the dynamics of the system is represented with differential equations, while discrete models rely on difference equations to model the system dynamics (see [10, 11] for further details and references). Macroscopic models of discrete type are the most common choice for freeway traffic control, since their low level of detail and their discretization allow a small computational complexity, particularly suitable for control schemes acting in real time in large freeway traffic networks.

Some important factors related to the sustainable vision of traffic are *traffic emissions* and *fuel consumptions*. These aspects are represented through appropriate models allowing to quantify, respectively, the quantities of pollutants released into the air and the consumption rates on the basis of the traffic state (i.e. traffic volume, traffic composition, vehicle speed, and vehicle acceleration) [12, 13]. Vehicular emissions and fuel consumptions strongly depend on the operating conditions of the vehicle and the driving style of the driver, being affected by the duration and the sequence of acceleration, deceleration and cruise mode phases. Moreover, emissions and consumptions 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, emission and fuel consumption models can be distinguished in microscopic, mesoscopic and macroscopic types. Among macroscopic emission models, one of the most used for freeway traffic control is COPERT [14], which is based on average speed values of vehicles. Other traffic control approaches adopt the macroscopic version of microscopic emission models, such as the VT-micro model and the VERSIT+ model, which have been extended to the macroscopic case and called VT-macro [15] and macroscopic VERSIT+ [16], 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.

Another aspect that is quite relevant to deal with sustainability in freeway traffic control is represented by *dispersion of pollutants* in the environment. Indeed, the polluting emissions released by vehicles are spread into the air and can seriously damage the surrounding environment. Several dispersion models have been developed in the literature to describe the accumulation of pollutants. Most of these models are characterized by a high level of complexity since they have to account for environmental aspects such as the presence of obstacles or the effects of air turbulences. In order to develop freeway traffic control schemes, specific dispersion models have been devised, such as the ones described in [17, 18].

Another very relevant issue for sustainable freeway traffic systems is represented by *road safety*. Aspects related to road safety have been investigated in many research works, since road accidents 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. 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 other factors, such as road geometry, drivers' behaviors and environmental factors. In [19] a risk indicator specifically devised for control purposes is proposed.

3. BIBLIOMETRIC ANALYSIS

In this section, a bibliometric analysis is reported to investigate how researchers' attention towards sustainability in freeway traffic control has evolved in the last twenty years and to assess which traffic control measures have been mostly used to address the main sustainability-related control objectives. Specifically, a words co-occurrence based analysis is proposed through the use of bibliometric maps, realized with the VOSviewer software [20]. VOSviewer is a free tool able to create different types of bibliometric maps related to authors or journals, based on co-citation data and word co-occurrence data. The graphical representations provided by VOSviewer adopt graphs in which

items are grouped in clusters and the distance among them indicates the relatedness level. For this work, co-occurrence maps have been adopted in which specific keywords are connected. The attributes of these maps are indicated by the term *occurrences*, which indicates the number of papers in which a specific keyword appears. In this study the calculation of the occurrences is binary, i.e. the term *occurrences*, related to a specific word, indicates the number of papers in which that keyword appears at least once.

Table 1. Scientific journals and related number of papers analyzed.

Journal	Papers
Transportation Research Part C	72
Transportation Research Record	66
IEEE Trans. on Intelligent Transportation Systems	55
Transportation Research Part B	23
Journal of Transportation Engineering	20
IFAC-PapersOnLine	16
Journal of Advanced Transportation	16
IET Intelligent Transport Systems	14
Transportation Research Part A	14
Journal of Intelligent Transportation Systems	13
Accident Analysis and Prevention	10
Physica A	9
Traffic Engineering and Control	8
Transportation Research Part D	8
Journal of Transportation Engineering Part A	7
Mathematical Problems in Engineering	7
Automatica	6
IEEE Trans. on Vehicular Technology	6
Transportation Science	6
IEEE Trans. on Control Systems Technology	5
Int. Journal of Robust and Nonlinear Control	5
Int. Journal of Transportation Science and Technology	5
Physical Review E	5
IEEE Intelligent Transportation Systems Magazine	4
Transportation Research Part F	4
Transportmetrica A	4
Transportmetrica B	4
Others	221

This study has been conducted by using the Scopus database and by selecting only the journal papers that explicitly refer to freeway traffic control and limiting the research to the field of engineering, mathematics and computer science [1] . This research has been further refined by including some keywords that refer to specific freeway traffic control measures [2] .

The outputs of these queries have been further analyzed, on the basis of *title*, *abstract* and *keywords* of the publications, in order to select only the papers considered relevant to the purposes of this research. As a result, 633 papers published in the period 2000-2019 were selected in the broad field of intelligent transportation systems, automatic control, physics, mathematics and computer science (see Table 1 for an overview of the scientific journals considered for this study). In order to carry out our study, this time span was divided into four consecutive time periods, i.e., 2000-2004, 2005-2009, 2010-2014 and 2015-2019, respectively with 64, 99, 190 and 280 papers.

3.1 Trend of sustainability-related control objectives

Let us now address the first objective of this bibliometric analysis, namely to assess how traffic control objectives have evolved over the last twenty years. To this end, for each of the four time spans, a certain number of keywords which refer to sustainability-related control objectives have been selected. The results of this analysis are shown in Figs. 1-4, depicting the bibliometric maps for each five-years time interval. These maps are represented through networks composed of nodes and links. Each node represents a keyword, the size depending on the number of occurrences of that keyword. The links represent the connections between the keywords. Each link is characterized by a *strength* that, in a co-occurrence based map, represents the number of documents in which two terms appear together. The strength of a link is graphically represented through the thickness of the line representing the connection.

Analyzing Fig. 1, it is observable that during the period 2000-2004 the most frequent keywords are those related to the improvement of traffic efficiency. The keywords *"traffic congestion"* and *"travel time"* have 16 occurrences, while the aspects related to environmental aspects have 9 occurrences, and economic issues have in total 3 occurrences. It is worth noting that not all the keywords are connected to each other and that the existing connections between environmental/economic issues and the aspects related to traffic performances are rather weak.

As shown in Fig. 2, in the period 2005-2009 there is a significant increase of keywords related to environmental issues, with 24 occurrences associated with this field of research. However, it is also possible to observe that the greatest number of keywords is still related to congestion and travel times, with 50 occurrences. Other keywords are associated with fuel consumption, with 6 occurrences, economic aspects, with 4 occurrences and safety, with 4 occurrences.

From 2010 to 2014 (see Fig. 3), in addition to the keywords related to congestion and vehicle emissions, with respectively 61 and 52 occurrences, also safety keywords increased significantly, showing 33 occurrences. The keywords related to economic aspects are instead very seldom with 5 occurrences.

The bibliometric map reported in Fig. 4 for the period 2014-2019 shows that the most frequent keywords are still those related to travel time and congestion, with 171 occurrences. It is also possible to observe that the aspects related to emissions and fuel consumption assume a significant role with 45 and 52 occurrences respectively, while higher frequency is observed for the keywords related

[1] The precise Scopus query is: "FREEWAY TRAFFIC CONTROL" OR "HIGHWAY TRAFFIC CONTROL" OR "MOTORWAY TRAFFIC CONTROL" AND (LIMIT-TO (SUBJAREA, "ENGI") OR LIMIT-TO (SUBJAREA, "COMP") OR LIMIT-TO (SUBJAREA, "MATH") OR LIMIT-TO (SUBJAREA , "ENVI")) AND (LIMIT-TO (PUBSTAGE, "final")) AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (SRCTYPE, "j"))

[2] The precise Scopus query is: "RAMP METERING" OR "VARIABLE SPEED LIMITS" OR "MAINSTREAM CONTROL" AND LIMIT-TO (PUBSTAGE, "final")) AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (SRCTYPE, "j"))

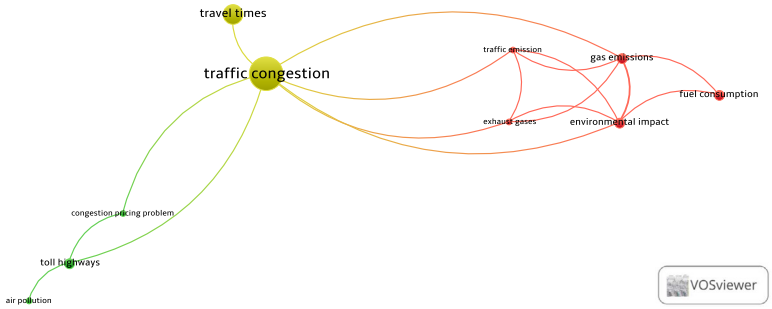

Fig. 1. Co-occurrence network based on control objectives in the period 2000-2004.

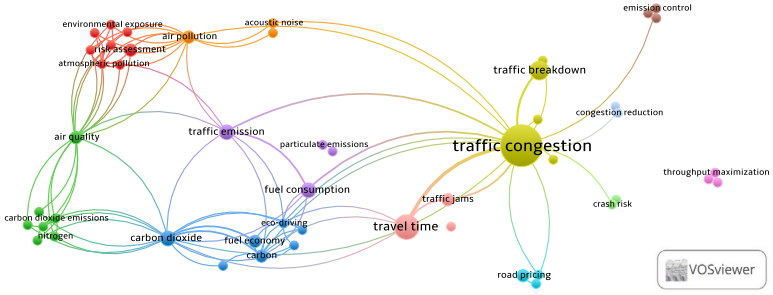

Fig. 2. Co-occurrence network based on control objectives in the period 2005-2009.

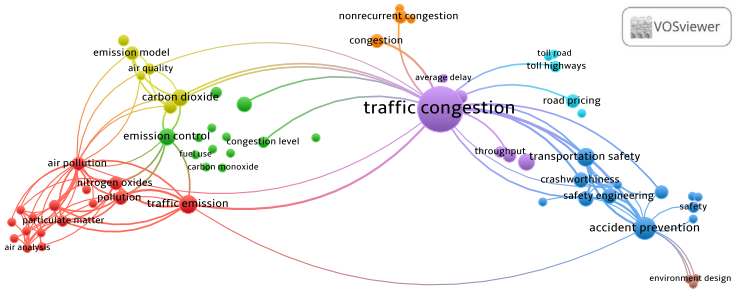

Fig. 3. Co-occurrence network based on control objectives in the period 2010-2014.

to safety aspects, with 60 occurrences. It is also interesting to note that all the addressed topics are much more correlated than in the past, showing an increasing interest by researchers to jointly address different objectives, with a growing attention to issues related to safety, emissions and fuel consumption.

3.2 Traffic control measures for sustainability

The second part of this analysis aims to assess how the keywords of the two main sustainable objectives, safety and environmental sustainability, are correlated with the keywords related to the main traffic control measures, i.e. ramp metering, speed control, route guidance, and so on. Let us start with the map showing the connections between traffic control measures and safety for the whole period 2000-2019, shown in Fig. 5. From this map it can be observed that the keyword *"variable speed limits"* is linked with 18 items in the network, *"speed control"* with 17 terms, *"ramp metering"* with 15 keywords, while *"route guidance"* is connected with only 2 keywords of the network. This suggests that the most commonly used control measures to address safety issues are those based on speed control. Furthermore, other connections between *"variable speed limits"* and *"ramp metering"* can be observed, indicating that these control measures are used in an integrated way in several approaches.

Finally, let us discuss the map shown in Fig. 6 regarding the connections between the keywords related to environmental sustainability and those associated to traffic control measures. In this map, the keyword *"variable speed limits"*

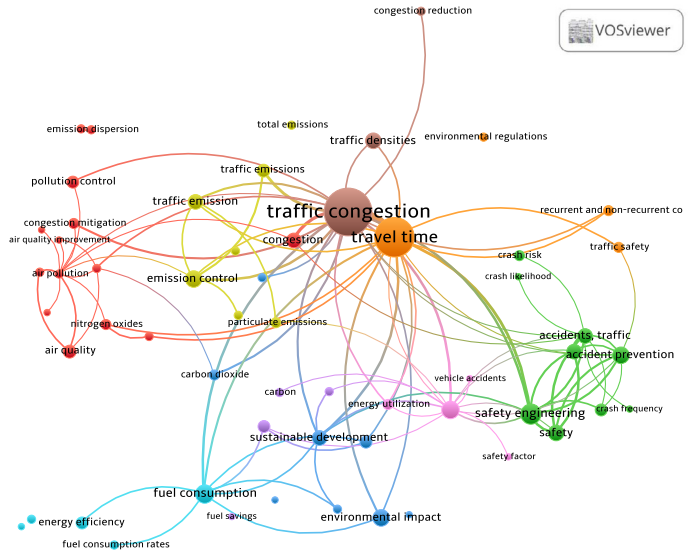

Fig. 4. Co-occurrence network based on control objectives in the period 2015-2019.

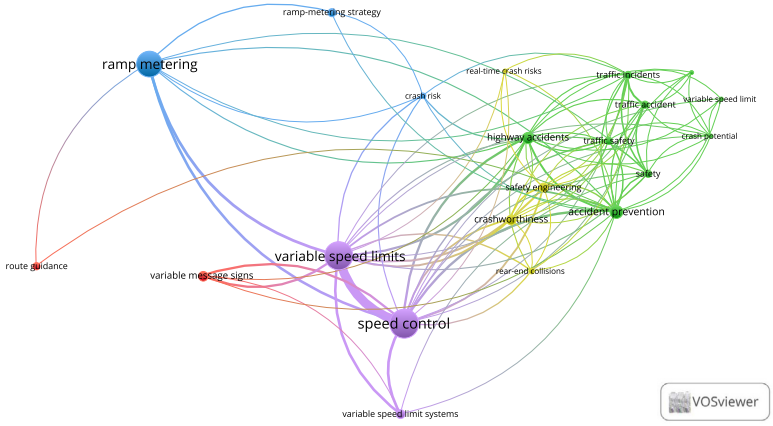

Fig. 5. Co-occurrence network based on safety and control measures in the period 2000-2019.

is connected with other 22 terms, *"speed control"* with 20 items, *"ramp metering"* with 13 keywords, while *"route guidance"* is connected with other 2 keywords.

In this case, it is interesting to note that the keywords referred to speed regulation are mostly connected with those indicating energy and fuel consumption, while the keywords related to ramp metering are mostly connected with the keywords associated with polluting emissions. Also in this map there are connections between *"variable speed limits"* and *"ramp metering"*, indicating that these control measures are jointly applied in some research works.

4. CONCLUSIONS

In this paper, a bibliometric analysis based on keyword counting has been reported about the scientific literature on freeway traffic control for the improvement of sustainability of the last twenty years. This analysis has, first of all, highlighted that there has been a growing interest of researchers towards sustainability-related objectives in the last decades, with specific attention to safety, emissions and fuel consumption issues, that are addressed in a more and more combined and correlated way.

Analyzing instead the relation between sustainability-related control objectives and traffic control measures, it can be observed that the control measures based on speed regulation are mostly connected with concepts of energy and fuel consumption, while ramp metering seems mainly aimed at the reduction of polluting emissions.

The bibliometric analysis developed in this paper shows that the research on sustainability for freeway traffic is growing and is producing results in which different sustainability-related issues are jointly considered. So far, the aspects included in traffic control schemes are mainly related to traffic emissions, fuel consumptions and accidents, but there are many other aspects that involve sustainability and could be addressed, such as noise, human health and quality of life, opening space for new further investigations in the research field.

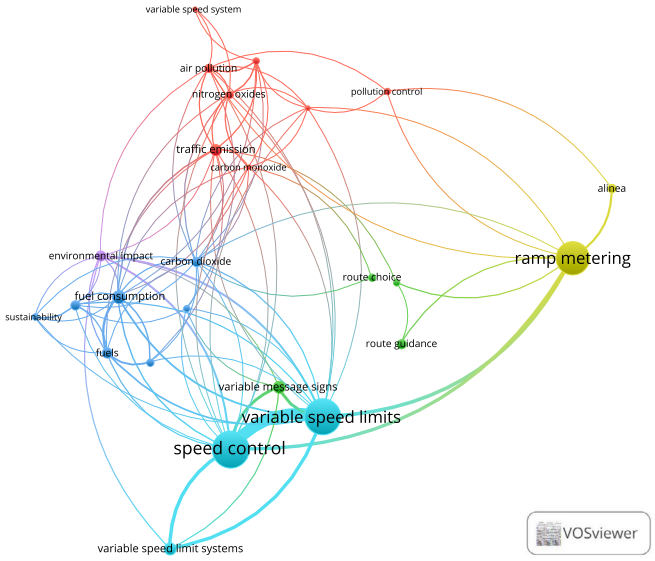

Fig. 6. Co-occurrence network based on environmental sustainability and control measures in the period 2000-2019.

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