used in our analysis, and strong assumptions (but standard) have been made concerning the arrival and the departure processes. It is important to emphasize that all of these have been made to facilitate the mathematical analysis and do not limit the basic ideas presented in this paper. Furthermore, we also assumed honesty and compliance on the part of drivers and charging stations and that the cell, within which balancing is taking place, is of small size. The relaxation of these assumptions and the city-partitioning problem is the subject of ongoing work. In this context, the initial insights and the results can be found in [15].

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A Bibliometric Analysis of the Intelligent Transportation Systems Research Based on Science Mapping

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***Abstract*—In this paper, we highlight the conceptual structure of the intelligent transportation systems (ITS) research field in the period 1992–2011. To do that, an automatic approach for detecting and visualizing hidden themes and their evolution across a consecutive span of years is applied. This automatic approach, which is based on co-word analysis, combines performance analysis and science mapping. To show the conceptual evolution of ITS, three consecutive periods have been defined, i.e., 1992–2001, 2002–2006, and 2007–2011. We have identified that the ITS research has been focused on six main thematic areas, i.e., *VEHICLE-AND-ROAD-TRACKING*, *DRIVER-BEHAVIOR-AND-SAFETY*, *SCENARIOS-SIMULATION*, *TRAFFIC-FLOW-AND-TRAFFIC-MANAGEMENT*, *VEHICLE-CONTROL*, and *VEHICLE-NAVIGATION*.**

***Index Terms*—Co-word analysis, h-index, intelligent transportation systems (ITS), science mapping analysis.**

I. Introduction

According to the IEEE Intelligent Transportation Systems (ITS) Society (http://sites.ieee.org/itss/), ITS can be described as systems that utilize “synergistic technologies and systems engineering concepts to develop and improve transportation systems of all kinds.”

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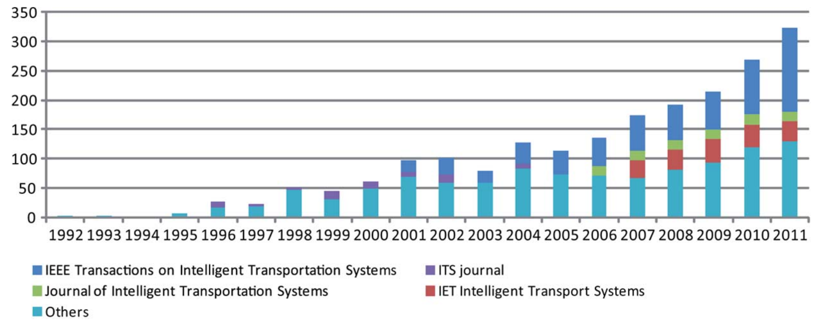


Fig. 1. ISIWoS ITS research documents published from 1992 to 2011.

Science mapping analysis [1], [2] is a powerful bibliometric technique that allows the study of the conceptual structure of a particular research field. It can be described as a spatial representation of how disciplines, fields, specialties, and individual documents or authors are related to one another. It is focused on monitoring a scientific field and delimiting research areas to determine its structure and its evolution.

In the ITS research community, we find few bibliometric studies. Only the journal IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATIONS SYSTEMS has shown interest in developing a bibliometric analysis of its particular output [3]–[6]. Therefore, a complete ITS science mapping study is still needed. In this paper, we present a complete longitudinal science mapping analysis, where the whole ITS research field is analyzed and its conceptual evolution discovered. We use the research documents related with ITS, during the period 1992–2011, published in the most important and influential journals in the field (*Journal of Intelligent Transportation Systems*, *ITS Journal, IET Intelligent Transport Systems*, and IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS). Furthermore, we complete the data set by selecting others documents containing the keyword "*Intelligent Transportation*." The science mapping analysis is performed using the software tool SciMAT [7], [8].

The rest of the paper is organized as follow: Section II shows the approach and software used in the science mapping analysis. Section III presents the results of our analysis. Finally, in Section IV, some conclusions are remarked.

II. SCIENCE MAPPING ANALYSIS: METHODOLOGY AND SOFTWARE TOOL

In bibliometrics, there are two main procedures to explore a research field: performance analysis and science mapping [9]. The former is focused on the citation-based impact of the scientific production, and the latter is focused on the discovering of the conceptual structure of the scientific production. In [7], we define a bibliometric approach that combines both approaches. Co-word analysis is used in a longitudinal framework, which allows us to analyze and track the evolution of a research field throughout consecutive time periods [10].

Our bibliometric methodology establishes four phases to analyze a research field [7].

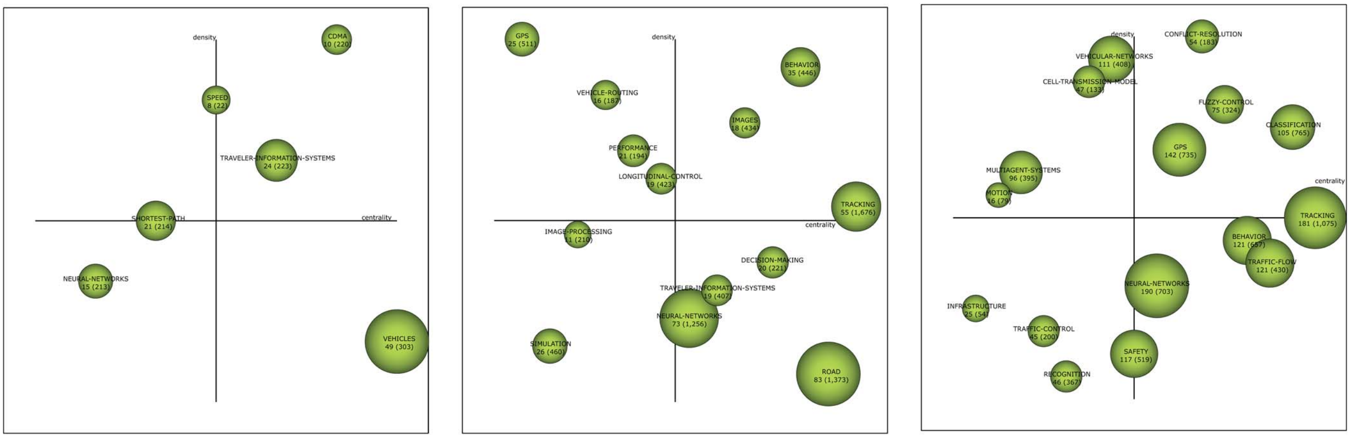
1) *Research themes detection*. To do so, an equivalence index [11] normalized bibliometric co-word network of keywords co-occurrence is built [12]. This is followed by a clustering of keywords to topics/themes using the simple centers algorithm.
2) *Low-dimensional space layout of research themes*. This is achieved by plotting research themes using 2-D strategic diagrams based on their centrality and density rank values [11]. Centrality measures the degree of interaction of a network with other networks, and it can be defined as $c = 10 * \sum e_{kh}$, with k being a keyword belonging to the theme and h a keyword belonging to other themes. Density measures the internal strength of the network, and it can be defined as $d = 100(\sum e_{ij}/w)$, with i and j keywords belonging to the theme and w being the number of keywords in the theme. Thus, the research themes can be classified into four groups [7]: 1) *motor themes*; 2) *basic and transversal themes*; 3) *emerging or declining themes*; and 4) *highly developed and isolated themes*.
3) *Discovery of thematic areas.* The evolution of the research themes is analyzed to detect the main general evolution areas of the research field, their origins, and their interrelationships. To do that, an evolution map is built. The inclusion index is used to detect the conceptual nexus between research themes of different periods.
4) *Performance analysis*. In this phase, the relative contribution of research themes and thematic areas to the whole research field is measured (quantitatively and qualitatively), which is used to establish the most prominent, productive, and highest impact subfields. Some bibliometric indicators used are the number of published documents, number of received citations, and h-index [13].

Finally, the open-source software SciMAT [7], [8] is used.

III. CONCEPTUAL STRUCTURE OF ITS RESEARCH FIELD

We develop our analysis of the ITS field by using the research documents published in the main journals of the field (*Journal of Intelligent Transportation Systems*, *ITS Journal*, *IET Intelligent Transport Systems*, and IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATIONS SYSTEMS). We complete the corpus with those documents containing the keyword "*Intelligent Transportation*." Then, we retrieve the necessary data from the ISI Web of Science (ISIWoS) using the following query: $TS =$ ("$INTELLIGENT\ TRANSPORT^{*}$") $OR\ SO =$ ("$Journal\ of\ Intelligent\ Transportation\ Systems$" OR "$ITS\ Journal$" OR "$IET\ Intelligent\ Transport\ Systems$" OR "$IEEE\ TRANSACTIONS\ ON\ INTELLIGENT\ TRANSPORTATION\ SYSTEMS$"). The query is divided into two parts: 1) documents related with the term "*Intelligent transport*" and its variations and 2) documents published in the main journals in the field. We retrieve a total of 2045 documents (articles, letters, notes, and reviews) from 1992 to 2011 (see Fig. 1). In this paper, the citations to the documents are also used; for this reason, citation counts up to September 11, 2012 were considered.

Once the data were downloaded, we import it into SciMAT [8]. A deduplicating process was applied over the keywords (as unit of analysis, we jointly use the author's keywords and the Keywords



(a) (b) (c)

Fig. 2. Strategic diagrams. (a) Period 1992–2001. (b) Period 2002–2006. (c) Period 2007–2011.

TABLE I
PERFORMANCE MEASURES FOR THE THEMES (1992–2001)

Theme name	Number of documents	Number of citations	h-index
VEHICLES	49	303	9
TRAVELER-INFORMATION-SYSTEMS	24	223	7
SHORTEST-PATH	21	214	6
NEURAL-NETWORKS	15	213	5
CDMA	10	220	7
SPEED	8	22	2

TABLE II
PERFORMANCE MEASURES FOR THE THEMES (2002–2006)

Theme name	Number of documents	Number of citations	h-index
ROAD	83	1,373	21
NEURAL-NETWORKS	73	1,256	20
TRACKING	55	1,676	25
BEHAVIOR	35	446	11
SIMULATION	26	460	11
GPS	25	511	15
PERFORMANCE	21	194	7
DECISION-MAKING	20	221	6
LONGITUDINAL-CONTROL	19	423	12
TRAVELER-INFORMATION-SYSTEMS	19	407	10
IMAGES	18	434	12
VEHICLE-ROUTING	16	187	7
IMAGE-PROCESSING	11	210	6

Plus) in order to group those words representing the same concept. Furthermore, since some documents did not contain any keywords, a manual addition of descriptive keywords matching title words with the keywords present in the knowledge base was done for completeness purposes. Finally, some keywords that are meaningless in this context, such as stop words, or words with a very broad and general meaning, such as *Intelligent Transportation Systems*, were removed.

To develop our study, the whole time period (1992–2011) is divided into three consecutive periods of time, i.e., 1992–2001, 2002–2006, and 2007–2011, with 793, 1565, and 3249 keywords, respectively.

In what follows, we identify the ITS research themes for each period and analyze the thematic evolution of the ITS field.

A. Identifying the ITS Research Themes

In order to analyze the most highlighted themes of the ITS field for each period, several strategic diagrams are shown. In addition, the sphere size is proportional to the number of published documents associated with each research theme. Furthermore, the number of citations achieved by each theme is shown in parenthesis.

During the period 1992–2001 (see Fig. 2(a) and Table I), the ITS research field was focused in three main themes [see Fig. 2(a)]: 1) *VEHICLES*, which is dedicated to vehicle surveillance, traffic, and incidents detection; 2) *TRAVELER-INFORMATION-SYSTEMS*, which is focused on assisting and guiding the traveler in the choice of route and also related with the management of traffic; 3) *SHORTEST-PATH*, which is centered on finding the best path, both in time and distance, in a traffic network.

From 2002 to 2006, we obtain the strategic diagrams shown in Fig. 2(b) and bibliometric indicators shown in Table II.

- The number of themes is increased.
- The majority of the basic and transversal themes are focused on vehicles, safety, and traffic management.
- The theme *TRACKING* emerges as an important motor theme, and it achieves the highest impact index.

TABLE III
PERFORMANCE MEASURES FOR THE THEMES (2007–2011)

Theme name	Number of documents	Number of citations	h-index
NEURAL-NETWORKS	190	703	11
TRACKING	181	1,075	17
GPS	142	735	12
BEHAVIOR	121	657	14
TRAFFIC-FLOW	121	430	11
SAFETY	117	519	12
VEHICULAR-NETWORKS	111	408	12
CLASSIFICATION	105	765	15
MULTIAGENT-SYSTEMS	96	395	11
FUZZY-CONTROL	75	324	10
CONFLICT-RESOLUTION	54	183	7
CELL-TRANSMISSION-MODEL	47	133	7
RECOGNITION	46	367	11
TRAFFIC-CONTROL	45	200	8
INFRASTRUCTURE	25	54	4
MOTION	16	79	5

- The theme *BEHAVIOR* appears as a motor theme with high density and centrality values. It is focused on the behavior of the drivers and how they choose their travel routes.
- The research themes *TRAVELER-INFORMATION-SYSTEMS* and *NEURAL-NETWORKS* related with traffic management, which previously were considered trend and emergent themes, respectively, have been consolidated as a basic theme.
- *DECISION-MAKING*, which is focused on safety and risk management, appears as a new basic and transversal theme.
- The highly developed and isolated themes are mainly focused on themes related with vehicle navigation, such as *GPS* and *VEHICLE-ROUTING*.

From 2007 to 2011, we obtain the strategic diagrams shown in Fig. 2(c) and bibliometric indicators shown in Table III.

- There are a higher number of motor themes than in the previous period. Indeed, there is an adequate number of emerging themes, which indicates that the ITS research field is still developing and growing.
- The ITS research field increments its interest in themes related with vehicle tracking, such as *TRACKING*, *CLASSIFICATION*, and *RECOGNITION*.
- The themes *NEURAL-NETWORKS* and *TRACKING* consolidate as basic and transversal themes.
- *BEHAVIOR* develops into an important basic and transversal theme.
- The theme *GPS* gains strong interest and becomes one of the major motor themes.
- *FUZZY-CONTROL*, which is related with vehicle control, emerges as a motor theme.
- The themes *TRAFFIC-CONTROL* and *RECOGNITION* appear as emerging themes, and they obtain a great interest.
- The highest density value is achieved by the motor theme *CONFLICT-RESOLUTION* related with air traffic control.

B. Thematic Evolution of the ITS Field

An analysis of the themes detected in each one of the three time periods evaluated, their keyword compositions, and their evolution across the consecutive defined periods of time leads to the detection of the following six main thematic areas (see Fig. 3): 1) VEHICLE-AND-ROAD-TRACKING; 2) DRIVER-BEHAVIOR-AND-SAFETY; 3) SCENARIOS-SIMULATION; 4) TRAFFIC-FLOW-AND-TRAFFIC-MANAGEMENT; 5) VEHICLE-CONTROL; 6) VEHICLE-NAVIGATION.

The solid lines mean a *thematic nexus*: both themes have the same name, or the name of one of them is part of the other theme. A dotted line means that the linked themes share keywords different to the name of the themes. The thickness of the edge is proportional to the inclusion index, and the sphere size is proportional to the number of published documents in each theme. The different color shadows group the themes that belong to the same thematic area.

Analyzing Fig. 3 and Table IV, several conclusions regarding different structural and performance aspects are noted.

1) With regard to the thematic composition, the following should be pointed out:
   - The thematic areas *VEHICLE-AND-ROAD-TRACKING* and *TRAFFIC-FLOW-AND-TRAFFIC-MANAGEMENT* are mainly composed by motor and basic themes. The former includes just one basic theme in its origin, and it becomes the thematic area with the most number of themes. The latter counts one motor theme and one emergence theme in its origin, and both evolve as basic and/or motor themes.
   - The thematic area *VEHICLE-NAVIGATION* starts as an isolated theme, and it develops into one of the most important motor themes in the last period.
   - *DRIVER-BEHAVIOR-AND-SAFETY* arises comprised by motor and basic themes and one isolated theme. This thematic area positively evolves, and their themes become important basic themes.
   - *SCENARIOS-SIMULATION* is mainly composed by highly developed but isolated themes.
   - *VEHICLE-CONTROL* starts from two isolated themes, and it converges into an important motor theme.
   - The theme *DECISION-MAKING* is shared by two thematic areas: *DRIVER-BEHAVIOR-AND-SAFETY* and *SCENARIOS-SIMULATION*. Similarly, the theme *GPS* belongs to two thematic areas: *GPS* and *VEHICLE-CONTROL*.
2) With regard to the structural evolution, the following should be pointed out:
   - The ITS field presents great cohesion, due to the fact that the majority of detected themes are grouped under a

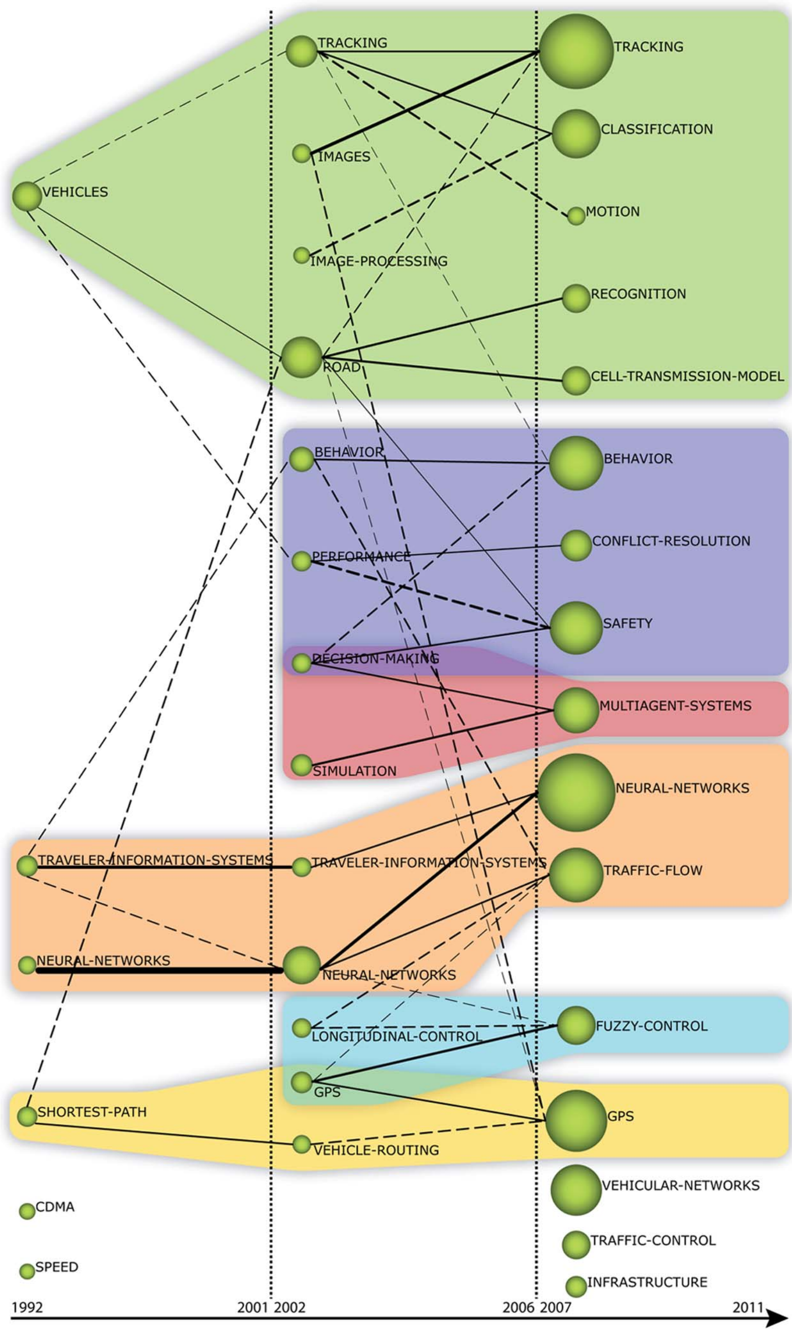


Fig. 3. Thematic evolution of the ITS research field (1992–2011).

TABLE IV
PERFORMANCE MEASURES FOR THE DETECTED THEMATIC AREAS

Thematic area	Number of documents	Number of citations	h-index
VEHICLE-AND-ROAD-TRACKING	473	4604	34
TRAFFIC-FLOW-AND-TRAFFIC-MANAGEMENT	409	3104	27
DRIVER-BEHAVIOR-AND-SAFETY	320	1891	21
VEHICLE-NAVIGATION	202	1617	22
SCENARIOS-SIMULATION	141	1076	17
VEHICLE-CONTROL	115	1081	20

thematic area and originate from a theme identified in a previous period. Furthermore, most of the evolutions are part of a *thematic nexus*.

- Three thematic areas start in the first period: *VEHICLE-AND-ROAD-TRACKING*, *TRAFFIC-FLOW-AND-TRAFFIC-MANAGEMENT*, and *VEHICLE-NAVIGATION*.

The second period also includes the start of the following three themes: *DRIVER-BEHAVIOR-AND-SAFETY*, *SCENARIOS-SIMULATION*, and *VEHICLE-CONTROL*.

- We find some very recent themes (for example, *VEHICULAR-NETWORKS* and *TRAFFIC-CONTROL*) that could not be identified with any thematic area. They could be considered as the beginning of a new thematic area.
- There are no gaps in the evolution of the majority of thematic areas.
- The thematic areas *VEHICLE-AND-ROAD-TRACKING* and *TRAFFIC-FLOW-AND-TRAFFIC-MANAGEMENT* present a growing pattern. On the other hand, *SCENARIOS-SIMULATION*, *VEHICLE-NAVIGATION*, and *VEHICLE-CONTROL* shrink in the last period.
- We should point out that, although a shrinking pattern is identified for *VEHICLE-NAVIGATION* and *VEHICLE-CONTROL*, they evolve as important thematic areas in the last period, merging together into one motor theme. In fact, *VEHICLE-CONTROL* appears as a bifurcation of *GPS*.

3) With regard to the performance and impact indicators, the following should be pointed out:
   - The thematic area *VEHICLE-AND-ROAD-TRACKING* is the most important in the number of documents and citations and with the highest h-index. In addition, *TRAFFIC-FLOW-AND-TRAFFIC-MANAGEMENT* reaches good bibliometric indicators, as it is shown in Table IV.
   - All thematic areas show a growing pattern in the number of documents. The case of *VEHICLE-NAVIGATION* and *VEHICLE-CONTROL* is particularly significant, which, despite reducing the number of themes across the periods, increase in number of documents.
   - Only *TRAFFIC-FLOW-AND-TRAFFIC-MANAGEMENT* presents a descending pattern in both number of citations received and h-index. This suggests that, although the research community is still interested in this thematic (it gets an adequate number of documents in the last period), the publication impact seems to be decreasing.

Once the thematic areas have been analyzed according to their structural, thematic, and performance aspects, we provide a more detailed analysis of the conceptual evolution of each thematic area through the different time spans. In what follows, we describe how each thematic area evolves.

The thematic area *VEHICLE-AND-ROAD-TRACKING* started in the period 1992–2001. In those years, the thematic area was not well developed being a transversal topic. In the next period (2002–2006), the thematic area broadened, covering topics related with the extraction of the visual information present in the streets and roads [14], detection and recognition of different objects [15], [16], road detection [17], vehicle tracking [18], etc. Finally, in the last period, the thematic area focused on object detection in complex situations, such as lane curvature [19] or night vision [20], as well as in advance problems, such as prediction of driver intentions [21] and object detection in real time [22].

DRIVER-BEHAVIOR-AND-SAFETY was mainly related with the improvement in the safety of the driver in the vehicle. To do that, techniques such as the driver's stress level detection [23], speed adaptation systems [24], and driver's behavior control [25] were developed. This thematic area also covers topics such as the behavior of drivers in traffic congestion [26].

SCENARIOS-SIMULATION started in the period 2002–2006, with a focus on the simulation of different aspects such as motorway network and traffic flow model [27]. Finally, in the period 2007–2001, the thematic area focused on the same topics, but using intelligent agents systems to develop simulations [28].

In the early years of the thematic area *TRAFFIC-FLOW-AND-TRAFFIC-MANAGEMENT*, we locate the first papers describing traveler information systems [29] and their use to reduce travel time and traffic congestion [30]. In the next period (2002–2006), the thematic area goes further in the development of advance traveler information systems [31]. Finally, in the last period, it evolves to focus on the prediction of traffic flow [32] in real-time environments [33].

In the period 2002–2006, the thematic area *VEHICLE-CONTROL* focused on several issues related to autonomous vehicle control [34], [35]. In the last period, i.e., 2007–2011, several advance developments on specific topics of autonomous vehicle control were carried out: lane change [36], unintended lane departure [37], etc.

In the period 1992–2001, the thematic area *VEHICLE-NAVIGATION* focused on solving the shortest route problem, both in distance [38] and time [39]. In the next period, the thematic area developed, and it was divided into two main topics: GPS [40] and vehicle routing in real time [41]. Finally, in the period 2007–2011, the thematic area focused on the topic GPS, as well as in improving its accuracy, availability, and continuity of service [42].

IV. Concluding Remarks

In this paper, we have analyzed the conceptual structure of the ITS research area by means of science mapping analysis and co-word networks. Three consecutive time periods have been studied, i.e., 1992–2001, 2002–2006, and 2007–2011. We have considered the research documents developed in the following ITS journals: *Journal of Intelligent Transportation Systems*, *ITS Journal*, *IET Intelligent Transport Systems*, and IEEE Transactions on Intelligent Transportations Systems. Moreover, we completed the data set by selecting others documents containing the keyword *Intelligent Transportation Systems*.

The presented analysis has provided a complete view of the conceptual structure of the ITS research field, giving us the ability to uncover the different topics researched by the ITS community from 1992 to 2011.

We have detected six different main thematic areas: 1) *VEHICLE-AND-ROAD-TRACKING*, which evolves from topics related with vehicle surveillance, traffic, and incidents detection to the tracking and detection of vehicles, pedestrian, etc.; 2) *DRIVER-BEHAVIOR-AND-SAFETY* related with accident avoidance, conflict resolution, and the behavior and safety of the driver; 3) *SCENARIOS-SIMULATION* associated with the simulations and test of traffic scenarios; 4) *TRAFFIC-FLOW-AND-TRAFFIC-MANAGEMENT* related with different aspects of the traffic management using intelligent techniques such as neural networks; 5) *VEHICLE-CONTROL* focused on the research of autonomous vehicles; and 6) *VEHICLE-NAVIGATION* related with different aspects of traffic networks and route guidance.

Taking into account the detected themes and thematic areas, the following findings can be highlighted:

- The thematic area *VEHICLE-AND-ROAD-TRACKING* is the most important in all the three criteria used in the analysis. It is a growing research area and presents a good rate of published documents. Furthermore, the research developed under this thematic

TABLE V
JOURNALS PER THEMATIC AREA (DOCUMENTS/CITATIONS)

Journal	VEHICLE AND ROAD TRACKING	DRIVER BEHAVIOR AND SAFETY	SCENARIOS SIMULATION	TRAFFIC FLOW AND TRAFFIC MANAGEMENT	VEHICLE CONTROL	VEHICLE NAVIGATION
IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS	220 / 3111	115 / 983	54 / 526	124 / 1157	3 / 761	76 / 861
IET INTELLIGENT TRANSPORT SYSTEMS	41 / 72	60 / 112	13 / 16	30 / 46	6 / 3	20 / 40
ITS JOURNAL	12 / 53	3 / 58	2 / 23	21 / 106	1 / 0	4 / 3
JOURNAL OF INTELLIGENT TRANSPORTATION SYSTEMS	16 / 58	13 / 62	8 / 21	39 / 170	5 / 68	27 / 119
Others	184 / 1310	132 / 721	64 / 490	195 / 1625	50 / 249	75 / 594

area captures the attention of the ITS field, as it is illustrated by the citations that it attracts.

- The thematic area *VEHICLE-NAVIGATION* and *VEHICLE-CONTROL* started as isolated themes with poor productive and impact rates, but in the last period, they got more attention from the community and became two of its most important research topics.
- The thematic area *TRAFFIC-FLOW-AND-TRAFFIC-MANAGEMENT* seems a mature research topic, and probably, in the near future, it might evolve following different directions.
- The thematic area *DRIVER-BEHAVIOR-AND-SAFETY* presents a constant growth.

Interestingly, the thematic areas are covered by the ITS journals in different ways, as it is shown in Table V. We can observe that the journal IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATIONS SYSTEMS is the most important journal of the research developed in ITS because it covers all the top ranked and most cited thematic areas. In particular, it is the core journal in both thematic areas *VEHICLE-AND-ROAD-TRACKING* and *VEHICLE-CONTROL*. The journal *IET Intelligent Transport Systems* is centered on *DRIVER-BEHAVIOR-AND-SAFETY* and *VEHICLE-AND-ROAD-TRACKING*. The *ITS Journal* and *Journal of Intelligent Transportation Systems* are mainly focused on *TRAFFIC-FLOW-AND-TRAFFIC-MANAGEMENT*.

Finally, we should note that the ITS research field is developing at a fast pace. Some of the recent scientific documents are published in conferences or special issues. Although a bibliometric analysis of those documents could be interesting, the amount of documents is not enough to develop a science mapping analysis based solely on them.

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