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

M. J. Cobo, F. Chiclana, A. Collop, J. de Oña, and E. Herrera-Viedma

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/itsss/), 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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Section III presents the results of our analysis. Finally, in Section IV, the approach and software used in 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 TRANSPORTATION 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.

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

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

- 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
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.

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

### TABLE IV

<table>
<thead>
<tr>
<th>Thematic area</th>
<th>Number of documents</th>
<th>Number of citations</th>
<th>h-index</th>
</tr>
</thead>
<tbody>
<tr>
<td>VEHICLE-AND-ROAD-TRACKING</td>
<td>473</td>
<td>4604</td>
<td>34</td>
</tr>
<tr>
<td>TRAFFIC-FLOW-AND-Traffic-Management</td>
<td>409</td>
<td>3104</td>
<td>27</td>
</tr>
<tr>
<td>DRIVER-BEHAVIOR-AND-SAFETY</td>
<td>320</td>
<td>1891</td>
<td>21</td>
</tr>
<tr>
<td>VEHICLE-NAVIGATION</td>
<td>202</td>
<td>1617</td>
<td>22</td>
</tr>
<tr>
<td>SCENARIOS-SIMULATION</td>
<td>141</td>
<td>1076</td>
<td>17</td>
</tr>
<tr>
<td>VEHICLE-CONTROL</td>
<td>115</td>
<td>1081</td>
<td>20</td>
</tr>
</tbody>
</table>
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 2007–2011, 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].
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 TRANSPORTATION 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 IEEE 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.

References


