Abstract—Problems in the transportation segment are accidents, increasing bad traffic flow and pollution. The intelligent transportation system using external infrastructure (ITS) can tackle these problems. To the best of our knowledge, there exists no current systematic review of the existing solutions. To fill this knowledge gap, this paper provides an overview about existing ITS which use external infrastructure. Furthermore, this paper discovers the currently not adequately answered research questions. For this reason, we performed a literature review to documents, which describes existing ITS solutions since 2009 until today. We categorized the results according to technology level and analyzed their properties. Thereby, we made the ITS solutions comparable and highlighted the past development as well as the current trends. According to the mentioned method, we analyzed more than 346 papers, which includes 40 test bed projects. In summary, the current ITS can deliver accurate information about individuals in traffic situations in real-time. However, further research in ITS should focus on more reliable perception of the traffic using modern sensors, plug and play mechanism as well as secure real-time distribution in decentralized manner for a high amount of data. By addressing these topics, the development of intelligent transportation systems is in a correction direction for the comprehensive roll-out.

Index Terms—Intelligent Transportation Systems, Intelligent Infrastructure, Distributed Systems, Autonomous Driving, C-ITS, Test Field, Test Bed

I. INTRODUCTION

More than 2 million traffic accidents happened in the United States from 2005 to 2007. With 94 %, the most critical reason for the crashes is the human error [1], [2]. In addition, in the transportation segment exists capacity problems and pollution problems [3]. Only in the United States, people spend in total 6.9 billion hours in traffic jams [2]. Furthermore, 50 % of the world population live in cities, where the mentioned issues are significantly noticeable. Unfortunately, this situation will become more critical: The share of the population in cities will increase to two thirds until 2050. Therefore, we have to consider especially cities for optimal mobility [4].

Intelligent transportation systems using external infrastructure (ITS) are a possible solution to tackle these problems [2], [3], [5]–[7]. Only in the United States, these systems can prevent approximately 400,000 to 600,000 accidents per year with parallel reduced travel time by around 42 %. In addition, modern ITS can reduce the fuel consumption for passenger vehicles up to 44 % and for trucks up to 18 % [2]. This fact results in the reduction of around 15 % of the greenhouse gases [8]. Therefore, the ITS can implement on the one handside a real-time synchronization of individual traffic with the public transport system with the support of "Park and Ride"-Parking, and on the other handside can exchange data with vehicles which are equipped with intelligent driver assistance systems. This V2X technology would enable a further foresight which results in an accurate warning against hazards and obstacles.

Of course, manufacturers of ITS and the automotive industry have also business opportunities: In 2014, the worldwide annual turnover was around 30 billion Euros for connected driving applications, it increased to 170 - 180 billion Euros in the year 2020. The application "Collaborative Cruise Control" which enables continuous exchange between vehicles and infrastructure is an important example. This function is already used by Tesla for its feature AutoPilot excessively in 4 billion miles on the road. Personalized on-board entertainment, fleet management and platooning [9] are further influential value-added services of ITS. Thus, these systems can make a valuable contribution in the transportation segment.

To the best of our knowledge, there exists no other current peer-reviewed systematic literature survey which provides technical details about existing intelligent transportation systems using external sensors and other infrastructures. The papers [10]–[13] and [14] list ITS in general. However, they do not give technical details nor the exact selection criterion of their listed systems. Hence, we aim to fill this gap by a systematic literature review from the last decade. Furthermore, we make for better understanding a historical summary of such systems. While this review does not cover a deep entry into the specific topics in the field of ITS (e.g. communication, architecture, object detection or tracking), it provides an overview about existing solutions, trends and current open research questions in the field.

In this paper, we select documents about implemented ITS from 2009 until today. Additionally, we accept for the historical insertion documents the first known ITS. Then, we categorize the test fields according to their general functionality. To make the systems comparable, we extract the important characteristic as well as the novelty of each ITS. Lastly, we highlight and visualize the results and show the trends of the development in the area of ITS.

The paper is organized as follows: First, section II explains the methods for collecting and reviewing the papers about in-
telligent transportation systems which use external infrastructure. The section III shows the results of the literature survey. Furthermore, this section contains a detailed analysis of each listed ITS. Section IV discuss the results, the requirements and the trends of modern ITS. Last, a conclusion and outlook for further research are given in Section V.

II. METHODOLOGY

In this paper, we perform a literature review about implemented intelligent transportation systems which use external infrastructure. The purpose of this review is to give an overview about the growing landscape of ITS. For that reason, we categorize the collected systems according to their features, analyze their properties as well as mention their scientific contributions in the field. Furthermore, we discover the open questions and research gaps in the field of ITS. To answer the questions above, first we look unsystematic into the literature and then, to achieve the highest possible coverage of existing literature, we performed a systematic review according to the method by Kitchenham [15]:

1) Identification of research: We collect documents with the known databases and search engines IEEE Xplore, Google Scholar and Google with the keywords "Testfeld ITS", "Test Field ITS", "Testbed ITS as well as "C-ITS". We also consider the sources of the collected publications. With this strategy, we get a pyramid scheme in our research. Unfortunately, a lot of intelligent transportation system projects do not publish their results in peer reviewed papers. Therefore, we accept in our literature survey papers as well as gray literature (e.g. official websites about the projects). We delete duplicates after collecting all documents.

2) Study selection: We follow several rules for the assessment respectively the filtering of collected sources. We select only ITS from 2009 to today. For the historical insertion, we choose exceptionally important first known test field projects. As an additional criterion, the ITS in this paper has to use external sensors or other infrastructure. The systems have to be implemented in real world, only a conceptual idea is not sufficient.

3) Study quality assessment: After the assessment of all documents, we categorize the ITS solutions according to their stage of development. The authors of [8] proposed the categories "Semi-intelligent infrastructure", "Intelligent or semismart infrastructure" and "Smart infrastructure " in 2017. Here, the categories of the ITS are in terms of real-time behavior, accuracy and independence working without human intervention. However, we suggest in our work the three categories "Early Days", "Situation-related Analysis" and "Creation Digital Twins". These categories should describe the stage of development according to general features and functionality of the system. The meaning of the categories are described in detail in Table I.

4) Data extraction: The ITS projects focus on different aspects. For instance, some test fields focus on the communication between vehicles and infrastructure, other test fields focus on the data fusion or object detection. To make the test fields comparable, we analyze the used sensors, the length of the test stretch, the overall architecture as well as the scientific novelty of each ITS. Hereby, we extract the purpose and the technical details of every project in the last decade.

5) Data synthesis: In the last step of our method, we highlight and visualize the qualitative and quantitative results of the collected ITS. We summarize the hard facts in a table and show the trend of the past development in suitable diagrams. Therefore, this synthesis gives a sufficient impression about the current development in the segment of ITS as well as anchor points for open research questions.

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early Days</td>
<td>This category gives a historical summarize about the concepts, challenges and successes of the first known ITS.</td>
</tr>
<tr>
<td>Situation-related Analysis</td>
<td>The ITS in this category can analyze and interpret individual traffic situations. Therefore, they can improve the safety and the flow of the traffic.</td>
</tr>
<tr>
<td>Creation Digital Twins</td>
<td>These systems are able to create complex digital twins of all traffic participants. They are characterized by high accuracy and real-time capacity. Such systems can have a high impact on autonomous and connected driving.</td>
</tr>
</tbody>
</table>

III. RESULTS

According to our proposed method, we have analyzed 346 papers about intelligent transportation systems with the use of external infrastructure, which were findable in the search engines of IEEE Xplore, Google Scholar as well as Google with the mentioned keywords. Since the search results from Google and Google Scholar were more than one million entries, only the first three result pages were taken into account. The precise number of documents for each keyword for every search engine is listed in Table I.

In the next step, we propose the details about the found ITS which fulfills our mentioned requirements. The feature categories "Early Days", "Situation-related Analysis" and "Creation Digital Twins" are described in the respective sections. The Table I gives a complete overview about the results.

A. Early Days

The origins of using external infrastructure in intelligent transportation systems can be found in the 80s and 90s. Here, the projects Prometheus and Path were decisive in the beginning development of ITS. In 1988, the PROMETHEUS
In real time. Based on this, the system offered dynamic route
system could measure the traffic load and generated forecasts
the data to a computer for further analysis. In summary, the
the use of counting loops in the freeway. The sensors sent
or other emergencies. In 2006, the concept was realized with
ITS, which should improve the traffic flow in case of accidents
project in Los Angeles created a concept and simulation for an
assignment for the Management of Information to Travelers)
widely available in modern road networks. For instance, in
input were achieved by induction loops in the asphalt. The
light logic [20] or with electronic gantries. The necessary data
control. As soon as cars arrived at the traffic light, they got a
jam, accidents, ice) were created. It should be emphasized that
the cars should provide information about the conditions in the
environment. The first ideas about hazard warning (e.g. traffic
violations. In addition, the ITS should optimize the fuel
construction sites, slippery roads, wrong-way drivers and red
a warning system against road hazards. The use cases were
and 5 backend offices were set up. The aim was to develop
in the project Compass4D. A total of 147 Road Side Units
European cities Bordeaux (France), Copenhagen (Denmark),
Helmond (Netherlands), Newcastle (England), Thessaloniki
(Greece), Verona (Italy) and Vigo (Spain) were installed ITS
in case of a disaster [26]–[28].

In contrast, for optimization of the traffic flow in the year
1986, the project PATH tried to influence the control of
vehicles on highways. For this purpose, the highways were
equipped with sensors and control units. For instance, in the
year 1992, the first platooning experiments of vehicles with
support of Doppler radar systems were successfully performed.
However, it was already recognized at that time that an
implementation until at least the turn of the millennium would
not be possible. The reasons are technical deficiencies and the
political acceptance by the population [18], [19].

After the first concepts and prototypes, the next ITS
generation were able to control and optimize the general traffic
flow. The systems did not influence the traffic participants
directly. They controlled it, for instance, with intelligent traffic
light logic [20] or with electronic gantries. The necessary data
input were achieved by induction loops in the asphalt. The first
ITS of this type came in the late 1990s. They are already
widely available in modern road networks. For instance, in the
year 1998, researcher in the DynaMIT (Dynamic Network
Assignment for the Management of Information to Travelers)
project in Los Angeles created a concept and simulation for an
ITS, which should improve the traffic flow in case of accidents
or other emergencies. In 2006, the concept was realized with
the use of counting loops in the freeway. The sensors sent
the data to a computer for further analysis. In summary, the
system could measure the traffic load and generated forecasts
in real time. Based on this, the system offered dynamic route
guidance, which has improved the traffic flow [21], [22].

In 2006, the SAFESPOT project researched on the interaction
between ITS and vehicles with the goal of increasing the
road safety (e.g. warning about "black spots") and optimizing
the traffic flow. The ITS was deployed in the following
places: 1.) Sweden: Stockholm and Goteborg. 2.) Germany:
Dortmund. 3.) Italy: Torino and Brescia-Padova-Freeway. 4.)
France and Spain: West Europe Test Site. 5.) Netherlands:
Corridor Rotterdam-Brabant-Antwerp. Therefore, the locations
covered the scenarios city center, country road as well as
freeway. In this huge European project the infrastructures were
equipped with Road Side Units (RSU), dynamic cooperative
networks were created. These systems allowed communication
between vehicles and infrastructure. With the shared
information, the driver of vehicles has got enhance perception of
the surrounded vehicles. The ITS has created "local dynamic
map" and a "safety margin assistant", which detected critical
situations in advance [23], [24].

B. Situation-related Analysis

The focus of ITS solutions in this section are in the detailed
analysis of specific traffic situations. Furthermore, they allow
an interaction with the individual participants. This gives a
clear added value in comparison to the ITS which give a rough
statement about the general traffic flow. In the year 2013, the
European cities Bordeaux (France), Copenhagen (Denmark),
Helmond (Netherlands), Newcastle (England), Thessaloniki
(Greece), Verona (Italy) and Vigo (Spain) were installed ITS
in the project Compass4D. A total of 147 Road Side Units
and 5 backend offices were set up. The aim was to develop
a warning system against road hazards. The use cases were
construction sites, slippery roads, wrong-way drivers and red
light violations. In addition, the ITS should optimize the fuel
consumption in intersection areas to achieve energy efficient.
The ITS has introduced a situation-adapted traffic light system
control. As soon as cars arrived at the traffic light, they got a
speed recommendation [25].

In the year 2012, the project INSIGHT (Intelligent Synthesis
and Realtime Response using Massive Streaming of Heteroge-
eous Data) set up a real world ITS in Dublin, Ireland. Here,
numerous of cameras in certain sections as well as GPS of
the local transport gave information about the current traffic
situation in real-time. They were bundled with messages from
Twitter, radio and possible callers. The purpose of this big
data application was the automated management of resources
to enable efficient actions in intelligent and networked cities
in case of a disaster [26]–[28].

In 2015, the follow-up project VaVel (Variety, Veracity,
VaLue: Handling the Multiplicity of Urban Sensors) extended
the INSIGHT system in Dublin and implemented it in Warsaw,
Poland too. The ITS collected the same data, as well as data
from trams and bicycles. The project had the same goal as the
mentioned INSIGHT project [26], [27], [29].

In the 2016 European project ICSI (Intelligent Cooperative
Sensing for Improved Traffic Efficiency) an ITS were imple-
mented in the cities of Lisbon, Portugal and Pisa, Italy. The

<table>
<thead>
<tr>
<th>Search Engine</th>
<th>Keyword</th>
<th>Number of results</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEEE Xplore</td>
<td>Testfield ITS</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Test Field ITS</td>
<td>78</td>
</tr>
<tr>
<td></td>
<td>C-ITS</td>
<td>180</td>
</tr>
<tr>
<td></td>
<td>Test Bed ITS</td>
<td>14</td>
</tr>
<tr>
<td>Google Scholar</td>
<td>Testfeld ITS</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Test Field ITS</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>C-ITS</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Test Bed ITS</td>
<td>1</td>
</tr>
<tr>
<td>Google</td>
<td>Testfield ITS</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Test Field ITS</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>C-ITS</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Test Bed ITS</td>
<td>7</td>
</tr>
<tr>
<td>SUM</td>
<td></td>
<td>346</td>
</tr>
</tbody>
</table>

*aWith topics filter "intelligent transportation systems".*
research goal was to find a high scalable distributed ITS for data acquisition and analysis. The use cases were traffic flow optimization and reduction of the emission level. On an 8 km long section of the A5 freeway in Lisbon, three measuring stations with cameras have analyzed the traffic flow, as well as have detected anomalies (e.g. construction sites, traffic jams, accidents). Parallel in the city center of Pisa, the focus was on a parking guidance system and the reduction of air pollution. For this purpose, on a stretch of 1 km, 5 measuring stations with sensor were set up. The charm of these systems lies in the decentralized horizontal architecture, so that a high level of scalability has guaranteed [30].

Within the scope of the project FED4FIRE+, the "Smart Highway: V2X Testbed" was created in the year 2018. The ITS had 7 RSUs on a length of 3 km at the E313 highway in Antwerp, Belgium. The system was part of the CityLab test bed too. The research topic of the project was the communication between vehicles and other vehicles or infrastructures (V2X). For this, the system used direct antennas and a backend respectively a cloud solution which is connected via 4G/5G internet. The system has achieved latency times of 10-15 ms. The infrastructure had no sensors. Instead, it used only vehicle data. For data-intensive applications, the ITS used high-performance computers. The FED4FIRE+ project has presented a new approach for collocation of Multi-Access Edge Computing platforms with the support of RSU. This has improved the Quality of Service in infotainment services for vehicles on the highway [31], [32].

The current Diginet-PS test field in Berlin, Germany, covers the scenarios federal road and secondary road in inner-cities areas. The ITS uses cameras, weather sensors and other traffic sensors (e.g. for measurement of the traffic flow, parking stores, pollution) for detection of the environment. On the RSU, local data processing is implemented as edge computing. Furthermore, a cloud system receives the results from the RSU. The main purposes of the cloud are to store, analyze and predict test bed wide data. Based on these ITS, the researcher focus on the development of services and applications to increase traffic safety for automated driving. For instance, the applications are evaluating parking space utilization, analyzing the road conditions and recognizing the traffic situations [26], [32], [34].

In 2016, the ConVeX project created two ITS solutions. The first ITS was located on the A9 Freeway near Nuremberg, Germany. Over a length of 30 km, it was equipped with 6 RSU. The second ITS was located in Rosenheim, Germany and had two RSU. The data inputs of the systems were induction loops from existing infrastructure and the sensor information of the connected cars. The data processing was in the RSU and in a traffic control center. The research focus of the project were value-added services, as well as the V2V and V2X communication. The project has implemented the value-added services "Emergency Electronic Brake Light", "Do Not Pass Warning", "Blind Spot Warning" and "Vulnerable Road User Collision Warning". To influence the traffic flow, the system has sent the relevant information directly to the road user or to the electronic gantries. Furthermore, the ITS has notified vulnerable groups (e.g. cyclists, pedestrians) with a smartphone app [35].

The ITS DRIVE-Testfeld Hessen (Dynamic Road Infrastructure Vehicle Environment) is located in the region of Frankfurt, Germany. The overall goal is the intelligent management of traffic and construction sites. Furthermore, the ITS focuses on new techniques for traffic data acquisition with the use of V2V and V2X communication as well as data fusion between vehicle and infrastructure. The DRIVE-Testfeld Hessen has implemented intelligent applications which should support automated driving as well as the general traffic flow. Therefore, the test bed has more than 120 RSU. The applications have been traffic hazard warnings, shockwave damping and Green Light Optimal Speed Advisory (GLOSAR) [26], [33], [36], [37]. The mentioned ITS was platform of several projects. The project simTD set up many RSU and an ITS Central Station. The valued-added services of this project were obstacle warning, electronic brake light and warning about arriving emergency vehicles and construction sites [38]. Then, the project CVIS (Cooperative Vehicle-Infrastructure Systems) focused on V2V and V2X communication issues for enhanced driver awareness in an inter-urban environment [12], [24], [39]. Last, but not least, the project DRIVE C2X has performed a comprehensive assessment of cooperative systems with field operational tests [12], [40].

Another ITS exists in the city center of Kassel, Germany. Here, the traffic lights are equipped with 15 RSU and an existing traffic management center is used. The system allows priority treatment of public transport and emergency vehicles at traffic lights. Furthermore, the ITS warns road users about approaching emergency vehicles. For this purpose, the system uses the so-called DENM (Decentralized Environmental Notification Messages) for V2V and V2X communication. As value-added services, the researchers have developed a forecast for the green phase and an alternative route control [26], [33], [41], [42].

The Midlands Future Mobility test field in the United Kingdom is used to research on connected and autonomous vehicles. Over a length of 300 kilometers, the ITS is located between the cities Coventry, Birmingham and Solihull. Therefore, the ITS covers the scenarios city center, country road and motorway. The test field use RSU, which offer various value-added services. For instance, the services could be in-vehicle signage, roadworks warnings as well as GLOSAR. Current research results on the ITS have achieved in the cooperative perception for 3D object detection with the use of infrastructure sensors [43], [44].

In the context of the European Cooperative ITS Corridor from 2013, vehicles communicated with support of the infrastructure on the Rotterdam-Frankfurt-Vienna route. The Eco-AT project (2016) in Austria, a follow-up project of Telematik, set up a central ITS station as well as a number of RSU. The architectural approach was more centralized. The researchers have generated the necessary specifications. The use cases were decentralized environmental notification
message applications (e.g. road works warnings), aggregation of cooperative awareness messages, in-vehicle information (e.g. speed restrictions) and intersection safety (e.g. red light detection) \[7, 45\].

In 2016, the overall goals of the European project InterCor (Interoperable Corridors) were improving the safety, the traffic flow as well as increasing the cybersecurity of the ITS system itself. The project aimed to link several ITS corridors to exchange innovation and best practice in solving common problems. Therefore, the project included the ITS operations in Belgium, France, Netherlands and United Kingdom. The environment scenarios of the ITS were in Belgium, Netherlands and France on freeways. Furthermore, the ITS in France was an extension of the SCOOP@F project, which is mentioned below. The environment scenario in the United Kingdom were urban roads and motorways too. The project installed RSU which allowed V2X communication. For instance, the project has achieved the value-added services road works warnings, in-vehicle signage, on-board signalling of hazardous and unexpected events, multi-modal cargo optimization, green light optimization, probe vehicle data, parking information services for trucks and tunnel management \[46–49\].

The project SAFE STRIP (SAFE and green Sensor Technologies for self-explaining and forgiving Road Interactive Applications) implements an unconventional new approach to increase the traffic safety. The ITS consists of intelligent infrastructure sensors in the form of strips with networking capabilities. They are on the road pavement surface and analyze the individual situations. For instance, the system measures environmental parameters (e.g. temperature, ice, ambient light), passing vehicles (speed, lateral position, vehicle type) as well as pedestrian crossings. Furthermore, these sensors communicate bidirectional with vehicles as well as external infrastructure (e.g. traffic management centers). For test and implementation, the project installs a ITS in a 9 km section near Rovereto on the A22 freeway in Italy as well as in an 70

TABLE III
OVERVIEW ABOUT ITS SPLITTED ACCORDING TO THE TECHNOLOGY LEVEL EARLY DAYS, SITUATION-RELATED ANALYSIS AND CREATION OF DIGITAL TWINS. SYSTEMS WITHOUT SENSORS USE DATA FROM THE CONNECTED VEHICLES.

<table>
<thead>
<tr>
<th>Year</th>
<th>Name</th>
<th>Length</th>
<th>Camera</th>
<th>Radar</th>
<th>Lidar</th>
<th>Induction loop</th>
<th>Special sensors / other remarks</th>
<th>Architecture</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013</td>
<td>Compass4D</td>
<td>&gt; 10 km</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Focusing V2X</td>
<td>Edge-Cloud</td>
</tr>
<tr>
<td>2012</td>
<td>INSIGHT</td>
<td>N/A</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>V2X/Use social networks</td>
<td>Cloud</td>
</tr>
<tr>
<td>2016</td>
<td>ICSI</td>
<td>9 km</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Decentralized</td>
</tr>
<tr>
<td>2018</td>
<td>Fed4Fire+</td>
<td>3 km</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Focusing V2X</td>
<td>Edge-Cloud</td>
</tr>
<tr>
<td>2017</td>
<td>DIGNET-PS</td>
<td>3.7 km</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Weather/parking/road</td>
<td>Edge-Cloud</td>
</tr>
<tr>
<td>2016</td>
<td>ConVeX</td>
<td>30 km</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>V2X</td>
<td>Edge-Cloud</td>
<td></td>
</tr>
<tr>
<td>2017</td>
<td>DRIVE Hessen</td>
<td>200 km</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Edge-Cloud</td>
</tr>
<tr>
<td>2012</td>
<td>Testfield Kassel</td>
<td>9 km</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Focusing V2X</td>
<td>Edge-Cloud</td>
</tr>
<tr>
<td>2018</td>
<td>Midlands Future Mobility</td>
<td>300 km</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Focusing V2X</td>
<td>Edge-Cloud</td>
</tr>
<tr>
<td>2016</td>
<td>ECo-AT</td>
<td>N/A</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Focusing V2X</td>
<td>Centralized</td>
</tr>
<tr>
<td>2016</td>
<td>InterCor</td>
<td>&gt; 100 km</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Focusing V2X</td>
<td>Cloud-Edge</td>
</tr>
<tr>
<td>2017</td>
<td>SafeStrip</td>
<td>79 km</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>V2X/Pavement sensors</td>
<td>Edge-Cloud</td>
</tr>
<tr>
<td>2016</td>
<td>AUTOICTS</td>
<td>&gt; 17 km</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>V2X/Internet</td>
<td>Edge-Cloud</td>
</tr>
<tr>
<td>2019</td>
<td>C-Roads CZ</td>
<td>&gt; 100 km</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Focusing V2X</td>
<td>Edge-Cloud</td>
</tr>
<tr>
<td>2014</td>
<td>SCOOP@F</td>
<td>2000 km</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Focusing V2X</td>
<td>Edge-Cloud</td>
</tr>
<tr>
<td>2017</td>
<td>SAFARI</td>
<td>16 km</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Focusing V2X</td>
<td>Cloud-Edge</td>
</tr>
<tr>
<td>2018</td>
<td>Testfield Friedrichshafen</td>
<td>&gt; 5.5 km</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Focusing V2X</td>
<td>Edge-Cloud</td>
</tr>
<tr>
<td>2019</td>
<td>ZulaZONE</td>
<td>&gt; 100 km</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Focusing V2X</td>
<td>N/A</td>
</tr>
<tr>
<td>2016</td>
<td>CARISSMA</td>
<td>N/A</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>N/A</td>
</tr>
<tr>
<td>2014</td>
<td>AstaZero</td>
<td>7.4 km</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Focusing V2X</td>
<td>N/A</td>
</tr>
<tr>
<td>2017</td>
<td>MEC-View</td>
<td>&lt; 1 km</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>Stereo camera, Laser scanner</td>
<td>Cloud</td>
</tr>
<tr>
<td>2019</td>
<td>Testfield Ger.-Fran.-Lux.</td>
<td>&gt; 100 km</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Focusing V2X</td>
<td>Edge-Cloud</td>
</tr>
<tr>
<td>2017</td>
<td>KoRa9</td>
<td>225 m</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Edge-Cloud</td>
</tr>
<tr>
<td>2018</td>
<td>5GMOBIX</td>
<td>&gt; 100 km</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>V2X/Weather/road/pedestrian</td>
<td>Edge-Cloud</td>
</tr>
<tr>
<td>2017</td>
<td>Providentia</td>
<td>3.5 km</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>Event camera</td>
<td>Edge-Cloud</td>
</tr>
<tr>
<td>2014</td>
<td>AIM Braunschweig</td>
<td>7 km</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>Stereo camera, Laser scanner</td>
<td>Edge-Cloud</td>
</tr>
<tr>
<td>2016</td>
<td>Testfeld Niedersachsen</td>
<td>280 km</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>Stereo camera on 7.5 km</td>
<td>Edge-Cloud</td>
</tr>
<tr>
<td>2017</td>
<td>Testfeld Düsseldorf</td>
<td>26 km</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>V2X</td>
<td>Edge-Cloud</td>
</tr>
<tr>
<td>2016</td>
<td>Testfeld Bad.-Württerm.</td>
<td>&gt; 100 km</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>V2X/Weather</td>
<td>Edge-Cloud</td>
</tr>
<tr>
<td>2009</td>
<td>Ko-PER</td>
<td>&lt; 1 km</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Cloud</td>
</tr>
<tr>
<td>2017</td>
<td>ALPLab</td>
<td>23 km</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>Edge-Cloud</td>
</tr>
<tr>
<td>2020</td>
<td>SMLL London</td>
<td>24 km</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Edge-Cloud</td>
</tr>
<tr>
<td>2021</td>
<td>IN2Lab</td>
<td>2 km</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>Edge-Cloud</td>
</tr>
<tr>
<td>2016</td>
<td>Testfeld Dresden</td>
<td>20 km</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>Focusing V2X</td>
<td>Edge-Cloud</td>
</tr>
<tr>
<td>2019</td>
<td>HEAT</td>
<td>1.8 km</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>V2X</td>
<td>Edge-Cloud</td>
</tr>
</tbody>
</table>
km section in the Attiki Odos urban freeway in Athen, Greece. Here, the project has placed sensors on 39 toll barriers in Athen and several strip sensors as well as 5 RSU in Rovereto [50]–[52].

The deployment of ITS solutions in Europe were aimed in the European Project AUTOCITS in the year 2016. The overall goal of the project is to boost the role of ITS as a catalyst for the implementation of autonomous driving. Therefore, several ITS in Lisbon (Portugal), Madrid (Spain) and Paris (France) were created. The test bed in Madrid consisted of 15 RSU which were set up at a high frequented freeway on a length of 10 km. On a total length of 8 km on freeway and urban road, the ITS in Lisbon used 5 RSU. Last, but not least, in a urban highway near to Paris, the ITS consisted of 1 RSU. The project has achieved various day 1 services. For instance, road works warning, slow or stationary vehicle warning as well as the providing of information about weather conditions has been implemented [53]–[55].

In the year 2019, the project C-Roads CZ focused on the implementation of ITS units as well as the test and evaluation of its functionalities. The features of the ITS were situated related analysis (e.g. road works warning, in-vehicle information, slow and stationary vehicles, traffic jam ahead warning, hazardous location notification). For testing under real conditions, seven test fields has been built in the Czech Republic. All this ITS solutions has been equipped with RSU which communicates with vehicles and a central processing system [57].

In the project SCOOP@F, an ITS was deployed in a nationwide scale in 2014. For this, in the project were equipped 2000 km of the road with RSU as well as 3000 vehicles with on-board units for V2X communication. The RSU were connected to traffic management centers. The main data sources of the test field were the vehicles itself. They deliver data about their own position, speed and direction. Furthermore, vehicles received information about unexpected events (e.g. construction, slippery road, reduced visibility) from external sources. The main goals of the ITS were to increase the safety and to improve the travel quality. The researchers have implemented a decentralized communication to alert road users about unexpected events. In addition, the enhancing of the coverage of VANETs, a secure cloud environment for connected vehicles as well as a novel detailed security protocol were achieved [58]–[63].

Another important test bed is SAFARI in Berlin. The ITS covers the scenarios main road, secondary road and a junction of a freeway. The overall goal of the project is the exchange of information and the dynamic update mechanism of the dynamic maps, which are basic requirements for automated driving. In detail, the project research on the handling of construction sites and unexpected events for automated and connected driving. The test field uses cloud platforms as well as mobile edge computing for the V2X processing [26], [33], [64].

In the test bed Friedrichshafen, traffic lights are equipped with RSU and V2X. In total, the ITS covers the traffic scenarios federal road, country road, city center and pedestrian zones. The research topic is the information exchange to infrastructure as well vehicles to each other. The current research project on the test field is Alfried [26], [33], [65].

The project ZalaZONE in Hungary has a cordoned-off proving ground as well as a real world ITS to the border to Austria. In the real world, the ITS covers the highway scenario. In the cordoned-off proving ground, it covers the scenarios of smart cities, high and low speed handling as well as high speed freeways and rural roads. The purposes are test and research in the field of autonomous and connected vehicles. For this, the test field is equipped V2X communication technique [66]. Another cordoned-off test facility for re-enacting and simulating traffic scenarios is implemented in the CARISSMA project in Ingolstadt. The test facility offers 4000 square meter for researching on V2X communication, accident detection, accident consequences reduction as well as the automated driving functions [67]. The next cordoned-off ITS is AstaZero (Active Safety Test Area). It was set up in 2014 in Sweden, and it is an open environment where vehicle OEMs, research institutes and universities perform development and research. The research topics are new active safety functions for road vehicles. The test field contains a city area, 700 m multilane road, 5.7 km long rural road and 1 km high-speed area [68].

C. Creation Digital Twins

Autonomous vehicles are developed by Google [69], Tesla [70] as well as many other automotive manufactures. They can tackle the known problems in the transportation segment, because they optimize the traffic flow and can increase the safety of the traffic participants. According to the current approaches in autonomous driving, the primary responsibility, which is associated with replacing human perception and control, lies on vehicle manufacturers. However, the ITS on the infrastructure can create high precision digital twins. The vehicles can use this data as ground truth information. Therefore, the responsibility can re-balanced between vehicles and infrastructure. Thus, high precision ITS can be an essential enabler for autonomous driving [71]. This section presents several ITS solutions which aims to the mentioned properties.

In the year 2017, the MEC-View project implemented an ITS in the city center of Ulm, Germany. Across roads and an intersection, the system contained 8 cameras, 4 stereo-cameras, 4 laser scanners as well as 8 Lidars. For object prediction and data fusion, the sensors were connected with a server. Vehicles communicated with the server via 5G. In addition, a 3D-HD map of the relevant road sections were created. The aim of the project was to create a digital twin of the road traffic. The researchers have achieved data transfer in real time [72], [73].

The digital test bed "Germany-France-Luxembourg" was created in 2016. The focus was on testing of automated and connected driving functions. The highlight of this project was in the challenges of national border crossing. As part of the mentioned test bed, the project iTeM (ITS Testfield Merzig) in Merzig, Germany, covered the environments city and rural read. The research on this ITS was on connected driving functions via C2V and C2X too. For traffic perception,
the infrastructure was extended with RSU, C2X technology
and cameras. The RSU communicated with vehicles and a
centralized server. The project have implemented applications
for hybrid access technologies and safety functions [26], [33],
[74], [75].

In 2017 on the freeway A9 in Germany, researchers of the
project KoRA9 (Kooperative Radarsensoren für das digitale
Testfeld A9. English: Cooperative radar sensors for the
test field A9) installed 10 novel 77 GHz radar sensors on five
masts along the freeway with a mutual distance of 45 m.
Furthermore, 2 Road Side Units were installed in a gantry
bridge for the V2X communication. The project goal was
to evaluate the potential of seamless sensory recording of
traffic with radars. For this purpose, the infrastructure sensors
performed automotive radar applications. The obtained data
streams were merged to a digital twin. The researchers have
analyzed the digital twin and have made it available to third
parties via the developed cloud platform. Furthermore,
they have developed services for infrastructure support during
overtaking maneuvers and traffic jam warnings [33], [76].

With the European Project 5GMOBIX (5G for cooperative &
connected automated MOBIlity on X-border corridors), sev-
eral ITS in Europe and Asia were created respectively reused
in 2018. The project showcased the benefits of 5G technology
for cooperative, connected and automated mobility. The Spain-
Portugal cross-border ITS between Vigo and Porto focused on
automated driving maneuvers. It was equipped with 2 MEC
nodes, 2 center clouds, 5 RSU, 4 traffic radars and 2 pedestrian
detectors. The ITS Greece-Turkey researched on platooning
and the use of external sensors. The external infrastructure
contains 6 Edge computer, 2 clouds, 4 RSU as well as 2
Lidars. The ITS in Eindhoven-Helmond in the Netherlands
focused on cooperative collision avoidance with extensive use
of cameras. Therefore, the ITS used 2 MEC servers, 2 cloud
systems and more than 50 cameras. The ITS in France were
located in Versailles and Paris. They focused on infrastructure-
assisted driving with 4 MEC nodes, 1 cloud, 2 Lidars as
well as 3 cameras. The ITS in Berlin and Stuttgart, Germany,
researched on RSU-assisted platooning and surround view
generation. Therefore, the system used 9 RSU, 1 Cloud, 18
cameras and 10 environmental condition sensors. The ESPOO
urban ITS in Finland focused on extended sensor processing
as well as on remote driving. The ITS were set up with 2
MEC nodes, 1 cloud, 1 Lidar and 1 camera. The researcher
of the Jinan ITS in China focused on cloud assisted advanced
driving, cloud-assisted platooning as well as remote driving.
The used equipment were 5 RSU nodes, 1 cloud, 5 Lidars,
6 cameras and 5 radars. Last, but not least, the cordoned-off
ITS Yeonggwang in South Korea focuses on remote driving
as well. The system used 1 cloud [77], [78].

With the support of external infrastructure, the Providentia
project created a digital twin of each traffic participant in real
time in the year 2017. This digital twin should provide a
foresight for autonomous vehicles as well as vehicles with
conventional driver assistance systems. For this purpose, an
ITS was built on the A9 freeway in Munich, Germany. The
ITS contained 2 measurement stations on gantry bridges which
collected data of the traffic. Each station was equipped with a
RSU, 4 cameras and 4 radars. Furthermore, a backend com-
puter realized the global data fusion as well as the connection
to the 5G network and the internet. The sensors have detected
the individual traffic participants and have sent the data to the
RSU. Then, the RSU has tracked the detections over several
time steps. The tracks have been merged into a local digital
twin for each RSU. In the end, the backend receives the local
twins of the RSU and has combined it again to a global
digital twin across all measuring points. With this, the ITS
of Providentia has created digital twins which combine the
advantages of radar and camera from different perspectives
[79]–[81]. In 2020, the follow-up project Providentia++ has
extended the ITS into urban areas. Thus enabled the analysis
of complex traffic scenarios in intersections and pedestrian
crossings. In total, the test bed had a length of 3.5 km,
contained 7 measuring stations with 75 sensors (e.g. cameras,
event-based cameras, radars and Lidars). Figure [1] shows the
hardware setup on a public road intersection in an urban
area. At the moment of writing this paper, the researchers of
Providentia++ have established a stable data stream of the high
precision digital twin for the broad public. To the best of our
knowledge, this feature is unique in the current development of ITS [82].

Fig. 1. An equipped intersection in the ITS of the project Providentia++.
Hannover, Hildesheim, Braunschweig and Wolfsburg. On a 7.5 km long section, the ITS has 71 measuring stations for high-precision recording of the traffic situations. The test bed is equipped with stereo cameras, 3 RSU which provides V2X communication as well as a backend server. The ITS aims to offer an open research platform which delivers ground truth data for autonomous and connected driving. The overall goals are reduction of accidents, improvement of perception and optimization of the traffic flow. The researchers have realized the value-added services’ maintenance vehicle warning, in-vehicle signage as well as lane management [87]–[90].

The digital test bed "Düsseldorf" in Germany runs on a length of 20 km on the A57 freeway from the Meerbusch junction near Krefeld via the Kaarst junction onto the A52 into downtown Düsseldorf. Therefore, the ITS covers the scenarios freeway, tunnel, bridge, city center and parking. The test bed grows with several projects. The project Ko-MoD researched on the interaction between infrastructure and vehicles in the scope of connected and automated driving functions. The ITS used vehicles as mobile sensors for the detection of obstacles on the road (e.g. pedestrians, wrong-way drivers). The project has developed the value-added services autonomous parking, prioritization of public transport system and cooperative traffic light [91]. Then, the follow-up project KoMoDnext should prepare numerous sections of the ITS for autonomous driving (level 4). The project has designed and implemented a high-resolution environment detection on the A57. This component has merged stationary and vehicle-generated data [33], [92]. Last, but not least, the project ACCorD expanded the corridor for New Mobility Aachen-Düsseldorf with additional 4 km. The central component of the project activity was the generation of a digital twin. The highlight was the extensive usage of the Lidar-technology: The ITS contained on 68 measurement stations. Each station has 2 cameras and 2 Lidars, so that 136 Lidars were set up. This data has been locally processed in various RSU and a central database, which offered the collected data to other research activities and simulation [93].

The ITS Testfeld Autonomes Fahren Baden-Württemberg (English: Test Bed Autonomous Driving Baden-Württemberg), which is located in Karlsruhe and Heilbronn, uses cameras, several RSU and a backend server. The test bed allows a sensor extension with radars and Lidars. Based on camera object tracking, the ITS aims to generate digital twins of the traffic. With this low-cost sensor setup, real-time recording in various traffic situations (e.g. traffic with vehicle, bicycle and pedestrian) are implemented. The purpose of the infrastructure is the testing of vehicle systems for automated and connected driving under real traffic conditions [33], [94], [95]. For instance, a current research on the test field is the CARAMEL project. The project research on the challenges in cybersecurity of modern vehicles. For this, CARAMEL applies advanced artificial intelligence and machine learning techniques [96], [97].

In the year 2009, the project Ko-PER of the research initiative Ko-FAS aimed to increase road safety. The goal was a precise creation of a digital twin of the traffic participants in real-time. Therefore, intersections in Germany were equipped with cameras and Lidars. The intersection in Ulm contained 2 Laser scanners and 2 cameras, in Alzenau 8 Laser scanners and 7 cameras and last, but not least, the intersection in Aschaffenburg contained 14 Laser scanners and 10 cameras. The data streams of the sensors on each intersection were combined locally. Then, the fusion result were combined with vehicle information. Therefore, V2X communication technology were implemented too. With this, the researchers has created a digital twin of the traffic [98]–[100].

As part of the project ALP.Lab - Austrian-Public Test Track Highway A2, an ITS near Graz was implemented in 2017. The test bed covered a distance of 23 km and was equipped with more than 100 sensors. For the creation of digital twins, the ITS used cameras, radars and Lidars. The goals of the ITS were extension of the vehicles’ perception rang and offering ground truth data for plausibility checks of vehicles sensor data. With this, the ITS offers comprehensive testing functions for automated driving and driver assistance systems. Interestingly, the researchers have achieved tracking of vehicles for more than 2 km [101], [102].

The Smart Mobility Living Lab in London is a real world environment for testing and developing future mobility solutions. For this purpose, the 24 km long test bed has 276 cameras, 40 RSU and 2 data centers, which are connected to each other via fiber optics. The RSU provides V2X communication service. With this hardware, the ITS collects high resolution and high confidence information about the road traffic. The overall goal is the support of development for autonomous vehicles to market-ready [103].

As extension of the mentioned cordoned-off test facility CARISSMA, the project IN2Lab offers a real world test bed in Ingolstadt, Germany. The ITS has a total length of approximate 2 km. Every 200 m exists a measurement stations with a 4.5 m high mast. There are 13 measuring stations which are connected to a central computing unit via optical fiber. On each measuring station are a RSU, cameras, Lidars, radar as well as V2X communication modules. The purpose of the test field is the research and the test of autonomous vehicles [104], [105].

In the scope of the project Testfeld Dresden (English: Dresden test bed), a cooperative ITS is deployed in the urban and suburban areas of Dresden, Germany. The test field provides on 20 km stretch various driving scenarios (e.g. urban roads, connection to freeways, complex junctions, tram tracks, bus lanes and separate cyclists lanes). Therefore, the test bed contains several camera systems, 10 RSU for research and 25 RSU for productive work. Furthermore, the ITS has a backend which hosts a centralized cloud service. The overall goal is the testing of automated and connected driving in a realistic traffic environment. The project has proposed a reference platform for heterogeneous ITS communication as well as several value-added services (e.g. GLOSAR, probe vehicle data and a cooperative lane change) [106]–[108].

In addition, further ITS solutions for connected and au-
tonomous driving were implemented in numerous cities in Germany. For instance, the project HEAT (Hamburg Electric Autonomous Transportation) installed in 2019 a test bed with a length of 2 km in Hamburg. The ITS contained of several RSU, radars and Lidars. The purpose of the sensors was to support the environment perception of an autonomous electric minibus in a real world scenario. So, the research goal of the HEAT project was the networking of an automated fleet of minibuses with traffic infrastructure. The researchers on this project has achieved successfully this goal [26], [109], [110].

IV. DISCUSSION

Intelligent transportation systems using external infrastructure offer great potential and possibility to support connected and autonomous driving. To fulfill this future use cases, the sensors and services of ITS becomes more demanding and more complex. To achieve political acceptance, the ITS must also take privacy and security aspects into account. Based on the mentioned literature survey, we investigate and discuss 1.) the trend of the general purpose of ITS, 2.) the necessary sensor setup, 3.) existing value-added services as well as 4.) the nonfunctional requirements of ITS. The open research questions that have not yet been adequately answered are identified.

A. General Purpose

The claim on the tasks of ITS increase significantly. In the Early Days, the ITS systems have improved safety and efficiency of the traffic flow. Therefore, the systems have allowed a general statement about the current traffic flow. Furthermore, prototypes of the first V2X have been developed. This development started in 1986 and ended in the first decade of the 2000s. In the next step, the ITS of the category Situation-related Analysis have analyzed and interpreted individual traffic situations. Furthermore, these ITS solutions could share their results with other traffic participants. Hereby, these systems have contributed to more safety and a better traffic flow. This category grew exponentially from 2010 to 2018 and then stagnated. Presumably, the functional scope of these systems is now no longer sufficient. Since 2012, more and more test beds exist which can generate highly accurate digital twins of road traffic. They allow a complete, high granularity analysis of the traffic. So far, there is no sign of stagnation. Because future ITS solutions should give control recommendations to autonomous vehicles, the current development is absolutely necessary. The Figure 2 shows the accumulated number of test beds in each category and therefore the general trend of ITS solutions.

B. Sensors

The first step in the process chain of ITS are the sensors. They collect information about the real world. Thus, they have the main impact on the precision and quality of the services. In the first test beds, the sensors for analyzing the traffic flow were induction loops. Unfortunately, only induction loops do not allow an individual situation analysis. Therefore, cameras have to be used in the most ITS since 2006. Cameras can create a bird’s-eye view of what is happening on the road so that they allow complex situation analysis. Weakness points are obvious: The camera does not deliver reliably data in case of night or extreme weather conditions (e.g. strong rain, fog or snow). For compensation, the modern ITS use more and more frequently a combination of cameras with radars, Lidars and other special sensors (e.g. IR camera, stereo camera, event camera or weather sensor). These hardware setup can percept the environment in any weather conditions. Most of the test beds use camera and Lidar. The Figure 3 includes the full trend of sensor setups in ITS.

C. Value-added services

The capture of the traffic and the creation of digital twins must not end in self-purpose. Otherwise, the ITS would be
useless to the society. Instead, the ITS has to offer meaningful services which support people in their daily life. For instance, an ITS can decrease maintenance costs, reducing pollution, improving transfer speed as well as protecting human life [4], [8]. Additionally to cover the high costs for installation and maintenance, the ITS services offer potentials for high sales too [9], [111]. The Table IV shows the value-added services [8].

Unfortunately, the Figure 4 shows a deficiency in the development of services, which are needs for operational maneuvers. This value-added services require the complete potential of the high accurate sensors. Most of the other value-added services do not need this accuracy. Therefore, further research should focus on the development of services which use the high data density of the digital twins. However, the ITS projects [76], [92], [95], [101], [103], [104] create digital twins with high data density to support the development of autonomous driving, there are still gaps of using this information in market-ready products to a broad public. This step is still necessary to cover the high costs of such systems, as well as to provide real added value to the users of ITS solutions.

D. Nonfunctional requirements

The ITS will be involved in the decision-making process for specific maneuver actions of traffic participants. The system must be reliable in its operation at all times, in extreme scenarios such as natural disasters, too. Therefore, ITS are critical infrastructure and needs several mechanisms for safety and cybersecurity. To fulfill the safety requirement, the systems must have functionality for self-diagnostic as well as for self-healing. Then, the ITS would be safe in operation against malfunction [3], [8], [112].

In addition, we need mechanisms to protect the ITS against cyberattacks. In particular with fatal consequences, the RSU are very exposed to this kind of attacks. There exists still research gaps. For instance, the communication between vehicles and the test beds are most of the time unencrypted. This makes the system very vulnerable. To tackle these problems, the researchers have developed communication encryption with cloud support [2], priority-based authentication techniques [9] and real-time secure communication without overloading the network with security overhead [113]. Fortunately, some test bed projects have addressed the cybersecurity too: The project InterCor have introduced a cyber-physical blockchain cryptographic architecture [47] and the project SCOOP@F a secure cloud environments as well as a novel security protocol [59], [62]. Furthermore, in the project CARAMEL on the ITS Baden-Württemberg are activities on advanced artificial intelligence and machine learning techniques to fulfill cybersecurity requirements, too [96]. However, it seems the challenges in cybersecurity have not yet been definitively solved. In particular, the secure transmission of high volumes of data, as occurs with detailed twins, still seems to require research. Therefore, further research on these security aspects are needed.

In case of a national wide rollout, the nonfunctional requirements’ scaleability, adaptability as well as real-time capability are important for ITS solutions [8], [114]. This high demands are big challenges in the software architecture: Centralized software solutions (e.g. with a cloud) are available for ITS, but they have numerous disadvantages in scalability, energy efficiency and failure tolerance. A scalable architecture to solve the mentioned problems could be a distributed approach. According to [113], this approach for intelligent sensor networks was not available, respectively was not adequately researched. Indeed, with the use of edge computing, the works of [5], [111] have presented distributed approaches for ITS architectures. Furthermore, the mentioned ICSI test bed have focused on high scalable distributed ITS, too [30]. However, this test bed has analyzed only specific situations. It has not processed digital twins in real-time. To the best of our knowledge, it is still unclear how this distributed systems performs in a high data density environment with digital twins. For this reason, further research in scaleability as well as adaptability in real world test beds is warranted.

V. CONCLUSION

In the scope of this work, 346 papers and documents have been collected with a systematic review to provide a summary of the current intelligent transportation systems. After passing the filtering, 115 documents with 40 test beds have been analyzed. Here, this paper has showed the fascinating development in the field of ITS using external infrastructure from the Early Days until the Creation of Digital Twins. So, this literature survey accompanies the reader from the beginning of ITS until the current state of the art.

According to the mentioned history, the complexity as well as the functionality of ITS have increased immensely. The current systems can deliver high accurate information about individuals in traffic situations in real-time. In the field of ITS, this development is a great success. However, there are still improvements in the reliability, scalability and security of the overall system needed. For this reason, further research in the ITS should focus on more reliable perception of the traffic with the use of modern sensors, plug and play mechanism as
### Table IV

**Overview about the Value-added Services of ITS.**

<table>
<thead>
<tr>
<th>Value-added service</th>
<th>Warning in operational maneuvers</th>
<th>Warning in road conditions</th>
<th>Warning in traffic situations</th>
<th>Controlling of vehicles</th>
<th>Controlling of traffic flow</th>
</tr>
</thead>
<tbody>
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<td>PROMETHEUS</td>
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<td>X</td>
<td>X</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PATH</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>-</td>
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Well as secure real-time distribution in decentralized manner for a high amount of data. Furthermore, to ensure the sense of such systems, services with a real added value for the broad public with autonomous as well as non-autonomous cars have to be developed.

In the end, the development of intelligent transportation systems using external infrastructure is in a correct direction. For the comprehensive roll-out, however, a few questions still need to be answered.

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**References**


