ACTA TECHNICA JAURINENSIS
Vol. 15, No. 2, pp. 58-73, 2022
10.14513/actatechjaur.00627

A survey on the use-cases and deployment efforts toward converged internet of things (IoT) and vehicle-to-everything (V2X) environments

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Submitted: 19/05/2021 Accepted: 01/10/2021 Published online: 27/12/2021

Abstract: In the past few years, automotive Internet of Things (IoT) solutions have become one of the most significant IoT application areas in the shape of vehicular communication to connect vehicles and such the so-called Internet of Vehicles (IoV) to be used in Intelligent Transportation Systems (ITS) environments. With an increasing level of cooperation, ITS could facilitate smart city operations by providing cooperative intelligent traffic solutions. Modern Cooperative ITS (C-ITS) solutions have started to be implemented in the whole world with various deployment models and significant improvements in the integration of Vehicle-to-Everything (V2X) communication and IoT solutions. To highlight the current V2X technology evolution towards an IoT/IoV era, this paper presents a comprehensive survey about the convergence between IoT and V2X use-cases together with their supporting technologies in the cooperative ITS ecosystem worldwide. We show how IoT could enable advanced V2X applications to get widespread and increase ITS efficiency.

Keywords: IoT-V2X convergence; Internet of Vehicles; Cooperative ITS; technology evolution; V2X applications

I. INTRODUCTION

Internet of Things (IoT) enables an enormous number of devices around the world to have immediate access to information, communicate and transfer data gathered from different environments to the upper layer of IoT platforms, promptly to the applications, or to the cloud for computing and data processing to provide a valuable service. According to Cisco, 25 - 50 billion 'things' will be connected to the Internet by 2020 [1]. IoT can be presented as a network of surrounding things connected to the Internet, such as various vehicles that can be monitored, detected, or controlled. The cars are embedded with sensors to sense the environment and communicate with other vehicles and ITS stations. For that, the environment is monitored by intelligent sensing and measurement techniques, and the collected data is transferred to the cloud by communication procedures between the widest scale of interconnected devices ("things").

IoT has been adapted to incorporate the digital information and the real world of devices; however, IoT platforms and management tools need to provide solutions to meet connectivity, heterogeneity, security, scalability, and data handling. The fast-growing IoT paradigm trends adumbrate that IoT will gain higher importance in several industries in the coming years [2]. This aggressive growth makes the emerging automotive industry and vehicular communications pose one of the most challenging tasks in integrating IoT and V2X.

V2X refers to the technology family that enables cars or any vehicles and even vulnerable road users (VRUs) to communicate and send messages between them and the surrounding environment [3]. This connectivity will enhance the traffic flow, navigation, and collision avoidance and provide an unobstructed view of traffic situations in the most hazardous situations. V2X enables vehicles to share dynamic data and information (such as speed, position, heading, curving, loss of stability, braking, etc.) in real-time to provide safer transportation and to help various value-added services like advanced traffic management.

The global relevance of IoT and how it can be applied to several domains (such as vehicular communications using a plethora of things like sensors, actuators, and devices) to communicate with each other directly or indirectly via the Internet introduce significant challenges in how IoT can be involved in vehicles industry. With these advantages of V2X, Cooperative Intelligent Transportation Systems (C-ITS) can be built with many valuable services [4].

It is expected that in a time frame till 2025, 150B USD will be generated as revenue for connected vehicles with a number near to 100M cars around the world [5][6]. The expected volume of data transmitted between the cloud and vehicles will be around 100 petabytes per month [7][8]. Also, there will be many deployment examples of ITS's worldwide with valuable automotive services provided to future connected vehicles, which will enable safety during the driving, the efficiency of the energy consumption, and reduce the emissions from the cars.

Cooperative Intelligent Transportation Systems incorporate vehicles that are interconnected with each other and various elements of the road infrastructure and the overall transportation ecosystem. ITS aims to fewer accidents, less congestion, and reduced emissions. The application of V2X communication technologies in different contexts such as Vehicle-to-Vehicle (V2V), Vehicle-to-Network (V2N), Vehicle-to-Pedestrians (V2P), Vehicle-to-Infrastructure (V2I), Vehicle-to-Grid (V2G), and Vehicle-to-Device (V2D), could create the essential infrastructure to help to reach this vision [9]. V2X augments sensors, computer vision, and live data analysis with different information sources, which can be supported by integrating IoT and V2X technologies and allow vehicles to see intersections and create/extend the visual horizon. Vehicles can connect and communicate in different connectivity options, such as the currently available Wi-Fi-based ITS-G5/DSRC without any pre-deployed communications equipment in the middle or by mobile cellular solutions such as 4G LTE technology. Cellular V2X (C-V2X) is also coming into the picture: LTE and 5G NR C-V2X are about to be deployed soon [10].

This paper introduces the convergence of IoT and V2X and its relation to enable ITS to accomplish and provide a valuable service by using most modern technologies such as 5G technology. In section II, we introduce the meaning and explain the concept of the Internet of Vehicles (IoV). In section III, joint use-cases for using IoT with V2X/C-V2X are presented. Then, in section IV, V2V with IoT communication technologies will be illustrated, such as the 5G technology convergence of Cellular IoT for V2X. After that, Different deployment models/examples of intelligent transportation systems will be given our survey results about these deployment activities besides the advantages of adding IoT features to them in section V. The study ends with concluding our key findings in section VI.

II. THE CONCEPT OF THE INTERNET OF VEHICLES (IOV)

The Internet of Vehicle (IoV) is a platform consisting of connected vehicles with V2X communication systems enhanced by IoT's power and allowing transferring and exchanging information in real-time with different relevant actors and surrounding environments with high reliability (**Fig.1**). These actors could be vehicles, infrastructure, pedestrians, communication network devices. IoV will help solve the common problems related to traffic, such as safety and congestion and reduce traffic crashes and emissions to save the environment [11].

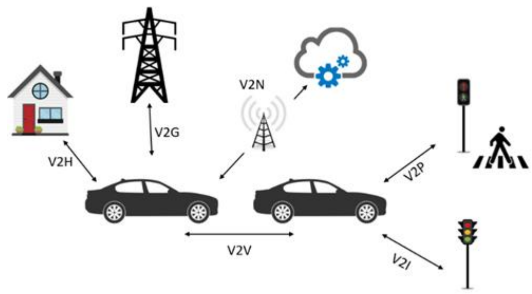

Figure 1. *Internet of Vehicles (IoV)*

An IoV platform can be created by starting with implementing a reliable V2X communication system. Then, the next phase is to integrate different devices and sensors to measure and monitor the vehicles for sensing the environmental conditions, getting information, and collecting data. This data can be analyzed locally by a middleware component place closer to the end-users according to the Mobile Edge Computing (MEC) paradigm. Another choice is sending the gathered data to the upper segments, known as cloud computing, to analyze the data and achieve the goal of integrating vehicular networks, also using different types of communications [12].

The first wave of solutions for initiating such systems will be based on the IEEE 802.11p technology. After Release 14 and beyond, cellular solutions based on sidelink communications will be implemented, C-V2X could also gain momentum. After detected information processing, representation, and visualization in deployment models such as ITS, the analyzed data dispatches towards end-users as apps on the mobile applications or as information to other vehicles to inform them about the traffic situations and detect the expected hazards [13].

However, IoV has many critical challenges concerning the integration of connected vehicles with IoT. Firstly, (i) heterogeneous IoT devices and cars pose a serious problem, which requires extensive connectivity to billions of heterogeneous IoT devices such as sensors, actuators with various vehicles from different manufacturers. Secondly, (ii) communications systems with network and low power communication protocols are required with stable wireless links to maximize the throughput for increasing transmission intensity of data exchange, driver safety, and awareness of critical situations [11]. The 5th generation of mobile cellular architectures becomes relevant to tackle the before-mentioned challenges, creating a flexible structure and advanced communication techniques designed to adapt to various use cases in IoT. Thirdly, (iii) security is also a considerable challenge. Security breaches in the vehicular domain could easily result in unacceptable consequences such as financial losses and loss of credibility. Alerting services such as self-driving mode charging, traffic rerouting, and localization and security procedures in case of abnormal status will enhance the security in different use cases of IoT integration with V2X. Fourthly, (iv) data management accounted as a significant challenge because of including data collection and data analytic, which need to handle promptly and actuate data providing in real-time and support data visualizations, management, incorporation, and security [14].

III. Joint use-cases of IoT and V2X/C-V2X

Vehicular communication systems are nowadays limited to vehicles and roadside infrastructure nodes; they can be connected directly or indirectly to various fields and environments such as traffic management centers, pedestrians, devices, networks, or even the power grid. Implementation of IoT with these scenarios will provide more privileges and a clear vision of situations to add value and build intelligent life and enhance connected vehicles with IoT. In the below subsections, we group and introduce the identified join use-cases of IoT and V2X/C-V2X (**Table 1**).

1. Vehicle-to Vehicle with IoT

Different types of vehicles, such as autonomous vehicles or smart ones, can communicate with each other directly by ad hoc networking techniques or indirectly by relying on the infrastructure using different protocols and networking topologies. The original goal of V2V systems was to alert drivers about abnormal events but not to control the vehicle. Later, with the advancement of self-driving vehicles, ADAS (Advanced Driver-Assistance Systems) solutions improved to act instead of the human drivers, such as steering around the obstacles or breaking [15]. For instance, if there are two vehicles with V2V following closely each other, and the vehicle in the front performs emergency braking, the following vehicle will receive a warning such as a flashing red light about that event. It could take action immediately by braking or overtaking. Such cooperative operations do not affect traffic. Simultaneously, the other vehicles with V2V systems and driving nearby will also get the notification that the drivers in the neighborhood can use to save time and be part of a more efficient traffic environment.

There are so many different use cases about how connected vehicles will enhance traffic efficiency and safety. These include alerting services such as the approach of emergency vehicles and traffic jams to enable collision avoidance in addition to entering intersection warnings, leaving highways, pre-crash indication, lane changing unexpected stop warnings, and overtaking between two vehicles [16]. IoT can be involved in all previous use cases by assisting the vehicles and drivers to be proactive because of collecting various data and information from different sources such as vehicles or infrastructure represented by roadside units. Then, alert the drivers or cars about the traffic, whether it is crowded or not, help drivers and cars make appropriate decisions and improve traffic efficiency.

2. Vehicle-to-Infrastructure with IoT

Communication of vehicles with traffic signals and roadside units or other stationary devices are known as Vehicle-to-Infrastructure (V2I). The cars and other road users send the collected data to one of the nodes previously presented as the contact point of the infrastructure and vice versa. Infrastructure components, including traffic lights, lane markings, and road signs, are also able to provide information to vehicles. The V2I context is the closest one to IoT because it groups the cars or vehicles (V) in general with other things (T) to give the meaning of Vehicle-to-Things (V2T) with various missions such as changing traffic lights or alerting drivers about road hazards, including obstacle discovery, accidents reporting, closed roads, roadworks or maintenance on the way and different hazardous location warnings [17].

IoT can be implemented in V2I use-cases to enable valuable advantages. For instance, IoT will provide more detailed information about the surrounding environment and traffic conditions such as weather conditions, roadside construction, faulty traffic lights, or even accident services such as Internet access. As a use-case of IoT applications with V2I, IoT technology could provide intelligence services such as automatic parking payments, toll charges, and creating dynamic traffic light control to manage the traffic lights for approaching emergency vehicles such as a fire brigade or police cars. Moreover, the information coming from IoT platforms can provide valuable information about the recommended speeds, sharp curves warnings with ideal speed to prevent accidents, slippery roads, and environment temperature [18].

3. Vehicle-to-Pedestrian with IoT

According to The U.S. Department of Transportation (USDOT), in 2013, there were 32,719 people killed in motor vehicle traffic crashes and incidents in the United States. Pedestrians and other road users' occupants made up 17 percent of these victims [19]. Moreover, according to a global status report on road safety 2018 by the World Health Organization, the number of annual road traffic deaths has reached 1.35 million. Road traffic injuries are currently the leading cause of death for pedestrians, cyclists, motorcyclists, and young adults aged 5–29 years [20]. The number of roadway fatalities has a steady reduction in recent years because of enabling different safety approaches. This effect is also expected with the spreading of vehicular communications such as V2V, V2I, and Vehicle-to-Pedestrian (V2P). The V2P approach includes vulnerable road users known as pedestrians (such as people walking, disabled people with wheelchairs or other mobility devices, passengers who come in and out from buses and trains, and also cyclists) into the V2X ecosystem.

V2P enhances the pedestrian's safety by using personal mobile devices or wearables to receive and send notices about the horizon by sending a note from a mobile app to the cloud in a related IoT platform [21]. Regarding that, drivers and vehicles in the area will receive alerts about that on concise notice. For instance, when pedestrians perform illegal crossing because of blind disability or low vision to the traffic signal, an automated call from a pedestrian's smartphone alert both the driver and pedestrian to turn on or stop. IoT can be involved in this use case by providing information collected by intelligence cameras or sensing the object crossing the crosswalk during the red signal and then alerting the driver about the illegal crossing. Moreover, it can use in the safety of public zones, such as the drivers on the way of the schools will receive warnings when students go out and make places crowded places of them.

4. Vehicle-to-Network with IoT

Mobile networking is an essential technology for vehicular communication. Vehicles can communicate with each other or with other environment objects wirelessly and bidirectionally by two distinct approaches: infrastructure-based and ad hoc networks. The infrastructure-based system depends on the cellular concept and terrestrial network infrastructure support. Ad hoc networks become available because of the widespread availability of wireless communications with no need for self-organizing networks and not require a pre-established infrastructure such as Mobile Ad Hoc Networks (MANET) [22]. MANET is a combination of wireless mobile nodes that exchange information and build networks dynamically without employ any pre-existing fixed network infrastructure or a centralized administration. The Vehicular version is known as Vehicular Ad Hoc Network, a variation of MANETs with nodes of vehicles [23].

IoT is mainly a network that extends the Internet, relying on various communication solutions between the IoT module and the platform such as LoRaWAN, NB-IoT, and 5G cellular [24]. These technologies are already implemented in vehicular communications by using the communication in the network layer and identification layer of IoT platforms and can also be used to enhance traffic efficiency. This integration between V2N and IoT with various supported communication protocols enables services in different communications scenarios in case of partial unavailability of services such as Internet accesses and cloud computing [25].

5. Vehicle-to-Home and Vehicle-to-Grid with IoT

In the case of Vehicle-to-Home (V2H) scenarios, vehicles are exchanging information with a smart home environment for advanced control and efficiency. Vehicle-to-Grid (V2G) communication is a power grid extension system that regulates the vehicle's charging rate or returns electricity to the

Table 1. *Use-cases of V2X/C-V2X and possible IoT enhancements*

Use-cases	***V2X Communication context***	***IoT enhancement***
Proactivity	Vehicle-to-Vehicle (V2V)	Awareness by collecting data and information from different resources to make the best decision.
Traffic Efficiency	Vehicle-to-Infrastructure (V2I)	Comprehensive behavior by collecting data and information from the surrounded environment.
Safety of Pedestrian	Vehicle-to-Pedestrian (V2P)	Personal mobile devices to receive notices about the horizon.
Connectivity	Vehicle-to-Network (V2N)	Connectivity is provided by a variety of communication solutions, technologies, and platforms.
Home Management	Vehicle -to-Home (V2H)	Support Recourse and smart home applications control.
Renewable Energy	Vehicle-to-Grid (V2G)	Renewable power storage alternative: improve power consumption.

grid. V2G could provide an energy storage alternative such as electric vehicle batteries could be used as alternatives for energy storage to provide home devices with the power needed. IoT in V2H can provide innovative home applications concerning vehicles such as air condition to control the home's temperature during driving and before reaching the house. In V2G, IoT platforms used in the power grid for intelligence charging determine the best time to charge vehicles batteries and improve power consumption and safety system [26].

The use-cases of interactions between IoT and vehicular communication will introduce and invent so many domains and applications to add value in different fields of life. A good example is the EC H2020 AUTOPILOT project, which also provides a vision for Vehicle-to-Users (V2U), Vehicle-to-Owner (V2O), and Vehicle-to-Maintenance (V2M) [27].

IV. Technologies supporting the convergence of IoT and V2X communication

Different types of V2X standards deal with vehicular networks in various layers. The IEEE 802.11p Wireless Access in Vehicular Environment (WAVE) standardization which is related to all layers and processes, originates from the allocation of the Dedicated Short-Range Communications (DSRC) spectrum band to use for safety applications in the U.S. [28]. Its European proportionate is ITS-G5, still relying on Wi-Fi-based technology. In recent years new cellular V2X (C-V2X) standard has been established and defined basic functionality by the 3rd Generation Partnership Project (3GPP), which provides vehicular communication standards for both Long Term Evolution (LTE) and 5th generation (5G) New Radio (NR) releases. Their goals are to enable extended reliability and improved range for enhanced safety and efficiency of the traffic, which can be exploited with the 5G NR technologies from 3GPP Rel 16 onwards [29][30]. Moreover, in the 3GPP specifications Rel 12, ProSe (Proximity Services), a device to device (D2D) technology, is introduced to enable LTE devices to communicate and detect each other directly depending on the various enhancements added to existing LTE standards, including new features such the "sideline" type of link for direct communication between devices. ProSe-enabled devices will be utilized in the mission-critical communications sector, such as V2X public safety applications, especially in V2P, such as traffic relaying for wearables [31].

IoT solutions use various communication solutions between the IoT module and the platform, such as LTE-M, LoRaWAN, NB-IoT, ZigBee, Z-Wave, Bluetooth / BLE, Sigfox, NFC, 6LowPAN, IEEE 802.11af (White-Fi), IEEE 802.11ah (HaLow), 2G/3G/4G/5G cellular [12][32]. These technologies are already implemented in vehicular communications by using the communication and identification layer of IoT platforms, which can also enhance traffic efficiency by enabling services with other communication scenarios in case of partial unavailability of services such as Internet accesses and cloud computing.

The power of the 5th generation (5G) cellular network connectivity with the broadest possible applications can be considered the gateway to the ubiquitous vehicular network access and V2X scenarios integration. This will enable vehicles to access any remote resources using coverages of 5G supported architectures to be connected to new radio technologies with ultra-low latency and high reliability [33]. In addition to that, 5G will provide a unified communications platform for the IoT, which extends the mobile communication services for heterogeneous devices offering the 5G ecosystem to be integrated with C-V2X and support Internet-of-Vehicle (IoV) use-cases [34].

There is always a question about how the fifth generation of mobile cellular technology will involve our life in the future, especially in V2X and IoT. Regarding the Internet of Things, 5G will provide enough bandwidth to include an enormous number of devices that can communicate with each other. Still, this ability is not a new feature compared to IoT, but the unique privilege is to connect almost unlimited devices on the same 5G network. The combination and development of IoT and 5G automatically leads to the IoV era by providing very low latency within 5G NR vehicular communications, robust traffic management, and collision avoidance probabilities [35].

The automotive industry keeps tracking the new techniques introduced for future V2X by cooperating with the 3GPP and enhancements provided on parts of 5G releases. This evolution requires V2X upgraded systems and technical designs except for native support by the 5G network to create valuable services and application scenarios such as vehicle platooning, dynamic ride sharing, remote driving, and collaborative environment perception. Implementing 5G with different V2X layers will introduce the next generation of network systems with several challenges, such as control signaling among vehicles and interference management [36].

These advantages provided by 5G [37] can reduce the latency to near zero and use the most critical digital payloads with high security. In addition to that, 5G can give us accurate in-time solutions in mobility and connected devices, especially in V2X such as 5G smart roads, to recognize critical indicators of an accident and trigger actions to alert the connected vehicles. Also, 5G provides additional privileges in the V2X industry, such as continuous coverage along tracks in high-speed trains and highways, enabling reliability and availability with low latency under high speed with full utilization traveling 500 kilometers per hour. 5G can give imagination about the future of V2X where autonomous vehicles do not require stoplights. The infrastructure provides self-reports such as potholes in the road, connected smart stop and street lights and intelligent parking in the urban, and proactive notification about services needed for vehicles and sent to the driver for scheduling a time in the calendar smartphone maintenance service time [38].

Vehicle manufacturers and automakers are planning and racing for developing future electric and autonomous vehicles. E.g., Ford and Mercedes are implementing 5G and IoT health technology by using in-seat sensors and infrared cameras to enable built-in health monitoring systems which can measure body temperature and monitor vital signs for drivers and passengers as well such as blood pressure and heart rate on the dashboard of the vehicle. Then they send the collected data by using 5G technology to the cloud for analysis, which could help be proactive and prevent unexpected incidents such as heart attacks by alerting the driver about any abnormal health events that could be occurred during the driving. The system could even stop the vehicle if required. Also, it is able to inform the emergency directly about the situation and the location, followed by the transmission of the vital data to a medical center to provide a clear vision of the driver or passenger's health [39] [40].

V. IoT and V2X convergence in recent C-ITS projects

In the last few years, governments worldwide have implemented significant improvements in the ITS/C-ITS domain. Vehicle manufacturers were also able to introduce communication techniques to improve roadway safety and effectively manage traffic flow in the longer run. These active deployments allocated in different geographical areas or regions involve two different technologies: C-ITS (Europe – ITS-G5) and DSRC (U.S. – WAVE) based on IEEE 802.11p protocol. The European Cooperative Intelligent Transport Systems (C-ITS) activities are continuously sharing the experience and knowledge about the implementation of these modes between member states. The U.S. Department of Transportation (USDOT), which is a federal Cabinet department of the U.S. government concerned with transportation, also manages several ITS projects and publishes results periodically [41]. These deployment activities also rely on IoT platforms or parts of them, such as cloud or edge computing or data management. In the following sections, we will introduce recent C-ITS/V2X deployment projects in different areas worldwide with their implementations, expectations, and future enhancements that will apply to these projects in a converged IoT/V2X ecosystem (**Table 2**).

1. CROCODILE

The CROCODILE corridor was conceived in 2013 and comprised road network elements of 13 Central and Eastern European countries with different network characteristics and crosses bi-national borders at more than 15 locations to increase road safety and efficiency along the corridor motorways [42]. Public authorities, road administrations, and traffic information service providers from different member countries cooperate to make the infrastructure more efficient in data and information exchange between public and private stakeholders. The primary goal is to provide information services in the whole corridor for the end-users and cross-border travelers. The core activities of CROCODILE are represented in data collection, processing, access, and end-user services. The CROCODILE platform had challenges with the gaps in traffic monitoring and management, which introduced to CROCODILE 2 to include traffic and road data exchange, implementation of National Access Points, which have been established by the delegated regulations between member states, cross-border agreements, and traffic management plans. The CROCODILE solution depends on the infrastructure and can be used by drivers and pedestrians through highway applications and crossing between the borders along the corridor. The IoT implementation related to the project is presented in the deployment of equipment to provide data collection (such as CCTV and sensors) and traffic management centers for improving infrastructure for data processing - which is one of the focus topics in the CROCODILE 2 project [43].

2. C-ROADS

C-ROADS is a C-ITS platform co-funded through the 2015 call of the Connecting Europe Facility (CEF) and implemented in 43 European cities, 16 European countries' core members, and associate members Australia and Russia [44]. The deployment model of C-ROADS consists of group C-ITS Actors represented as organizations or entities. The mission is to operate C-ITS stations and/or provide C-ITS services through the information-sharing network using AMQP (Advanced Message Queuing Protocol) broker(s). In addition, they plan to use Hybrid C-ITS, which enables multiple communication channels for transmission of C-ITS messages with conditions of the policy, location and requirements set [45].

The purpose of the model is to create cooperation on all deployment levels of C-ITS and different stakeholders. Because of various country regulations and incoherence in the implementation issues, the member states should detect and address these challenges and evaluate them to reach interoperable C-ITS services in all C-Roads member states [46]. C-roads is built to send and receive messages between vehicles (V2V) or between vehicles and infrastructure (V2I) with various services known as "Day-1-services" encompassing messages about hazardous location notification, signage application, road-works warning (RWW), and infrastructure-related data [47]. The noticeable challenge in C-ROADS is implementing the platform in different countries could be led to interference, such as ITS-G5 frequency should not interfere with older systems and regulations in member states and implement and support other vehicular communications use cases such as V2P. C-ROADS implemented complete IoT platforms as parts of the project's system architecture, starting with on-board units (OBU), representing the sensors in vehicles, and Road site units (RSU) which sent/receive data such as C-ITS messages. After that, the collected data transfer to central systems for processing and distribution due to the Integration Platform (IP), responsible for collecting C-ITS messages from each back office and forwarding these messages to the other associated members [48].

3. NordicWay

NordicWay was a three-year (2015-2017) real-life deployment pilot established to test cellular C-ITS services' interoperability in the whole NordicWay network, including 4 Nordic countries: Denmark, Finland, Norway, and Sweden [49]. NordicWay provides services for both passenger and freight traffic. In the NordicWay environment, vehicles indirectly communicate via cellular communications as the underlying communication infrastructure. NordicWay was followed by broader deployment in the Nordic countries and Europe (NordicWay2 and C-ROADS Platform).

NordicWay provided "Day-1-services" such as hazard warning services through cellular networks. After that, NordicWay2 was established to offer interoperable Day-1 and Day 1.5 C-ITS services and support infrastructure readiness for connected and automated driving such as enhance traffic safety, support cloud to cloud hybrid communication, and contribute to European CCAM (Cooperative, Connected and Automated Mobility) harmonization through C-ROADS. Last year, NordicWay 3 - Urban Connection was signed by the partners and the E.U. in Eindhoven in June 2019. One of the objectives for pilot deployment in NordicWay and NordicWay2 projects is an IoT platform implementation for support infrastructure readiness for connected and automated driving and scaling up C-ITS services by supporting cloud-to-cloud hybrid communication from the upper layer of this IoT platform [50].

4. Scoop@F

SCOOP is a project for C-ITS pilot deployment launched in (2014-2019) in France to connect 3,000 vehicles with 2,000 km of road network with various typologies to improve road safety and efficiency. The first part (2014-2015) was related to ITS-G5 and priority services such as Day-1 C-ITS services. The second part (2016-2019) was about hybrid cellular/ITS G5 and additional services, such as enabling large-scale deployment and contributing to C-ITS interoperability in the E.U. [51]. The SCOOP@F system has been developed with vehicle manufacturers to build a robust backend architecture, including a traffic management system to enable automated driving and react to road conditions adaptively. ITS central station contains SCOOP IoT platform connecting to the roadside unit infrastructure, road operator On-Board Unit (OBU), or User On-Board Unit [52]. The closing of the SCOOP project took place on November 20th-21st, 2019, in Bordeaux. The next step for the project is testing the interoperability among different systems by using the SCOOP@F system with other countries and existing C-ITS implementations [53].

5. SAFER -LC

SAFER-LC (Safer level crossing by integrating and optimizing road-rail infrastructure management and design) is an E.U. project started on May 1, 2017, with durations three years composed of 17 partners from 10 different countries represented in railway infrastructure owners, road and railway operators, academic research centers, universities, and industry suppliers. SAFER-LC provides safety monitoring systems and advanced mobile communication technologies, including the use of IoT platforms parts such as CCTV and cooperative communications to develop innovative solutions [54]. The main objectives of SAFER-LC, including firstly, developing innovative solutions to enhance the safety of level crossing for road and railway users. After that, demonstrate new technologies and solutions that can be integrated and provide the required performance and manage the level crossing the user's perspective and behavior. Finally, deliver these solutions for implementation and develop a toolbox with a user-friendly interface to help both rail and road managers to improve the safety at level crossings [55].

6. AUTOPILOT

The AUTOPILOT (AUTOmated driving Progressed by Internet Of Things) project is a pilot of the IoT European Large-Scale Pilots (LSP) Programme. LSPs Programme launched in 2016 to apply IoT approaches and deployment of IoT solutions through the integration of advanced IoT technologies. The LSPS includes seven pilots dependent on addressing the IoT applications based on European relevance.

These pilots are: (1) ACTIVAGE for breaking barriers for sustainability Active and Healthy Ageing through IoT technologies, (2) IOF2020 for IoT deployment with strengthening the competitiveness of farming and food chains in Europe, (3) MONICA for sound and security solutions for large open-air events in the smart city, (4) SYNCHRONICITY for creating single digital city market of Europe, (5) U4IoT for actively engage end-users and citizens to achieve IoT societal acceptance, (6) CREATE-IoT to stimulate collaboration between IoT initiatives, by supporting the development and growth of IoT ecosystems based on available technologies and platforms, and finally, (7) AUTOPILOT to unlock the potential of IoT to participate the next level of autonomous driving [56].

AUTOPILOT was concluded between 2017-2019 with the cooperation of 45 partners from 14 European countries and one from South Korea to increase traffic safety and create new opportunities for mobility services. AUTOPILOT was initiated to expect that automated vehicles will be part of the IoT revolution because IoT connectivity is expected to have essential impacts on highly and fully automated driving generations [57].

AUTOPILOT used IoT-enabled autonomous driving vehicles in a connected real-life testbed environment at large-scale pilot sites in the Netherlands, Italy, France, Finland, Spain, and South Korea. The focus was on safety-critical aspects of automated driving and providing valuable services such as autonomous car sharing, automated parking, and building better digital maps for autonomous vehicles [58].

7. InterCor

Interoperable Corridors (InterCor), an innovative European project, was established in 2016 and ended in 2019, co-financed by the European Union under the Connecting Europe Facility (CEF) 2014-2020 had 16 project partners. The project aimed to connect and create Interoperable Corridors linking the C-ITS corridor initiatives of the Netherlands C-ITS Corridor, the French corridor defined in the SCOOP@F project, and extended to the United Kingdom and Belgian C-ITS initiatives. The goal was to enable interoperable cross-border C-ITS services through ITS-G5, cellular, and hybrid communication within the four-member states and tested by several test fests with vehicles from different member states and others driving on each other's test sites [59].

InterCor was established to achieve a sustainable network of corridors providing continuity of C-ITS services and offering a testbed for beyond Day 1 C-ITS service development. The project members worked together to develop and test effective new services for road users on highways, such as road works warning, truck parking, green light optimal speed advisory, and multimodal cargo transport optimization. The international cooperation of InterCor relying on the combined technologies within the project proved that safer and more efficient mobility is achievable. For IoT aspects, InterCor used road infrastructure for exchange data and connectivity between the project members, which enable heterogeneous IoT platforms to communicate and achieve the proposed results from the project [60].

8. DRIVE C2X

DRIVE Car-to-Everything (C2X) project started in 2011 and finished in 2014. The project was supported by the European Union and had 33 partners and 13 associated partners. The main goals of DRIVE C2X were accelerating cooperative mobility and creating European references for cooperative driving by bringing together seven national test sites in Germany, France, Finland, Italy, Netherlands, Spain, and Sweden for enabling a consistent Europe-wide testing environment [61].

The project aimed at operational field tests using the cooperative driving reference system to enable reliable results under real and various conditions, providing valuable and accurate information about road safety and efficiency and the environmental and economic benefits of cooperative driving for public users and decision-makers. DRIVE C2X succeeded in accomplishing the C2X system prototyped and evaluated under real-life conditions with European-wide interoperability. The project results positively impacted safety, such as In-Vehicle Signage speed limit could reduce, on average, 23 % in fatalities and 13% in injuries, and weather warning leads to 6% fewer victims and 5% fewer injuries. Moreover, the positive impact also appeared on efficiency, environment, and user acceptance. The impact of in-vehicle signage grows with penetration rate, and green light optimal speed advisory reduced the fuel consumption and CO2, and 9 out of 10 test users liked the cooperative system. They wanted to use it if it were available on their vehicles [62]. The IoT aspects are not so apparent in Drive C2X. However, one of the project's primary goals was to collect massive data from various resources and help the drivers making the best decision. This mission will not be successful without involving IoT privileges.

9. Other European C-ITS activities

Other deployments or activities aimed to enable road safety, efficiency, cooperative services, and save people's lives. For instance, Cooperative, Connected, and Automated Mobility (CCAM) is a platform to enable the C-ITS in the European union by testing and exchange experiences from current pilots and discovering the issues related to achieve full convergence of all developments [63].

European Corridor – Austrian Testbed for Cooperative Systems (ECo-AT) is an Austrian project established to create ITS applications with partners Netherlands and Germany to build cooperation between industry manufacturers and road operators for C-ITS services deployment. The project ECo-AT had two phases: the first phase for cooperative services tested and in the second phase: these services and systems have been implemented [64].

Moreover, there are several other deployments, projects, or groups established for a long time to achieve and build successive automotive innovations. E.g., PROgraMme for a European Traffic of Highest Efficiency and Unprecedented Safety (PROMETHEUS) from 1986 to 1994 to build the basis of cooperative ITS and automated driving, or the Safe Intelligent Mobility Test field Germany (simTD) project from 2009 to 2013 for cooperative V2X intelligent communication systems testing and development to achieve road safety and mobility enhancements [65]. Furthermore, Amsterdam Group to achieve and improve road safety and mobility depending on European-wide deployment of C-ITS based on cooperative V2V and V2I communications.

There are still unlimited deployments globally, especially in Europe, to improve and support C-ITS applications and services such as European Standardization Mandate M/453 to support the Interoperability of Cooperative Systems for Intelligent Transport in the European Community [66]. For IoT aspects in relation with these various projects from the past until now, we noticed that IoT appears either in part or the whole project and helps to achieve the proposed goals more accurately by using IoT platforms with the advantage of connectivity or by using IoT devices which are built-in infrastructures and foundations of these projects and most significant key enablers for them.

10. USDOT C-ITS Deployment Projects

USDOT deployment approaches in NYC, Tampa, and Wyoming use Traffic Management Center with IoT management tools to interact with the traffic control. The collected data will be processed and normalized before transmission to the USDOT for additional evaluation. The differences between these approaches could be addressed in the focused objectives and applications or services provided, such as NYC only has Stationary Vehicle Ahead (SVA) application. In contrast, Tampa (THEA) focuses more on traffic monitoring and optimization than Wyoming, which focuses more on Situational Awareness, such as weather warnings [67].

A. NYCDOT Connected Vehicle Pilot

The NYCDOT is led by the New York Department of Transportation, which began in 2015 and aimed to enhance pedestrians' and drivers' safety by deploying Connected Vehicle (CV) technologies. NYCDOT's objective is reaching Vision Zero goals, which mainly focused on safety applications that rely on V2P, V2V, and V2I communications. These applications' mission is to provide warnings and alerts to road users, enable them to take action in emergency cases, save pedestrians, or reduce injuries or damages to infrastructure and vehicles. The NYCDOT project pursues to encourage auto manufacturers to ideal opportunity to evaluate and create models outfitting the CV technology and safety applications and invest and use Dedicated Short-Range Communication (DSRC) [68]. The deployment of NYCDOT CV Pilot includes approximately 310 signalized intersections for V2I technology, 8 RSUs along the higher-speed way, and 36 RSUs at other strategic locations throughout the city in addition to 8000 equipped vehicles. For pedestrians, approximately 100 users with personal devices that help them safely cross the street receive alerts from Roadside Equipment (RSE) [69]. The project uses an IoT platform architecture to analyze collected data, signals, and vehicles to store in the Traffic Management Center (TMC), then forward to a data processing center and send information to USDOT for evaluation purposes.

B. Tampa DOT Connected Vehicle Pilot

Tampa-Hillsborough Expressway Authority (THEA), known as Tampa (THEA) Pilot, is another project for USDOT that began in 2015 to address urban congestion and use connected vehicle technology in Tampa's Downtown. THEA pilot deployed various V2V and V2I applications such as Rush Hour Collision Avoidance, Pedestrian Safety, and Traffic Flow Optimization. The THEA CV Pilot includes approximately 47 RSUs and 1020 equipped vehicles with On-Board Unit (OBU) use DSRC 5.9 GHz utilized as communication technology in addition to 12 V2V, V2I, and V2P applications [70]. The project integrates IoT and V2I by collecting information from the road environments and transmitting the gathering date to RSUs then for performance measures [71].

C. Wyoming DOT Connected Vehicle Pilot

WYDOT CV Pilot was deployed in 2015 in I-80 Corridor in the State of Wyoming in the U.S., a critical freight corridor located between the United States, Canada, and Mexico. The WYDOT CV Pilot's objective is to improve the safety road for commercial vehicles and reduce weather-related incidents. WYDOT deploys DSRC communications-based applications that leverage V2V and V2I connectivity. It uses approximately 75 RSUs, and 400 equipped vehicles with OBUs and mobile weather sensors [72]. The usage of IoT in the WYOMING pilot project represented in the deployment of connected vehicles technology on partner vehicles, OBUs, RSUs in terms to transfer collected data to TMC systems [73].

11. Other Relevant C-ITS Projects Around The World

The efforts on the development and deployment of C-ITS environments keep going not just in Europe and the USA but also in the majority of the world's other countries as well. Good examples are The Ministry of Land, Infrastructure, and Transport (MOLIT) C-ITS program in South Korea, the C-ITS Program for Japan's highway system, and Austroads in Australia and New Zealand, South Korea, and Japan [74].

Austroads is the strategic plan from 2020 to 2024 that contains transport agencies from Australia, and New Zealand cooperated in providing information, tools, and services for these agencies' members to achieve reliable, efficient, and safe mobility to their customers. Austroads focusing on solving problems related to transportation systems for members and their customers. For members, Austroads works on optimizing the infrastructure and benefits of new technologies, improving the safety of road users and workers, achieving sustainability by reusing materials, reducing emissions, and mitigating the impacts of climate change. For customers, Austroads provide services related to decision making depends on the power of data collected, optimizing transport investment, and understanding the customer's needs [75]. For IoT aspects, Austroads uses IoT platforms and devices represent in vehicle manufacturer information systems, accident information retrieval systems, navigation, and driver assistance devices, Bluetooth and cellular devices, and electronic tags [76].

12. C-ITS Projects with 5G Technology

The nature of the convergence phenomena between IoT and V2X technologies enables C-ITS projects implementation to provide valuable services by using most modern technologies such as 5G. A recent deployment effort for 5G in the relation of IoT and V2X could be given with the results of the 5GCAR project, which is a collaboration of 14 partners such as HUAWEI, ERICSSON, and NOKIA to evaluate different use-cases and perform demonstrations. The 5GCAR project testbed was built on the UTAC-TEQMO track in France in 2019 with a 5G architecture for vehicular automotive use-cases. The system's core features consist of 5G NR sidelink communication, 5G NR positioning, and cellular communication using advanced 5G deployment schemes based on Edge Computing and Network Slicing [77].

5GCAR uses an IoT platform, which includes a maneuver planning system which applied in a lane merge coordination use-case to optimize the merging process for vehicles joining the way by sent information from the central maneuver planning system to connected vehicles, besides, to collect information from roadside cameras about unconnected vehicles to provide real-time video between nearby vehicles via V2V communication and facilitate safe overtaking maneuver. The connected cars in 5GCAR, which use Lidar sensor, then send the collecting information, which consists of data estimating the position and the speed of detected vehicles to the server infrastructure known as V2I in the IoT platform. The server predicts vehicles' trajectories in real-time by analyzing this information, estimates the expected collision risk, and warns the affected drivers to safely and comfortably avoid the collision. Another important feature and use case in 5GCAR is about road user protection system that distinguishes and detects the pedestrian crosses the street behind an obstacle and stops the vehicle where the pedestrian is close to it and alert the driver about collision warning before [78].

There are also 5G V2X deployment projects around the world in connection with IoT, such as 5GCroCo [79],5G-DRIVE [80], Wuxi Internet of Vehicle (C-V2X) project was deployed by Huawei on a city-level C-V2X network in Wuxi in China [81]. In the USA, the first C-V2X Connected Car Technology Trials were announced in 2017 in San Diego for demonstrating the potential of C-V2X technologies [82].

VI. CONCLUSIONS

V2X can be efficiently supported by a mesh network of connected nodes using wireless communication systems that could interconnect vehicles, roadside units, road smart traffic signals, pedestrians, cloud platforms, home applications, and smart grid infrastructures with the ability to send, receive and transmit signals between each other.

IoT enables an enormous number of devices to have immediate access to information, communicate and collect data from different environments. The gathering data transfers to the upper layer of IoT platforms, promptly to the applications, or to the cloud for computing and data processing to provide a valuable service. The fast-growing IoT paradigm trends adumbrate that IoT will gain higher importance in several industries in the coming years.

Bringing connected vehicles and intelligent IoT environments together makes the approach known as the Internet of Vehicles (IoV) alive. It creates innovative deployment models that enhance the efficiency of traffic, safe driving and opens the way

Table 2. *Recent deployment and R&D activities*

Approach	*Year of Establishment*	*Place and Countries*	*Main Objective*	*User Application*	*IoT aspects*	*Future Work*
5.1 Crocodile	2013	Europe, 13 countries	Data Management End-user services	Yes, mobile application	Data Management	Crocodile2 and Crocodile3: National Access Points
5.2 C-roads	2015	Europe, 16 countries	Day-1 C-ITS services	No, vehicle notification		C-roads2
5.3 NordicWay	2015	Europe, 4 countries	Day-1 and Day 1,5 C-ITS services	No, vehicle notification	Multiservice	NordicWay2 and NordicWay3: Full Day 1,5 C-ITS services.
5.4 Scoop@F	2014	Europe, France	Day-1 C-ITS services and additional services	No, vehicle notification	Interoperability	Interoperability with other countries.
5.5 SAFER -L.C.	2017	Europe, 13 countries	Safety monitoring systems for road and railway safety	Yes, a toolbox for road and railway managers.	Awareness	*
5.6 AUTOPILOT	2017	Europe, 14 countries, and South Korea	Traffic safety and create new opportunities for mobility services	Yes, Safety applications	Use of IoT ecosystems	*
5.7 InterCor	2016	Europe, 4 countries	Day-One C-ITS services	No, just vehicle apps	Proactive	interconnect with Scoop@F and C-roads
5.8 DRIVE C2X	2011	Europe, 7 countries	reference system for cooperative driving in Europe	No	Safety	*

5.10 USDOT Deployment Projects

Approach	*Year of Establishment*	*City*	*Number of Units*	*Main Objective*	*User Application*	*IoT aspects*	*Future Work*
5.10.1 NYC DOT Connected Vehicle Pilot	2015	USA, New York	353 RSU, 8000 Equipped Vehicles	• Vision Zero goal • Safety applications	Yes, 100 pedestrians with mobile applications.	IoT Platform contains Traffic Management Center (TMC) For Achieving Safety And Traffic Efficiency	Eliminating traffic deaths and serious injuries in the city by 2024
5.10.2 Tampa DOT Connected Vehicle Pilot	2015	USA, Florida, Tampa Downtown	47 RSU, ~1,018 Equipped Vehicles	• Traffic Management and Optimization • Congestion Avoidance and Safety improvement during morning commuting hours	Yes, 500 Personal Safety Devices		Eliminating traffic deaths and serious injuries in the city by 2024
5.10.3 NYC DOT Connected Vehicle Pilot	2015	USA, Wyoming, I-80 Corridor	75 RSU, 400 Equipped Vehicles	• Safety road for • Commercial vehicles Weather-warnings	Yes, Drivers of Trucks		Evaluations by USDOT

to tackle several research challenges regarding multimodal mobility, the hybrid/heterogeneous nature of V2X communication technologies, and many other factors.

The mixing of V2X with IoT is a natural evolution step represented in smart mobility applications such as vehicle monitoring and autonomous vehicles, building smart cities such as public warning systems in critical infrastructures to manage different situations, creating smart energy such as future energy grids to charge cars, involving in intelligent manufacturing such as high-performance production comes for collected data and alerting service from intelligent vehicles. In addition to enhancing innovative electronic health use-cases, implementing advanced sensors infrastructure and emergency response systems in cars will also help drive safety. A whole new set of services and applications could arise. Our survey concludes that any C-ITS project relates to IoT aspects which will add huge benefits and privileges to be reliable and operational services.

AUTHOR CONTRIBUTIONS

H. Hejazi: Conceptualization, Theoretical analysis, Writing.

L. Bokor: Supervision, Review and editing.

DISCLOSURE STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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REFERENCES

[1] D. Evans, How the Next Evolution of the Internet Is Changing Everything, Cisco Internet Business Solutions Group (IBSG), (2011). http://115.112.165.74:81/Krishna Akalamkam/digital marketing/articles/The Internet of Things .pdf

[2] B. Umar, H. Hejazi et al, Evaluation of IoT Device Management Tools, ACCSE 2018: The Third International Conference on Advances in Computation, Communications and Services, (2018), pp. 22–26.

[3] A. Napolitano, Implementation of a MEC-based vulnerable road user warning system, Jul. 2019, pp. 1-6. https://doi.org/10.23919/EETA.2019.8804497

[4] E. Torres-Zapata, V. Guerra et al, Vehicular communications in tunnels using VLC, Jul.2019, pp. 1-6. https://doi.org/10.1109/ConTEL.2019.8848500

[5] A. Mai and D. Schlesinger, A Business Case for Connecting Vehicles, April, (2011). https://www.cisco.com/c/dam/en_us/about/ac79/docs/mfg/Connected-Vehicles_Exec_Summary.pdf

[6] S. GSMA, GSMA Connected Living programme: mAutomotive Executive summary, (2012). https://www.gsma.com/iot/wp-content/uploads/2012/04/gsmaconnectingcarstthetechnologyroadmapv2.pdf

[7] SBD, Connected Car Global Forecast 2015, (2015) [cited 2020-06-19]. https://www.sbdautomotive.com/files/sbd/pdfs/536%20connected%20car%20forecast%20ib%2015.pdf

[8] Pwc, Connected car report 2016, PwC 2016, (2016) [cited 2020-06-19]. www.pwc.com/digital

[9] I. Ivanov, C. Maple et al, Cyber security standards and issues in V2X communications for Internet of vehicles, IET Conference Publications, 2018, vol. 2018, no. CP740, pp. 1–6. https://doi.org/10.1049/cp.2018.0046

[10] W. Anwar, N. Franchi et al, Physical layer evaluation of V2X communications technologies: 5G NR-V2X, LTE-V2X, IEEE 802.11bd, and IEEE 802.11p, IEEE Vehicular Technology Conference, 2019, vol. 2019-Septe, pp. 1–7. https://doi.org/10.1109/VTCFall.2019.8891313

[11] S. Datta, J. Harri et al, Integrating connected vehicles in Internet of Things ecosystems: Challenges and solutions, WoWMoM 2016 - 17th International Symposium on a World of Wireless, Mobile and Multimedia Networks, (2016), pp. 1-6. https://doi.org/10.1109/WoWMoM.2016.7523574

[12] K. Kiela, M. Jurgo et al, Structure of V2X-IoT framework for ITS applications, 2020 43rd International Conference on Telecommunications and Signal Processing, TSP 2020, 2020, pp. 229–234. https://doi.org/10.1109/TSP49548.2020.9163539

[13] A. A. Brincat, F. Pacifici et al, The Internet of Things for Intelligent Transportation Systems in Real Smart Cities Scenarios, IEEE 5th World Forum on Internet of Things, WF-IoT 2019 - Conference Proceedings, 2019, pp. 128–132. https://doi.org/10.1109/WF-IoT.2019.8767247

[14] S. Husain, A. Kunz et al, An overview of standardization efforts for enabling vehicular-To-everything services, 2017 IEEE Conference on Standards for Communications and Networking, CSCN 2017, Oct. 2017, pp. 109–114. https://doi.org/10.1109/CSCN.2017.8088607

[15] R. Chitanvis, N. Ravi et al, Collision avoidance and Drone surveillance using Thread protocol in V2V and V2I communications, Proceedings of the IEEE National Aerospace Electronics Conference, NAECON, Jul. 2019, vol. 2019-July, pp. 406–411. https://doi.org/10.1109/NAECON46414.2019.9058170

[16] J. Lozano and T. Mateo, Review on V2X, I2X, and P2X Communications and Their Applications: A Comprehensive Analysis over Time, Sensors, 2019, vol. 19, no. 12, p. 2756. https://doi.org/10.3390/s19122756
[17] J. Choi, V. Marojevic, and C. DIetrich, Measurements and Analysis of DSRC for V2T Safety-Critical Communications, IEEE Vehicular Technology Conference, 2018, vol. 2018-August, pp. 1-5. https://doi.org/10.1109/VTCFall.2018.8691032
[18] R. Jurgen, V2V/V2I Communications for Improved Road Safety and Efficiency, V2V/V2I Communications for Improved Road Safety and Efficiency, SAE, 2012, pp.i-viii.
[19] U.S. Department of Transportation, V2P Devices and Applications, p. 2004, (2005), [cited 2020-06-21]. www.its.dot.gov
[20] WHO, Global Status Report on Road Safety 2018, (2018). https://www.who.int/publications/i/item/9789241565684
[21] A. Hussein, F. García et al, P2V and V2P communication for pedestrian warning on the basis of autonomous vehicles, IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC, Dec. 2016, pp. 2034–2039. https://doi.org/10.1109/ITSC.2016.7795885
[22] K. Lakhtaria, Analyzing Zone Routing Protocol in MANET Applying Authentic Parameter, 2010, pp. 114-118. http://arxiv.org/abs/1012.2510
[23] F. Barsotti, A. Caruso, and S. Chessa, The localized vehicular multicast middleware: A framework for Ad Hoc inter-vehicles multicast communications, WSEAS Transactions on Communications, 2006,vol. 5, no. 9, pp. 1763–1768.
[24] C. Sharma and N. Gondhi, Communication Protocol Stack for Constrained IoT Systems, 2018 3rd International Conference On Internet of Things: Smart Innovation and Usages (IoT-SIU), 2018, pp. 1-6. https://doi.org/10.1109/IoT-SIU.2018.8519904
[25] H. Hejazi, Investigation and Testing IoT Platforms Manufacture and Architecture, Master thesis, Budapest University of Technology and Economics (2018). https://diplomaterv.vik.bme.hu/en/Theses/Investigation-and-Testing-IoT-Platforms
[26] C. Liu, K. Chau et al, Opportunities and challenges of vehicle-to-home, vehicle-to-vehicle, and vehicle-to-grid technologies, Proceedings of the IEEE, 2013, vol. 101, no. 11, pp. 2409–2427, https://doi.org/10.1109/JPROC.2013.2271951
[27] V. Monteiro, J. Pinto, J. Afonso, Operation Modes for the Electric Vehicle in Smart Grids and Smart Homes: Present and Proposed Modes, IEEE Transactions on Vehicular Technology, 2016, vol. 65, no. 3, pp. 1007–1020. https://doi.org/10.1109/TVT.2015.2481005
[28] A. Bustamante, S. Inca et al, Design of a V2V communications antenna based on LTE technology and IEEE802.11p standard, Proceedings of the 2017 IEEE 24th International Congress on Electronics, Electrical Engineering and Computing, INTERCON 2017, Aug. 2017, pp. 1–4. https://doi.org/10.1109/INTERCON.2017.8079710
[29] R. Weber, J. Misener, V. Park, C-V2X - A communication technology for cooperative, connected and automated mobility, 24. ITG-Symposium on Mobile Communication - Technologies and Applications, 2020, pp. 111–116.
[30] H. Abou-Zeid, F. Pervez et al, Cellular V2X Transmission for Connected and Autonomous Vehicles Standardization, Applications, and Enabling Technologies, IEEE Consumer Electronics Magazine, 2019, vol. 8, no. 6, pp. 91–98. https://doi.org/10.1109/MCE.2019.2941467
[31] K. Ahmed, M. Lee, Secure LTE-Based V2X Service," IEEE Internet of Things Journal, 2018, vol. 5, no. 5, pp. 3724–3732. https://doi.org/10.1109/JIOT.2017.2697949
[32] H. Hejazi, H. Rajab et al, survey of platforms for massive IoT, 2018 IEEE International Conference on Future IoT Technologies, Future IoT 2018, Mar. 2018, vol. 2018-January, pp. 1–8. https://doi.org/10.1109/FIOT.2018.8325598
[33] A. Kunz, L. Nkenyereye, J. Song, 5G Evolution of Cellular IoT for V2X, 2018 IEEE Conference on Standards for Communications and Networking (CSCN), 2018, pp. 1-6. https://doi.org/10.1109/CSCN.2018.8581830
[34] C. Storck, F. Duarte-Figueiredo, A 5G V2X ecosystem providing Internet of vehicles," Sensors (Switzerland), 2019, vol. 19, no. 3, p. 550. https://doi.org/10.3390/s19030550
[35] M. Agiwal, A. Roy, N. Saxena, Next generation 5G wireless networks: A comprehensive survey, IEEE Communications Surveys and Tutorials, 2016, vol. 18, no. 3. Institute of Electrical and Electronics Engineers Inc., pp. 1617–1655. https://doi.org/10.1109/COMST.2016.2532458
[36] S. Singh, D2D and V2X Communications, 5G System Design, John Wiley & Sons, Ltd, 2018, pp. 409–449.

https://doi.org/10.1002/9781119425144.ch14

[37] B. Gopal, P. Kuppusamy, A Comparative Study on 4G and 5G Technology for Wireless Applications, IOSR Journal of Electronics and Communication Engineering, 2015, vol. 10, no. 6, pp. 2278–2834.

[38] S. Chen, Vehicle-to-Everything (v2x) Services Supported by LTE-Based Systems and 5G, IEEE Communications Standards Magazine, 2017, vol. 1, no. 2, pp. 70–76. https://doi.org/10.1109/MCOMSTD.2017.1700015

[39] P. Gaudillat, I. Antonopoulos et al, Best Environmental Management Practice for the Public Administration Sector. 2017. https://doi.org/10.2760/202143

[40] E. Strickland, 3 Ways Ford Cars Could Monitor Your Health - IEEE Spectrum, IEEE Spectrum. (2017) [cited 2021-04-05]. https://spectrum.ieee.org/the-human-os/biomedical/diagnostics/3-ways-ford-cars-could-monitor-your-health

[41] W. Fehr, T. Lusco, et al, Southeast Michigan 2014 Test Bed project architecture update: Developing, refining and implementing the USDOT's Connected Vehicle Reference Implementation Architecture, 2014 International Conference on Connected Vehicles and Expo, ICCVE 2014 - Proceedings, 2014, pp. 16–23. https://doi.org/10.1109/ICCVE.2014.7297535

[42] Crocodile, Harmonisation of Data Exchange, Results Of The Crocodile Project, 2016. https://www.its-platform.eu/filedepot_download/1838/5838

[43] Crocodile, IMPLEMENTATION OF HARMONISED INFORMATION EXCHANGE RESULTS OF THE CROCODILE 2 PROJECT, 2019. https://www.its-platform.eu/filedepot_download/1838/6552

[44] C-Roads, Core Members: C-Roads, (2019) [Cited 2020-02-02]. https://www.c-roads.eu/pilots/core-members.html

[45] C. Platform, Specification for interoperability of backend hybrid C-ITS communication, 2019. https://itscorridor.mett.nl/c-its+corridor/Achtergronddocumenten/handlerdownloadfiles.ashx?idnv=1514256

[46] A. Froetscher, B. Monschiebl, C-roads: Elements of C-ITS service evaluation to reach interoperability in Europe within a wide stakeholder network: Validation steps and comparative elements used in a living lab environment in Austria, IEEE Vehicular Technology Conference, Jul. 2018, vol. 2018-June, pp. 1–5. https://doi.org/10.1109/VTCSpring.2018.8417874

[47] C-ROADS, C-ITS deployment takes off, increasing road safety and decreasing congestion, (2019) [cited 2021-02-19]. https://www.car-2-car.org/press-media/press-releases/press-details/c-its-deployment-takes-off-increasing-road-safety-and-decreasing-congestion-80/

[48] Z. Lokaj, M. Srotyr et al, Technical part of evaluation solution for cooperative vehicles within C-ROADS CZ project, 2020 Smart City Symposium Prague (SCSP), 2020, pp. 1-5. https://doi.org/10.1109/SCSP49987.2020.9133885

[49] NordicWay, Deployment Roadmap Recommendations for future work NordicWay, (2017). https://uploads-ssl.webflow.com/5c487d8f7febe4125879c2d8/5c5c02c69c00c4851bedf1cb_NordicWay_Final%20Report.pdf

[50] Nordicway2, (2017) [cited 2020-02-06]. https://www.nordicway.net/

[51] SCOOP@F Part 2, EUROPA - SCOOP@F Part 2 | TRIMIS - European Commission, (2018) [cited 2020-02-06]. https://trimis.ec.europa.eu/project/scoopf-part-2

[52] D. Kountche, J. Bonnin, H. Labiod, The problem of privacy in cooperative intelligent transportation systems (C-ITS), 2017 IEEE Conference on Computer Communications Workshops, INFOCOM WKSHPS 2017, Nov. 2017, pp. 482–486. https://doi.org/10.1109/INFCOMW.2017.8116424

[53] SCOOP, SCOOP Cross Tests : a key step for European interoperability - SCOOP Project : connected road and vehicle (2019) [cited 2020-02-06]. http://www.scoop.developpement-durable.gouv.fr/en/scoop-cross-tests-a-key-step-for-european-a43.html

[54] A. Boniou, About SAFER-LC – SAFER-LC project, SAFER-LC project, (2020) [cited 2020-02-07]. https://safer-lc.eu/about-safer-lc

[55] SAFER-LC, SAFER Level Crossing By Integrating And Optimizing Road-Rail Infrastructure Management And Design, (2017) [cited 2020-02-07]. www.safer-lc.eu

[56] European IoT Large-Scale Pilots, European IoT Large-Scale Pilots Programme Broachure, (2018). https://european-iot-pilots.eu/wp-content/uploads/2018/06/IOT-Booklet-Def.pdf

[57] S. Antipolis, D. Brevi, R. Scopigno, "linksfoundation.com LINKS ACTIVITIES ON VULNERABLE ROAD USERS, (2019). https://autopilot-project.eu/wp-content/uploads/sites/3/2019/03/LINKS-VRUs-activitiesv01.pdf

[58] G. Larini, Autonomous Driving Progressed by oneM2M: The Experience of the AUTOPILOT Project, 2019 European Conference on Networks and Communications, EuCNC 2019, Jun. 2019, pp. 204–208. https://doi.org/10.1109/EuCNC.2019.8801948

[59] Intercor, Validation event InterCor in the Netherlands, pp. 4–5. https://intercor-project.eu/wp-content/uploads/sites/15/2017/10/Factsheet_Intercor-Testfest-DEF.pdf

[60] G. Crockford, B. Netten, P. Wadsworth, Establishing a common approach to evaluating the InterCor C-ITS pilot project, IEEE Vehicular Technology Conference, Jul. 2018, vol. 2018-June, pp. 1–2. https://doi.org/10.1109/VTCSpring.2018.8417875

[61] Mayaivanova, DRIVE C2X 27/06/2014 Deliverable D55.1 Version 2.1 I Report on compliance of DRIVE C2X system and applications with international ITS standards 201 Deliverable D55.1 Report on compliance of DRIVE C2X system and applications with international ITS standard, (2014).

[62] Drive C2X, Drive C2X Project, p. 2, (2011) [cited 2021-02-21]. http://drive-c2x.eu/project

[63] Cooperative Connected and Automated Mobility (CCAM). MDPI, 2020. https://doi.org/10.3390/books978-3-03928-159-6

[64] ECo-AT, European Corridor – Austrian Testbed for Cooperative Systems- Publication Event of Release 1 Documents, (2015). http://eco-at.info/downloads-206.html?file=tl_files/dynamic_dropdown/uploads/Presse/Praesentationen/ECo-AT_Publication%20Event%20of%20Release%201%20Documents_20150115.pdf

[65] Ejct, European Center for Information and Communication Technologies - ejct, (2013) [cited 2020-06-14]. https://www.eict.de/projekte/#project-19

[66] C-ITS, Cooperative Intelligent Transport Systems and Services -Projects, (2019) [cited 2020-06-14]. https://www.car-2-car.org/about-c-its/

[67] K. Hartman, connected-vehicle-pilot-deployment-program, Program Evaluation Survey Plan,(2019). https://rosap.ntl.bts.gov/view/dot/42403/dot_42403_DS1.pdf

[68] C. Vargas, Together for Safer Roads, Anheuser-Busch First to Join NYC Connected Vehicle PilotNew Public-Private Partnership Supports City's Vision Zero Goals – TogetherForSaferRoads, pp. 5–7, (2019).

[69] United States Department of Transportation, Intelligent Transportation Systems - Connected Vehicle Pilot Deployment Program, (2019) [cited 2020-02-03]. https://www.its.dot.gov/pilots/pilots_wydot.htm

[70] DOT Connected Vehicle Pilot, THEA CONNECTED VEHICLE PILOT-FACT SHEET. (2019) [cited 2020-02-03]. https://www.its.dot.gov/pilots/pilots_thea.htm

[71] THEA, Connected Vehicle Pilot, (2019) [cited 2021-04-01]. https://www.fdot.gov/traffic/its/projects-deploy/cv/maplocations/thea-cvp.shtm

[72] ITS Joint Program Office, "WyomingCVPilot_Factsheet," vol. 80, (2016). https://www.its.dot.gov/factsheets/pdf/WyomingCVPilot_Factsheet.pdf

[73] DOT Connected Vehicle Pilot, Wyoming DOT Connected Vehicle Pilot Deployment Program, (2015) [cited 2021-04-01]. https://www.its.dot.gov/pilots/pilots_wydot.htm

[74] THEA, Intelligent Transportation Systems - ITS Deployments, (2019) [cited 2021-04-01]. https://www.its.dot.gov/pilots/cv_pilot_worldwide.htm

[75] Austroads, Austroads Strategic Plan 2020-2024, AP-C29-20 (2020).

[76] P. van Dijk, S. Australia, Privacy Impact Assessment (PIA) for Cooperative Intelligent Transport System (C-ITS) data messages, (2017) [cited 2021-05-14]. www.austroads.com.au

[77] M. Fallgran, On Selected V2X Technology Components and Enablers from the 5GCAR Project, IEEE International Symposium on Broadband Multimedia Systems and Broadcasting, BMSB, 2018, pp. 1-5. https://doi.org/10.1109/BMSB.2018.8436731

[78] M. Fallgren, "White Paper 5GCAR : Executive Summary White Paper 5GCAR : Executive Summary," no. 761510, (2019). https://5gcar.eu/wp-content/uploads/2019/12/5GCAR-Executive-Summary-White-Paper.pdf

[79] G. Vazquez, Deliverable D5.1 Description of 5GCroCo Business Potentials Deliverable D5.1 Description of 5GCroCo Business Potentials Description of 5GCroCo Business Potentials, Marc, (2019) [cited 2021-05-14]. http://www.5g-ppp.eu

[80] F. Ertico, F. Fischer, J. Ferragut, 5G HarmoniseD Research and TrIals for serVice

Evolution between EU and China D4 . 1 : V2X Development and Test Plan, (2019).

[81] HUAWEI, Wuxi Internet of Vehicle (C-V2X) Project Use Cases list - Huawei United Kingdom, www.huawei.com, (2019) [cited 2020-12-06]. https://www.huawei.com/en/industry-insights/outlook/mobile-broadband/lte/use-cases/wuxi-internet-of-vehiclec-project-use-cases

[82] P. Lancia and J. Sinnott, AT, Ford, Nokia and Qualcomm Launch Cellular-V2X Connected Car Technology Trials Planned for the San Diego Regional Proving Ground with Support From McCain | Qualcomm, (2017) [cited 2020-12-06]. https://www.qualcomm.com/news/releases/2017/10/31/att-ford-nokia-and-qualcomm-launch-cellular-v2x-connected-car-technology

ACTA TECHNICA JAURINENSIS
Vol. 15, No. 2, pp. 74-90, 2022
10.14513/actatechjaur.00647

A bibliometric analysis of humanitarian logistics

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Submitted: 02/12/2021 Accepted: 14/04/2022 Published online: 29/04/2022

Abstract: Recent years have seen a surge in interest in humanitarian logistics (HL) research. This study conducted a bibliometric analysis of 894 HL-related studies. The publications were chosen using a combination of keywords from their titles, abstracts and author-supplied keywords from the leading database Scopus. The publications were classified according to their publication year, country of origin, type of publication, most relevant journals, and most influential authors. The review's findings indicate that over a four-decade period, HL research progressed through three distinct stages. In terms of national contribution, the United States of America leads with the most studies published on HL. Additionally, the HL literature is advanced primarily through academic journal articles. The Journal of Humanitarian Logistics and Supply Chain Management is the leading journal in the field, with 148 articles published. The study makes a significant contribution by providing relevant analysis that may inform and guide scholars and researchers as they explore the evolution of HL research and foster networking and collaboration opportunities across multiple institutions.

Keywords: humanitarian logistics; bibliometric analysis; review; disaster relief management

I. INTRODUCTION

During emergencies, humanitarian logistics (HL) is an integral element for providing relief to vulnerable people in regions severely affected by hardship and disaster [1]. According to [2], HL is conceptualized as the "*process of planning, implementing and controlling the efficient, cost-effective flow and storage of goods and materials as well as related information from the point of origin to the point of consumption for the purpose of alleviating the suffering of vulnerable people.*" The main goal of HL is to mitigate the negative impacts of a disaster and effectively respond to the requirements of beneficiaries [3]. Unlike commercial logistics, HL is plagued by different uncertainties and unknowns since demands from disaster regions cannot be predicted [4]. Moreover, HL is more centred on effectiveness than efficiency, even though achieving cost efficiencies is becoming increasingly relevant [5]. The alignment of incentives and goals is essential among partners in HL networks because the effective partnership between the involved stakeholders (e.g., military and humanitarian organizations, local authorities, non-governmental organizations) is necessary for delivering relief [6]. While actors in business logistics operate in an uninterrupted environment and are driven by the profit motive, HL actors face several supply chain interruptions, which require more concerted efforts to save lives and serve vulnerable victims in dire conditions. Therefore, there is a need to effectively manage the multiple distinctive features of HL, including the uncertainty of demand in terms of time, location, type, and size; the unexpectedly high demand volumes of a wide variety of supplies in very short lead times; the high stakes related to the timeliness of deliveries; and the shortage of financial, technological, human, and infrastructure resources [7]–[9].

Recently, HL has attracted significant attention from scholars [10]–[13]. However, a few studies have examined the intellectual structure of this field using bibliometrics. For example, [14] conducts a bibliometric analysis of the humanitarian supply chain using 1152 documents extracted from the Web of Science (WOS) database. The author concludes that HL logistics is a relatively new field and calls for expanding the findings of his study using other renowned databases such as Business Source Premier, Science Direct and Scopus. Similarly, [15] conduct a bibliometric analysis of HL-related studies using citation and co-citation articles in this field. While the authors seek to offer valuable information regarding the knowledge network among the article published in this area, several filters were applied during the literature selection, such as document type and year of publication. [16] carries out a systematic literature review and bibliometric analysis to understand the evolution of scholarly works published in the field of the humanitarian supply chain between 2009 and 2015. The key indicators analyzed by the author are the trends in humanitarian supply chain publications, number of influential papers, top productive authors, top productive institutions, most frequent keywords and citation measures. In another study, [17] perform a bibliometric mapping analysis using many scientific databases except Scopus and excluding non-peer-reviewed literature such as conference proceedings and book chapters. Lastly, [18] conduct a mapping of humanitarian operations literature using bibliometric methods to provide major research topics and clusters covering this research field. Summarizing, the research gaps we revealed from these past studies were the following:

- Lack of studies using the Scopus database as an alternative source of citations to conduct a bibliometric analysis of HL
- Lack of bibliometric analyses considering all sources of literature, both peer-reviewed and non-peer-reviewed literature
- The need to update the HL field on what bibliometric data can be gathered in this research area to confirm or extend the findings of the previous studies and derive novel insights

Given the progress in the literature on HL and the topical richness of this field, this study examines and shows how research on HL has developed over time. Moreover, this study investigates the bibliometric profile of the literature pertaining to HL. The study adopts a bibliometric analysis using data from citations of articles, chapters, books, conference proceedings, and other materials available at the Scopus database to attain these objectives.

This research analyzes 894 documents on HL dating from 1978 to 2020, revealing how the number of publications on HL has evolved. The study considers all research published from 1978 onwards because the earliest research on HL in Scopus is carried out this year.

After the introduction, we present a brief overview of HL literature. Section 3 provides the research method used. Section 4 presents the results of the bibliometric analysis. Finally, Section 5 concludes the paper highlighting the study's limitations and the future directions and opportunities arising from this research.

II. Literature review

Over the last 20 years, the HL field has observed a lot of attention from scholars [19]. Several reasons explain the increasing focus on HL. For instance, HL is based on a combination of service and manufacturing to respond to emergencies at a given point in time [20]. Humanitarian emergencies are characterized by their unpredictable nature and uncertain demand patterns [21], thereby necessitating HL to optimize humanitarian aid and disaster relief efforts [22]. The main goal of HL is to alleviate the suffering of vulnerable people through planning, implementing and controlling the efficient and cost-effective flow of storage emergency supplies as well as related information from the point of origin to the point of consumption [23]. During a humanitarian crisis, several actors may be involved in HL and relief planning, such as citizens, governments, and non-governmental organizations (NGOs) [24]. The role of citizens is to ensure more preparedness for disasters to reduce property damage and save lives [25]. Preparedness is manifested in actions taken in advance of an emergency to build operational capabilities and facilitate effective responses when an emergency occurs [26]. The contribution made by citizens or communities can be a valuable source of economic support that can be harnessed to help victims suffering from a humanitarian disaster [12]. The efforts of citizens in HL cannot be undermined because they take a participatory approach in disaster relief operations and assume the role of first responders during a disaster with or without invitation [27]. [27] argue that local citizens are well-positioned to provide operational support to streamline emergency supplies flow to beneficiaries from local distribution points, working alongside volunteer organizations and official agencies.

The government is also one of the key players in HL. The intervention of government in HL can impact the utility and performance of aid agencies because of its power and authority [28]. To reduce HL complexity and uncertainty, the government can play an influential role in humanitarian spaces by allocating the necessary funds to the relief operations and utilizing their services for capacity building and rehabilitation [29]. In their study, [30] note that the government is the second most crucial stakeholder in HL after the beneficiaries because it mobilizes the funds required, supports the military and paramilitary forces, delivers necessary infrastructure to humanitarian organizations, and facilitates relief missions. For example, in India, the government has made considerable efforts to control situations once disasters have occurred by managing humanitarian supplies, initiating rehabilitation plans for the disaster-affected regions [31], and minimizing the impact of natural disasters [29]. In China, the government has been involved in several disaster relief activities following the SARS infectious disease crisis. [32] posits that the government's role at that time was to speed up the transmission of disaster information. In the USA, the government provided assistance and aids to several nations hit by humanitarian catastrophes such as Haiti [33]. Therefore, governments can alleviate the suffering caused by disasters [34] as they are responsible for invoking protocols and reducing or mitigating the probability of disasters [35].

Several NGOs have dedicated technical support and developed human resources for HL response [36]. According to several studies (e.g. [37]), NGOs serve as vehicles for financial and health assistance for disaster-affected regions. In this context, [38] illustrate that some NGOs like the International Committee for the Red Cross have developed policies to support their field teams in providing care for patients inflicted by a disaster and not expected to survive. In some instances, NGOs have better access to global resources. They can employ their connections to represent vulnerable communities' issues internationally, thereby improving the effectiveness of HL operations [39]. By working together, NGOs can manage disasters more efficiently, facilitate knowledge and resource sharing, and reduce the costs of HL operations [28].

The stakeholders of HL have conflicting interests; however, they are working on minimizing the suffering of vulnerable people. Also, humanitarian actors attribute significant value to HL due to its importance for the effectiveness and speed of response for major humanitarian programs, such as food, water, health, shelter and sanitation [21]. HL is also concerned with allocating scarce resources to complex relief operations in the most efficient manner [40], while serving victims quickly and minimizing the suffering [41]. HL shares some commonalities with business logistics since the basic principle of managing the flow of goods, information, funds remain valid for HL [8]. As such, HL comprises a set of stakeholders who operate in environments featured by irregular and uncertain demand. HL is necessary throughout the different disaster management stages, including mitigation, preparedness, response, and rehabilitation [42]. According to [43], mitigation is any activity aiming to prevent the likelihood of a disaster and reduce its impact during and after the disaster. Through HL, it is possible to apply different measures to prevent a disaster or reduce its impacts in case one occurs. For instance, humanitarian organizations can carry out risk mapping, identify communities' vulnerabilities and capacities for responding to potential hazards based on the available data, and develop plans that address likely scenarios. In the disaster preparedness phase, HL focuses on developing organizational structures, organizing supply chain resources, draft plans, and support training to ensure efficient response if preparedness is called for. Investing in HL for disaster preparedness is crucial because effective preparedness enables to save lives, prevent injuries, reduce property losses and minimizes disruptions [25]. Furthermore, the primary goals of HL in disaster response are to shorten lead times [44], coordinate relief efforts [45], and ensure fast delivery of emergency supplies. Studies anchored in the disaster rehabilitation stage emphasized HL's primitive position as a critical enabler for successful humanitarian interventions and disaster management [25]. HL actions protect against the devastating impacts that a disaster can cause on a country, safeguarding development goals and maintaining the disaster-affected nation [46]. Therefore, HL research is broad in scope, covering multiple stakeholders, diverse themes, and topics that have differing dynamics. It is an emerging field informed by various disciplines and still lacks a holistic assessment and general overview of HL research's status quo. The upcoming sections discuss the research method used and the results obtained from the analysis.

III. RESEARCH METHOD

The term bibliometric was first used in 1969 in the Journal of Documentation [47]. Bibliometric is a broad term that refers to the statistical analysis of publication metadata [48], and it is typically used to evaluate publications and citations that are related to a particular phenomenon. To gain a better understanding of how a scientific domain develops and grows, bibliometric analysis examines the scholarly output and productivity over time. The premise at the heart of bibliometric analysis is that citations are a valid indicator of the impact of publications or academics in a given field of study [49]. In comparison to conventional and systematic literature reviews, bibliometric analysis are objective and free of subjective biases introduced by the researchers as they choose publications [50]. Similarly, it assists in overcoming the inapplicability of traditional review methods for large-scale literature studies. However, bibliometric analysis alone does not capture all of the complexities of scientific impact and research quality [51]. Bibliometric results should be interpreted with caution, as they are not a review of the literature, a qualitative examination of the content, or an assessment of how the knowledge contained in publications is applied in real practice. In conducting the current bibliometric analysis of HL research, this study analyzes the most productive authors, the most relevant journals, the most common type of publication, and the most active countries in the HL field.

Our bibliometric analysis consists of six steps: 1) define the topic under study, 2) select the database, 3) apply the search criteria, 4) retrieve bibliometric data, 5) codify the retrieved data, and lastly, 6) analyze results.

We first identified the database for collecting information based on research gaps found in the HL literature. The study considered Scopus as the adequate scientific database that best met the objectives of the review. Scopus seems to be the most relevant because it is the largest abstract and citation database covering over 20000 peer-reviewed journals, including those published by Elsevier, EmeraldInsight, Springer, Taylor and Francis and Inderscience [52]. The reason for choosing Scopus instead of alternatives such as the WOS is its comprehensive coverage and indexing of logistics and supply chain-related peer-reviewed articles [53]. Scopus is also more accurate than Google Scholar [54] because it maintains better control over the referred publications and the controlled indexing [55].

The first scientific publication on HL appeared in 1978, and this research explored publications up to 2020. Related to the indicators used, quantity refers to the number of documents published on HL. However, quality is reflected in the impact of publication and the number of citations that a publication receives. The final indicator serves to measure the relationships between the reviewed publications in the sample. For this study, we only considered the quality and quantity indicators since our goal was to reveal and measure how HL's scholarly interest has evolved in recent years. During the search for the literature, the following search query was used in Scopus:

TITLE-ABS-KEY ("humanitarian logistic*" OR "humanitarian supply chain*" OR "humanitarian operation*" OR "disaster relief*" OR "humanitarian supply network*") AND (LIMIT-TO (SUBJAREA,"BUSI")) AND (LIMIT-TO (LANGUAGE,"English"))

The search keywords were used in the fields of title, abstract and keywords. Only English publications were retrieved, and the subject areas were limited to business and management. As a result, the search query returned 894 publications, which were retrieved for codification. We encoded the 894 publications using different variables: year of publication, country of publication, type of publication, leading journals, and most influential authors. Analyzing these bibliometric data enables us to observe the scholarly productivity in the field of HL. To conduct the analysis, the codification process took place in September 2020.

IV. RESULTS

The scope of our analysis includes all English publications and countries involved in HL research. The study analyzed all documents published from 1978 to 2020. As there is no temporal restriction, the pool of analyzed literature is significant, given HL's incipient nature.

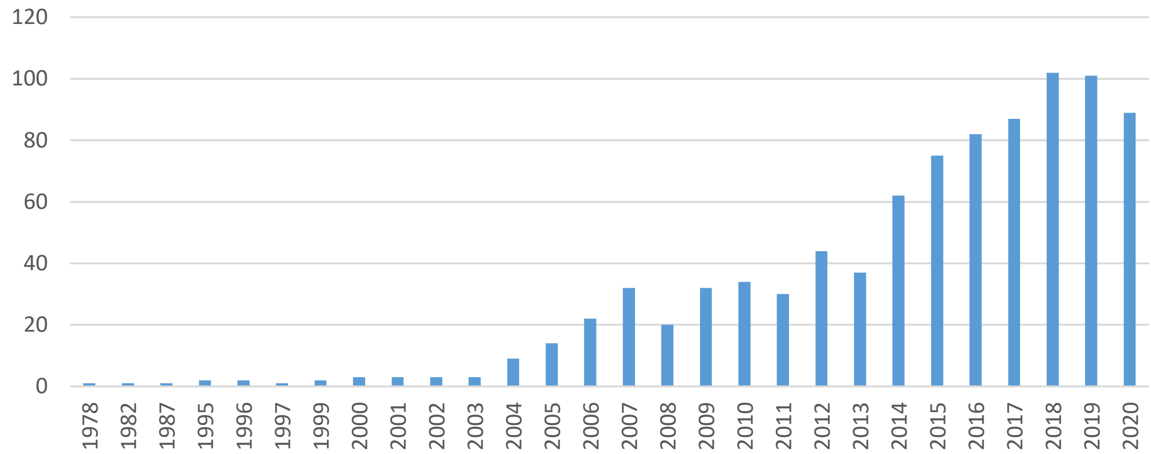

Figure 1*. The number of publications per year*

1. Publications per year

The topic of HL appears in academic research between 1978 and 2020. As can be seen in **Fig.1**, three phases marked the evolution of HL research. The first phase corresponds to the period 1978-2003, which forms the starting point of the HL research. From 2004 to 2013, HL research increased moderately.

However, during the final phase, 2014-2020, the number of HL publications grows considerably and consistently. This exponential increase in the total number of publications from 2014 may owe to the critical role of HL throughout all the stages of the disaster management cycle and its contributions to successful disaster relief missions.

2. The most productive countries in HL research

Table 1 presents the countries where researchers produce the most research output in the HL field. This bibliometric analysis considered different metrics that reflect both the quantity and quality of research output. These include the total number of publications, the number of citations received, the average citations per publication, and the h-index.

As can be observed from the table, the USA leads the race with the most quantity of publications, citations, and the highest h-index. During the period 1978-2020, researchers from the USA published 284 papers with 8011 total citations, 28.21 citations per publication, and an h-index of 47. Frequently, US researchers published their works in US journals (e.g., *Production and Operations Management*), enjoying greater access and opportunity than researchers in other nations. This suggests that the quality of publications should be improved, and further co-authorship cooperation should be promoted.

The next most productive countries are France and the United Kingdom, with 68 publications each. HL research has also gained traction in some developing countries. For example, according to the number of publications, India and China hold the fifth and sixth positions, respectively. At the same time, Iran and Turkey are ranked with 35 and 29 publications at the eleventh and fourteenth position, respectively. Even though developing countries have a considerable research output, their h-index is lower than developed countries on the list. This finding indicates that researchers should focus on the quantity and guarantee and ensure the high quality of HL research output. It is observed that Finland and The Netherlands have been remarkably involved in

Table 1. *Top 15 most productive countries in HL research*

	Country	Number of publications	Number of citations	Average citations per publication	h-index
1	USA	284	8011	28.21	47
2	France	68	3039	44.69	25
3	United Kingdom	68	2147	31.57	25
4	Australia	64	1647	25.73	19
5	India	60	639	10.65	12
6	China	55	551	10.02	13
7	Finland	49	1723	35.16	18
8	Canada	39	768	19.69	15
9	Germany	38	878	23.11	16
10	The Netherlands	37	1105	29.86	16
11	Iran	35	809	23.11	10
12	Sweden	29	497	17.14	16
13	Turkey	29	807	27.83	13
14	Italy	24	265	11.04	10
15	Ireland	21	446	21.24	10

HL research, especially in terms of the average citations per publication. Although these two countries produced fewer papers than some countries on the list, the overall quality of research is very high since Finland and the Netherlands receive higher average citations per publication than many publications from other countries.

3. Publications per type

Table 2 depicts the distribution of HL research according to the type of publications. The sample of records comprises 678 journal articles, 89 conference papers, 54 book chapters, and 43 reviews. This finding suggests that journal articles are the most important source of knowledge dissemination in the HL literature, and they are vital carriers of research results. Through journal articles, researchers would observe the flows of knowledge in the HL field and acquire more validated knowledge.

Surprisingly, the total number of conference papers is meager compared to the total number of journal articles.

This is somewhat contradicting since HL is an emerging field, and conference papers are often dedicated to reflecting the emerging topics and themes, while journal articles take a longer time to publish [56].

It is also more likely that some conference papers are reworked and submitted as journal articles.

4. Most relevant journals

This review identifies 678 articles published in various academic journals. **Table 3** lists all journals publishing at least ten articles. *The International*

Table 2. *Distribution of publications according to type*

Rank	Type of publication	Total number of publications
1	Article	678
2	Conference Paper	89
3	Book Chapter	54
4	Review	43
5	Editorial	8
6	Short Survey	8
7	Book	7
8	Note	3
9	Conference Review	2
10	Erratum	1
11	Letter	1

Journal of Humanitarian Logistics and Supply Chain Management is the most influential outlet for HL contributions. Three academic journals are active devoting more space to HL related studies; *Production and Operations Management* with 48 articles, *Jane's Defence Weekly* with 46 articles, and *Socio-Economic Planning Sciences* with 37 articles. Overall, **Table 3** shows the dominance of *The International Journal of Humanitarian Logistics and Supply Chain Management* and its significant influence and leading position in scientific output. The wide variety of journals in **Table 3** reinforces the fact that HL is a multidisciplinary field attracting scholars from operations management, supply chain management and logistics, production economics, and social sciences.

Table 3*. Most relevant journals*

Journal	Number of publications
Journal of Humanitarian Logistics and Supply Chain Management	144
Production and Operations Management	48
Jane’s Defence Weekly	46
Socio-Economic Planning Sciences	37
Transportation Research Part E: Logistics and Transportation Review	28
International Journal of Production Economics	23
International Journal of Production Research	21
Journal of Operations Management	17
International Journal of Physical Distribution and Logistics Management	13
Journal of the Operational Research Society	10
Lecture Notes in Business Information Processing	10
Supply Chain Management	10

5. Most productive authors

Finally, the review analyzes the influence of the most productive scholars in the HL field. **Table 4** shows that three authors are very active in HL research: van Wassenhove L.N, Tatham P., and Kovacs G. These authors published 33, 31, and 26 papers, respectively.

Table 4. *Most productive authors*

Name of author	Number of publications	Number of citations	Average citations per publication	h-index
van Wassenhove L.N.	33	2288	69.33	18
Tatham P.	31	849	27.39	15
Kovacs G.	26	1457	56.04	13
Heaslip G.	14	170	12.14	5
Dubey R.	11	501	45.55	9
De Souza R.	10	72	7.20	4
Pedraza-Martinez A.J.	10	408	40.80	8
Jahre M.	10	312	31.20	8
Spens K.	10	1070	107.00	6
Lodree E.J.	9	231	25.67	6
Kunz N.	9	276	30.67	7
Apte A.	8	254	31.75	5
Gunasekaran A.	8	463	57.88	8
Besiou M.	8	129	16.13	4
Hanaoka S.	8	48	6.00	5
de Leeuw S.	8	193	24.13	6
Pazirandeh A.	8	132	16.50	7

In terms of citation counts, van Wassenhove L.N stands out from the rest, receiving the highest number of citations, 2288. To a lesser extent, Kovacs G. is the second highly cited scholar with 1457 citations, and Spens K. is the third highly cited author with 1070 citations. Despite having more publications, Tatham P. holds the fourth position according to the number of citations received.

V. Conclusions and Future Research

This bibliometric review reports scientific output evolution in the HL field from 1978-2020 and publications indexed in the Scopus database. The study confirms past research findings in that HL is still an emerging field with a multidisciplinary nature. This review provides a holistic overview of the research progress in the HL field using various bibliometric indicators.

Initially, the review analyzes the evolution of academic publications on HL, revealing three different phases throughout the 40 years of scholarly work in this field. Moreover, the review examines the national productivity, identifying the leading country with the largest number of publications in the USA. This may be explained by the high proportion of journals publishing on HL in the USA. Nonetheless, the high productivity of a country does not often mirror the high quality of research output. Most publications in the reviewed sample journal articles as this format enable authors to disseminate knowledge, promote research, and publish scientific outputs in prestigious academic journals. To inform researchers, this study identifies that the most relevant journal to stay current with HL research is *The International Journal of Humanitarian Logistics* and *Supply Chain Management* with 148 articles, *Production and Operations Management* with 48 articles, and *Jane's Defence Weekly* with 46 articles. The first journal's popularity is explained by its exclusive focus on HL research and the increasing number of submissions to the journal over recent years. The eminent scholars with the largest number of publications on HL are van Wassenhove L.N., Tatham P., and Kovacs G. Being aware of the influential authors in the HL field, researchers would be able to discover the seminal studies reshaping the development of HL research and to create more networking and co-authorship opportunities with authors from the HL field and beyond. The findings of the bibliometric analysis also suggest that HL research still has poor representation in business and management because top-tier supply chain management and logistics journals published few articles over a four-decade period, with only one journal dominating the annual publication output.

Given the critical role that modern technologies such as big data analytics [57], [58], blockchain [59], [60], drones [61], [62], and artificial intelligence [63], [64] play in enhancing not only cooperation and coordination among various HL stakeholders, but also humanitarian processes during disaster response, additional research on the intersection of these technologies and HL is highly recommended. For example, future research may look at how these technological advancements can improve all stages of the disaster management cycle, including preparedness, response, recovery, and mitigation. Additionally, future research may employ a multidisciplinary approach and incorporate well-established theories to assess the impact of emerging technologies on HL.

More precisely, examining how social media platforms such as Facebook, Instagram, and Twitter, plus additive manufacturing, big data analytics, drones, robotics, and artificial intelligence can be used in disaster response is an intriguing and nascent area of research. Indeed, social media platforms have been successfully used at various stages of HL [65]. As an example, Twitter has been successfully used to improve early warning and response to disasters [66]. Facebook has also been used to forecast demand relief products during disaster relief efforts [67]. Potential research directions in this area include an examination of the key issues and benefits associated with the integration of data generated across multiple social media platforms in order to enhance HL activities and decision-making processes. Researchers could concentrate on the impact of big data analytics on HL, as this technology application has been demonstrated to be critical for achieving sustainable disaster management [68], collaborative performance and trust among various HL stakeholders (e.g., NGOs, military organizations) engaged in emergency relief activities [69].

Future research could also focus on the use of drones to map and survey disaster-stricken areas [61], particularly those that are landlocked. This technology is expected to improve disaster response times, aid supply distribution and enhance search and rescue operations.

Additionally, future research could examine how additive manufacturing could be used to rapidly produce critical relief supplies that can be used for shelter and to augment or repair vital infrastructures [70]. Clearly, the growing body of knowledge on additive manufacturing has demonstrated the ability to efficiently produce relief supplies, such as sanitation items and health-related equipment [71]. Additionally, scholars could investigate the value of robots to support disaster relief efforts [61].

With the exception of a few developing countries, developed countries are the most productive contributing to HL logistics. As a result, academic institutions from both developed and developing countries should engage and collaborate to expand this knowledge field. Academic organizations located in disaster-prone areas have the advantage of being on the ground and will have a better understanding of the specific circumstances including the political and social environments and immediate relief needs. The difficulty of collecting empirical data in disaster areas has been identified as a major issue in evidence-based research on HL [72]. More collaborative partnerships with local aid organizations and academic institutions are encouraged in future research efforts to address this challenge.

Despite its contributions, the present study has several limitations. The bibliometric indicators analyzed enable us to obtain a static picture of the HL literature within a particular research period (1978-2020). Furthermore, bibliographic citations need time to accumulate, making backward-looking more biased towards older publications. Therefore, future researchers may conduct co-citation analysis to examine the constant change and development of topics studied in HL. This review does not capture all studies discussing HL because many publications on HL are available in non-indexed journals, which are not available in Scopus. As a result, researchers should consider other databases such as Google Scholar when replicating this bibliometric analysis. The comparison of the results from other databases with those of this review is another intriguing research opportunity.

AUTHOR CONTRIBUTIONS

A. Rejeb: conceptualization, experiments, theoretical analysis.

K. Rejeb: finite element modelling, writing, review and editing.

J.G. Keogh: supervision, review and editing.

DISCLOSURE STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

[1] S. P. Goffnett, O. Keith Helferich, and E. Buschlen, “Integrating service-learning and humanitarian logistics education,” *J. Humanit. Logist. Supply Chain Manag.*, vol. 3, no. 2, pp. 161–186, Jan. 2013, https://doi.org/10.1108/JHLSCM-09-2012-0022

[2] R. M. Tomasini and L. N. V. Wassenhove, “From preparedness to partnerships: case study research on humanitarian logistics,” *Int. Trans. Oper. Res.*, vol. 16, no. 5, pp. 549–559, 2009, https://doi.org/10.1111/j.1475-3995.2009.00697.x

[3] A. Şahin, M. Alp Ertem, and E. Emür, “Using containers as storage facilities in humanitarian logistics,” *J. Humanit. Logist. Supply Chain Manag.*, vol. 4, no. 2, pp. 286–307, Jan. 2014, https://doi.org/10.1108/JHLSCM-08-2013-0029

[4] T. Ashinaka, M. Kubo, and A. Namatame, “A Decision-Support Tool for Humanitarian Logistics,” in *Intelligent and Evolutionary Systems*, Cham, 2016, pp. 293–304. https://doi.org/10.1007/978-3-319-27000-5_24

[5] B. Vitoriano, “Humanitarian Logistics,” in *Handbook of Disaster Risk Reduction & Management*, 0 vols., WORLD SCIENTIFIC, 2016, pp. 745–772. https://doi.org/10.1142/9789813207950_0031

[6] A. Apte, *Humanitarian Logistics: A New Field of Research and Action*. Now Publishers Inc, 2010.

[7] B. Balcik and B. M. Beamon, “Facility location in humanitarian relief,” *Int. J. Logist. Res. Appl.*, vol. 11, no. 2, pp. 101–121, Apr. 2008, https://doi.org/10.1080/13675560701561789

[8] G. Kovács and K. M. Spens, “Humanitarian logistics in disaster relief operations,” *Int. J. Phys. Distrib. Logist. Manag.*, vol. 37, no. 2, pp. 99–114, Jan. 2007, https://doi.org/10.1108/09600030710734820

[9] R. Oloruntoba and R. Gray, “Humanitarian aid: an agile supply chain?,” *Supply Chain Manag. Int. J.*, vol. 11, no. 2, pp. 115–120, Jan. 2006, https://doi.org/10.1108/13598540610652492

[10] M. Aghajani and S. A. Torabi, “A mixed procurement model for humanitarian relief chains,” *J. Humanit. Logist. Supply Chain Manag.*, vol. 10, no. 1, pp. 45–74, Jan. 2019, https://doi.org/10.1108/JHLSCM-10-2018-0067

[11] M. Ahmadi, A. Seifi, and B. Tootooni, “A humanitarian logistics model for disaster relief operation considering network failure and standard relief time: A case study on San Francisco district,” *Transp. Res. Part E Logist. Transp. Rev.*, vol. 75, pp. 145–163, Mar. 2015, https://doi.org/10.1016/j.tre.2015.01.008

[12] A. Behl and P. Dutta, “Social and financial aid for disaster relief operations using CSR and crowdfunding: Moderating effect of information quality,” *Benchmarking Int. J.*, vol. 27, no. 2, pp. 732–759, Oct. 2019, https://doi.org/10.1108/BIJ-08-2019-0372

[13] M. Sharifi-Sedeh, A. Ardalan, S.-A. Torabi, and D. Khorasani-Zavareh, “Factors behind the prepositioning of relief items in Iran: A qualitative study,” *Injury*, vol. 51, no. 4, pp. 906–912, Apr. 2020, https://doi.org/10.1016/j.injury.2020.02.08

[14] S. Fosso Wamba, “Humanitarian supply chain: a bibliometric analysis and future research directions,” *Ann. Oper. Res.*, Apr. 2020, https://doi.org/10.1007/s10479-020-03594-9

[15] B. Zary, R. Bandeira, and V. Campos, “The Contribution of Scientific Productions at the Beginning of the Third Millennium (2001 – 2014) for Humanitarian Logistics: A Bibliometric Analysis,” *Transp. Res. Procedia*, vol. C, no. 3, pp. 537–546, 2014, https://doi.org/10.1016/j.trpro.2014.10.002

[16] S. Bag, “Humanitarian supply chain management: a bibliometric analysis of the literature,” *AIMS Int. J. Manag.*, vol. 10, no. 3, pp. 175–202, 2016.

[17] P. Wanjantuk and R. Banomyong, “Bibliometric mapping of humanitarian logistics research,” 2017.

[18] R. M. S. Nunes and S. C. F. Pereira, “Mapping of Humanitarian Operations Literature: A Bibliometric Approach,” in *Operations Management for Social Good*, Cham, 2020, pp. 351–360. https://doi.org/10.1007/978-3-030-23816-2_34

[19] M. Lauras, J. Vargas, L. Dupont, and A. Charles, “A Location-Allocation Model for More Consistent Humanitarian Supply Chains,” in *Information Systems for Crisis Response and Management in Mediterranean Countries*, Cham, 2014, pp. 1–12. https://doi.org/10.1007/978-3-319-11818-5_1

[20] J. Chandes and G. Paché, "Investigating humanitarian logistics issues: from operations management to strategic action," *J. Manuf. Technol. Manag.*, vol. 21, no. 3, pp. 320–340, Jan. 2010, https://doi.org/10.1108/17410381011024313

[21] D. K. Yadav and A. Barve, "Analysis of critical success factors of humanitarian supply chain: an application of Interpretive Structural Modeling," *Int. J. Disaster Risk Reduct.*, vol. 12, pp. 213–225, 2015, https://doi.org/10.1016/j.ijdrr.2015.01.008

[22] M. Morales and D. E. Sandlin, "Managing airborne relief during international disasters," *J. Humanit. Logist. Supply Chain Manag.*, vol. 5, no. 1, pp. 12–34, Jan. 2015, https://doi.org/10.1108/JHLSCM-01-2014-0008

[23] A. S. Thomas and L. R. Kopczak, "From logistics to supply chain management: the path forward in the humanitarian sector.," *Fritz Inst.*, vol. 15, pp. 1–15, 2005.

[24] S. Kimiagari and B. Montreuil, "Hybrid modeling approach to market deployment planning: an application to a natural disaster relief supply business venture," *Int. J. Prod. Res.*, vol. 56, no. 4, pp. 1675–1707, Feb. 2018, https://doi.org/10.1080/00207543.2017.1359425

[25] A. K. Bardhan and H. K. Dangi, "Drivers and Indicators of Performance in Relief Chain: An Empirical Study," *Glob. Bus. Rev.*, vol. 17, no. 1, pp. 88–104, Feb. 2016, https://doi.org/10.1177/0972150915610693

[26] D. A. McEntire and A. Myers, "Preparing communities for disasters: issues and processes for government readiness," *Disaster Prev. Manag. Int. J.*, vol. 13, no. 2, pp. 140–152, Jan. 2004, https://doi.org/10.1108/09653560410534289

[27] S. Gunessee, N. Subramanian, S. Roscoe, and J. Ramanathan, "The social preferences of local citizens and spontaneous volunteerism during disaster relief operations," *Int. J. Prod. Res.*, vol. 56, no. 21, pp. 6793–6808, Nov. 2018, https://doi.org/10.1080/00207543.2017.1414330

[28] S. Fathalikhani, A. Hafezalkotob, and R. Soltani, "Government intervention on cooperation, competition, and coopetition of humanitarian supply chains," *Socioecon. Plann. Sci.*, vol. 69, no. C, 2020, Accessed: Oct. 05, 2020. [Online]. Available: https://econpapers.repec.org/article/eeesoceps/v_3a69_3ay_3a2020_3ai_3ac_3as0038012118303288.htm

[29] R. N. Garge, H. Ha, and S. Khoo, "Disaster Risk Management and the Role of the Armed Forces: Critical Analysis of Reactive Disaster Management in India," in *Strategic Disaster Risk Management in Asia*, H. Ha, R. L. S. Fernando, and A. Mahmood, Eds. New Delhi: Springer India, 2015, pp. 49–67. https://doi.org/10.1007/978-81-322-2373-3_5

[30] L. John and A. Ramesh, "Humanitarian supply chain management in India: a SAP-LAP framework," *J. Adv. Manag. Res.*, vol. 9, no. 2, pp. 217–235, Jan. 2012, https://doi.org/10.1108/09727981211271968

[31] E. Cohen, "Tourism and Land Grab in the Aftermath of the Indian Ocean Tsunami," *Scand. J. Hosp. Tour.*, vol. 11, no. 3, pp. 224–236, Oct. 2011, https://doi.org/10.1080/15022250.2011.593359

[32] G.-L. Luo, "A research and defects analysis of the disaster relief system of China," *J. Risk Res.*, vol. 17, no. 3, pp. 383–404, Mar. 2014,

https://doi.org/10.1080/13669877.2013.815651

[33] M. Sheller, "The islanding effect: post-disaster mobility systems and humanitarian logistics in Haiti," *Cult. Geogr.*, vol. 20, no. 2, pp. 185–204, Apr. 2013, https://doi.org/10.1177/1474474012438828

[34] A. Cozzolino, "Humanitarian Logistics and Supply Chain Management," in *Humanitarian Logistics: Cross-Sector Cooperation in Disaster Relief Management*, A. Cozzolino, Ed. Berlin, Heidelberg: Springer, 2012, pp. 5–16. https://doi.org/10.1007/978-3-642-30186-5_2

[35] R. Dubey and A. Gunasekaran, "The sustainable humanitarian supply chain design: agility, adaptability and alignment," *Int. J. Logist. Res. Appl.*, vol. 19, no. 1, pp. 62–82, Jan. 2016, https://doi.org/10.1080/13675567.2015.1015511

[36] M. J. V. Rooyen, J. C. Strickler, R. Brennan, and P. G. Greenough, "Challenges of Humanitarian Health Response to Disasters and Crises," *Prehospital Disaster Med.*, vol. 22, no. 5, pp. 349–350, Oct. 2007, https://doi.org/10.1017/S1049023X00005045

[37] N. G. Campos and P. Farmer, "Partners: Discernment and Humanitarian Efforts in Settings of Violence," *J. Law. Med. Ethics*, vol. 31, no. 4, pp. 506–515, Dec. 2003, https://doi.org/10.1111/j.1748-720X.2003.tb00118.x

[38] M. Hunt *et al.*, "Moral experiences of humanitarian health professionals caring for patients who are dying or likely to die in a humanitarian crisis," *J. Int. Humanit. Action*, vol. 3, no. 1, p. 12, Sep. 2018, https://doi.org/10.1186/s41018-018-0040-9

[39] S. A. Adem, P. Childerhouse, T. Egbelakin, and B. Wang, "International and local NGO supply chain collaboration: An investigation of the Syrian refugee crises in Jordan," *J. Humanit. Logist. Supply Chain Manag.*, vol. 8, no. 3, pp. 295–322, Jan. 2018, https://doi.org/10.1108/JHLSCM-05-2017-0020

[40] L. N. V. Wassenhove and A. J. P. Martinez, "Using OR to adapt supply chain management best practices to humanitarian logistics," *Int. Trans. Oper. Res.*, vol. 19, no. 1–2, pp. 307–322, 2012, https://doi.org/10.1111/j.1475-3995.2010.00792.x

[41] M. F. N. Maghfiroh and S. Hanaoka, "Last mile distribution in humanitarian logistics under stochastic and dynamic consideration," in *2017 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)*, Dec. 2017, pp. 1411–1415. https://doi.org/10.1109/IEEM.2017.8290125

[42] F. S. Lima, D. de Oliveira, M. B. Gonçalves, and M. M. A. Samed, "Humanitarian Logistics: a Clustering Methodology for Assisting Humanitarian Operations," *J. Technol. Manag. Innov.*, vol. 9, no. 2, pp. 86–97, 2014, Accessed: Oct. 05, 2020. [Online]. Available: https://dialnet.unirioja.es/servlet/articulo?codigo=4936455

[43] J.-D. Hong and K.-Y. Jeong, "Goal programming and data envelopment analysis approach to disaster relief supply chain design," *Int. J. Logist. Syst. Manag.*, vol. 33, no. 3, pp. 291–321, Jan. 2019, https://doi.org/10.1504/IJLSM.2019.101158

[44] R. D. Swanson and R. J. Smith, "A Path to a Public–Private Partnership: Commercial Logistics Concepts Applied to Disaster Response," *J. Bus. Logist.*,

vol. 34, no. 4, pp. 335–346, 2013, https://doi.org/10.1111/jbl.12031

[45] A. M. Eikenberry, V. Arroyave, and T. Cooper, "Administrative Failure and the International NGO Response to Hurricane Katrina," *Public Adm. Rev.*, vol. 67, no. s1, pp. 160–170, 2007, https://doi.org/10.1111/j.1540-6210.2007.00825.x

[46] K. H. Goldschmidt and S. Kumar, "Humanitarian operations and crisis/disaster management: A retrospective review of the literature and framework for development," *Int. J. Disaster Risk Reduct.*, vol. 20, pp. 1–13, Dec. 2016, https://doi.org/10.1016/j.ijdrr.2016.10.001

[47] A. Pritchard, "Statistical Bibliography or Bibliometrics," *J. Doc.*, vol. 25, no. 4, pp. 348–349, 1969.

[48] R. N. Broadus, "Toward a definition of 'bibliometrics,'" *Scientometrics*, vol. 12, no. 5, pp. 373–379, Nov. 1987, https://doi.org/10.1007/BF02016680

[49] H. Small, "Co-citation in the scientific literature: A new measure of the relationship between two documents," *J. Am. Soc. Inf. Sci.*, vol. 24, no. 4, pp. 265–269, 1973, https://doi.org/10.1002/asi.4630240406

[50] S. Raghuram, P. Tuertscher, and R. Garud, "Research Note—Mapping the Field of Virtual Work: A Cocitation Analysis," *Inf. Syst. Res.*, vol. 21, no. 4, pp. 983–999, Dec. 2010, https://doi.org/10.1287/isre.1080.0227

[51] T. L. Milfont, K. Amirbagheri, E. Hermanns, and J. M. Merigó, "Celebrating Half a Century of Environment and Behavior: A Bibliometric Review," *Environ. Behav.*, vol. 51, no. 5, pp. 469–501, Jun. 2019, https://doi.org/10.1177/0013916519843126

[52] H. Davarzani, B. Fahimnia, M. Bell, and J. Sarkis, "Greening ports and maritime logistics: A review," *Transp. Res. Part Transp. Environ.*, vol. C, no. 48, pp. 473–487, 2016, https://doi.org/10.1016/j.trd.2015.07.007

[53] D. Chicksand, G. Watson, H. Walker, Z. Radnor, and R. Johnston, "Theoretical perspectives in purchasing and supply chain management: an analysis of the literature," *Supply Chain Manag. Int. J.*, vol. 17, no. 4, pp. 454–472, Jan. 2012, https://doi.org/10.1108/13598541211246611

[54] S. H. Zyoud and D. Fuchs-Hanusch, "Estimates of Arab world research productivity associated with groundwater: a bibliometric analysis," *Appl. Water Sci.*, vol. 7, no. 3, pp. 1255–1272, Jun. 2017, https://doi.org/10.1007/s13201-016-0520-2

[55] B. Dinić and T. Jevremov, "Trends in research related to the Dark Triad: A bibliometric analysis," *Curr. Psychol.*, vol. 2019, pp. 1–10, Jan. 2019, https://doi.org/10.1007/s12144-019-00250-9

[56] R. Vatananan-Thesenvitz, A.-A. Schaller, and R. Shannon, "A Bibliometric Review of the Knowledge Base for Innovation in Sustainable Development," *Sustainability*, vol. 11, no. 20, Art. no. 20, Jan. 2019, https://doi.org/10.3390/su11205783

[57] N. P. Nagendra, G. Narayanamurthy, and R. Moser, "Management of humanitarian relief operations using satellite big data analytics: the case of Kerala floods," *Ann. Oper. Res.*, Apr. 2020, https://doi.org/10.1007/s10479-020-03593-w

[58] P. Sharma and A. Joshi, "Challenges of using big data for humanitarian relief: lessons from the literature," *J. Humanit. Logist. Supply Chain Manag.*, vol. 10, no. 4, pp. 423–446, Jan. 2019,

https://doi.org/10.1108/JHLSCM-05-2018-0031

[59] M. Khan, S. Imtiaz, G. S. Parvaiz, A. Hussain, and J. Bae, "Integration of Internet-of-Things With Blockchain Technology to Enhance Humanitarian Logistics Performance," *IEEE Access*, vol. 9, pp. 25422–25436, 2021, https://doi.org/10.1109/ACCESS.2021.3054771

[60] I. G. Sahebi, B. Masoomi, and S. Ghorbani, "Expert oriented approach for analyzing the blockchain adoption barriers in humanitarian supply chain," *Technol. Soc.*, vol. 63, p. 101427, Nov. 2020, https://doi.org/10.1016/j.techsoc.2020.101427

[61] A. Rejeb, K. Rejeb, S. Simske, and H. Treiblmaier, "Humanitarian Drones: A Review and Research Agenda," *Internet Things*, vol. 16, p. 100434, Dec. 2021, https://doi.org/10.1016/j.iot.2021.100434

[62] A. Rejeb, K. Rejeb, S. J. Simske, and H. Treiblmaier, "Drones for supply chain management and logistics: a review and research agenda," *Int. J. Logist. Res. Appl.*, vol. 0, no. 0, pp. 1–24, Sep. 2021, https://doi.org/10.1080/13675567.2021.1981273

[63] O. Rodríguez-Espíndola, S. Chowdhury, A. Beltagui, and P. Albores, "The potential of emergent disruptive technologies for humanitarian supply chains: the integration of blockchain, Artificial Intelligence and 3D printing," *Int. J. Prod. Res.*, vol. 58, no. 15, pp. 4610–4630, Aug. 2020, https://doi.org/10.1080/00207543.2020.1761565

[64] M. Zhao and X. Liu, "Development of decision support tool for optimizing urban emergency rescue facility locations to improve humanitarian logistics management," *Saf. Sci.*, vol. 102, pp. 110–117, Feb. 2018, https://doi.org/10.1016/j.ssci.2017.10.007

[65] N. Bhuvana and I. Arul Aram, "Facebook and Whatsapp as disaster management tools during the Chennai (India) floods of 2015," *Int. J. Disaster Risk Reduct.*, vol. 39, p. 101135, Oct. 2019, https://doi.org/10.1016/j.ijdrr.2019.101135

[66] P. M. Landwehr, W. Wei, M. Kowalchuck, and K. M. Carley, "Using tweets to support disaster planning, warning and response," *Saf. Sci.*, vol. 90, pp. 33–47, 2016, https://doi.org/10.1016/j.ssci.2016.04.012

[67] D. Sarma, A. Das, and U. K. Bera, "Uncertain demand estimation with optimization of time and cost using Facebook disaster map in emergency relief operation," *Appl. Soft Comput.*, vol. 87, p. 105992, Feb. 2020, https://doi.org/10.1016/j.asoc.2019.105992

[68] S. Gupta, N. Altay, and Z. Luo, "Big data in humanitarian supply chain management: a review and further research directions," *Ann. Oper. Res.*, vol. 283, no. 1, pp. 1153–1173, Dec. 2019, https://doi.org/10.1007/s10479-017-2671-4

[69] R. Dubey *et al.*, "Big data analytics and organizational culture as complements to swift trust and collaborative performance in the humanitarian supply chain," *Int. J. Prod. Econ.*, vol. 210, pp. 120–136, Apr. 2019, https://doi.org/10.1016/j.ijpe.2019.01.023

[70] P. Tatham, J. Loy, and U. Peretti, "Three dimensional printing – a key tool for the humanitarian logistician?," *J. Humanit. Logist. Supply Chain Manag.*, vol. 5, no. 2, pp. 188–208, Jan. 2015,

https://doi.org/10.1108/JHLSCM-01-2014-0006

[71] B. L. Savonen, T. J. Mahan, M. W. Curtis, J. W. Schreier, J. K. Gershenson, and J. M. Pearce, "Development of a Resilient 3-D Printer for Humanitarian Crisis Response," *Technologies*, vol. 6, no. 1, Art. no. 1, Mar. 2018, https://doi.org/10.3390/technologies6010030

[72] G. Kovacs, M. Moshtari, H. Kachali, and P. Polsa, "Research methods in humanitarian logistics," *J. Humanit. Logist. Supply Chain Manag.*, vol. 9, no. 3, pp. 325–331, Jan. 2019, https://doi.org/10.1108/JHLSCM-12-2019-082

ACTA TECHNICA JAURINENSIS
Vol. 15, No. 2, pp. 91-98, 2022
10.14513/actatechjaur.00648

Dielectric properties of *Raphia* Fiber from *Epidermis* of young *Raphia Vinifera* leaflet

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Submitted: 03/12/2021 Accepted: 02/05/2022 Published online: 06/05/2022

Abstract: There are materials that could serve useful purpose(s) in many fields, but they are left unutilized due to lack of both the knowledge on their useful properties and availability of values as per such properties. Notably, the knowledge of dielectric properties of some materials of plant origin is lacking whereas such is necessary for industrial, agricultural, electrical, electronics, biophysical and medical applications as well as other uses of a material. In this research, *Raphia Vinifera* is a material of choice. The experimental determination and computation of some dielectric properties of *Raphia* fiber from *epidemis* of young leaflets of *Raphia Vinifera* is explored. The properties considered for determination were dielectric permittivity, loss angle and dissipation factor. A Schering Bridge arrangement was employed, with a fixed thickness and varying areas of sample at various select frequencies. The values of the investigated properties recorded for our research sample trended towards being dependent of frequency. At frequency values above 1 kHz, the values of the properties determined decreased with increase in frequency. The values compared favorably with those of the already known and commonly used dielectric materials. The preliminary investigation showed that *Raphia Vinifera* would have usefulness in the electrical and electronic industries as raw material for the production of capacitor among other uses.

Keywords: Capacitance; Dielectric permittivity; Dissipation factor; Frequency, Loss angle

I. INTRODUCTION

Dielectrics are a class of materials (insulators and high-E_g semiconductors) that show polarization effects (separation of the centres of positive and negative charges) upon the application of an external electric field [1]. The dipole orientation and charge migration in broad frequency, temperature and pressure range can be examined via dielectric spectroscopy [2]. Knowledge upon the dielectric properties of materials can be utilized in several fields of science, engineering and industry including agriculture, biophysics, electronics and electrical industry, and medical applications [1, 2, 3, 4, 5]. The most important and frequently used frequency-dependent dielectric formalisms include though not limited to namely relative permittivity, impedance, ac conductivity and electric modulus [6]. The use of the appropriate formalism is decided depending on the data and the electrical characteristics of the investigated materials. In recent times, the search for electrically-insulating materials has been of great concern with elaborate dielectric factors determining the behavior of such materials.

The use of new bioplastics, green polymers and plant-origin materials is a significant contribution towards a sustainable future [2, 7, 8]. This is achieved by employing economically attractive and environmentally friendly biodegradable materials to increase their disposability [8]. *Raphia vinifera* is commonly known as Bamboo palm while others commonly refer to it as the West African piassava palm, an evergreen tree growing to 6 m that is commonly found in Africa [9, 10]. It is a monocotyledon plant, characterized by solid unbranched trunks having fan-shaped pinnate leaves when fully matured [11, 12]. Each leaf is about twice as long as the stem and may contain as many as 80 to 100 leaflets. The soft silk-like fiber from the epidermis of the tender leaves of the *raphia* palm is an important fiber used locally for weaving of hats, mats, baskets, bags, ropes, and ceremonial costumes. *Raphia vinifera* belongs to the family called *Arecaceae* [13] and it is a native to Benin, Ghana, Nigeria, Gambia, Togo, Central African Republic, Democratic Republic of Congo, and Cameroun. With dielectric measurements, the molecular dynamics and structural behavior can be understood and contribute to the structure-property understanding for such materials [2].

In the present study, the dielectric properties of *raphia* fiber obtained from the epidermis of young leaves of the *Raphia vinifera* plant are presented at room temperature and in a frequency range of 0.10 to 100 kHz, a material that has not been investigated before dielectrically. The aim of this research is to provide data for plausible utilization of the fiber as dielectric material in electrical/electronic industry as well as other purposes it may be deemed fit based on its dielectric data. Since several fibers can be got from each leaf which is mostly discarded as waste, findings from this study will help to solve associated waste disposal problems while ensure sustainable development.

II. Materials and Method

1. Materials

The young leaves of *raphia vinifera*, which were used in this work, were obtained from Ididep village in Ibiono Ibom Local Government Area of Akwa Ibom State, Nigeria. The young leaves were randomly selected and used in this study. The epidermis of the young leaflets were, on arrival in the laboratory, separated from other parts of the leaflets and immediately placed on a flat dry clean transparent glass plate holding the extreme ends with strong adhesive tape to the glass. It was kept very flat and firm on the glass surface to avoid folding itself and kinking when dry. Several epidermises were gotten from many young leaflets and treated using the same procedure applied in each case. The samples were allowed to remain in their positions on the glass plate at room temperature ranging between 27°C and 30°C (monitored with digital thermometer using type-K probe with sensor) for 21 days. This was necessary to allow for complete dryness before the samples were removed from the glass plate. **Fig. 1** shows the *Raphia* (bamboo) palm and also its fiber (when subjected to drying).

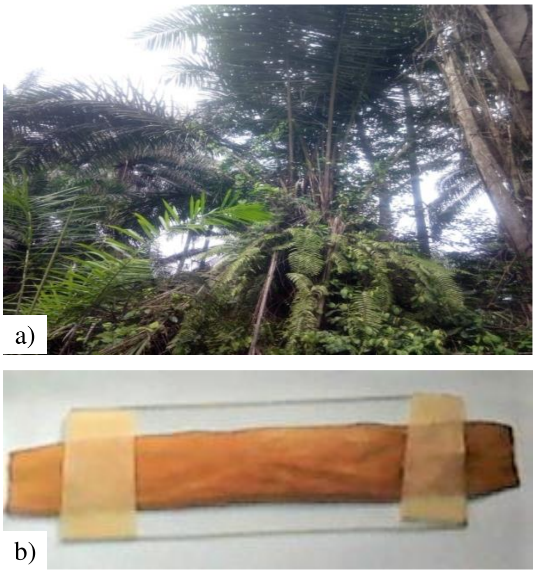

Figure 1. *Photographs of (a) Raphia vinifera palm (b) the raphia fiber under drying*

2. Procedure for measurement of dielectric properties of the *raphia* fiber

A parallel-plate capacitor method employing Schering Bridge [14, 15, 16] was used to determine the dielectric permittivity of the *raphia* fiber in this research work. The fiber was placed between two parallel copper plates, each measuring $4.95 \cdot 10^{-4}$ m^2 in area, A to form a parallel-plate capacitor having electrical conducting leads attached to each plate at their outer surfaces. The formation was weighed down uniformly using a load of about 20N to leave the sandwiched *raphia* fiber with relatively no air gap between the fiber (employed as dielectric material) and the copper plates. Very importantly, care was taken to avoid direct contact between the two copper plates. A synthesized signal generator (Agilent 83732A) as AC source and a dual trace oscilloscope (Model CA620) as a display instrument to monitor the balance point were used with the Schering Bridge arrangement (**Fig. 2**).

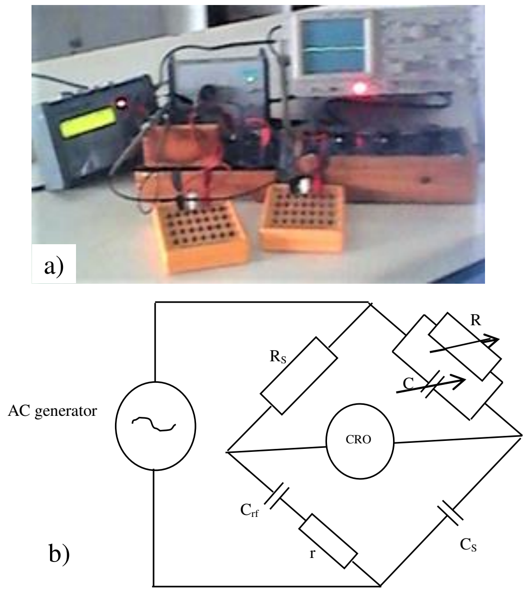

Figure 2. *Setup of Schering Bridge used in the study (a)Experimental photo (b) Schematic diagram*

The procedure was repeated for raphia fiber samples sandwiched between copper plates with areas measuring $4.40{\cdot}10^{-4}$ m^2, $3.63{\cdot}10^{-4}$ m^2, $3.30{\cdot}10^{-4}$ m^2, and $2.75{\cdot}10^{-4}$ m^2 while the thickness, d of the *raphia* fiber sample remained fairly constant (d =0.05mm), measured with digital vernier calipers at several positions along the length with a mean value. The experimental data obtained were employed, to compute the capacitance, dissipation factor, and loss angle of the *raphia* fiber sample at varying frequencies from 0.10 to 100 kHz. The measurement in each case was taken five times after which the mean value was calculated and recorded.

The capacitance, C_{rf}, of the *raphia vinifera* young leaflet fiber was calculated at the balance point of the Schering Bridge, in each case, using the mathematical formula given by several authors including [16]

$$C_{rf} = \frac{RC_s}{R_s} \quad (1)$$

The leakage resistance, r of the capacitor arrangement under test was obtained by employing the mathematical relationship

$$r = \frac{CR_s}{C_s} \quad (2)$$

Dissipation factor, D in each case was computed using the equation

$$D = \omega C_{rf}\, r = tan\emptyset \quad (3)$$

R_s and R are select resistance values from decade resistance boxes, C_s and $C$are select capacitance values from decade capacitance boxes, $\omega = 2\pi f$ (where f is the frequency of the applied AC signal), $\emptyset$ is the loss angle. Dielectric loss is affected by the loss angle, and dielectric loss is an essential element of power factor [17, 18]. It is believed to be determined by the amount of current wave being 90° out of phase with voltage, a phenomenon known as dielectric loss angle.

By employing Origin software, the capacitance, C_{rf} values got at different frequencies versus the area, A were plotted for the *raphia* fibre investigated. The value of dielectric permittivity, ε_{rf} was deduced from the slope of the graph making use of the mathematical relationship as expressed by several authors including [19, 20, 21, 22]

$$C_{rf} = \frac{\varepsilon_o \varepsilon_{rf} A}{d} \quad (4)$$

where d is the common thickness of the *raphia* fiber, ε_{rf} is the dielectric permittivity of the *raphia* fiber investigated, ε_o is the relative permittivity of free space, which is $8.854{\cdot}10^{-12}$ Fm^{-1}.

By substituting for the actual values of d and ε_0 in equation (4), we have

$$C_{rf} = 1.7708{\cdot}10^{-7}\ \varepsilon_{rf} A \quad (5)$$

Every measurement taken was at room temperature of (28 ± 1)°C and relative humidity of 50%. Dielectric constant, otherwise known as relative permittivity values for conventional dielectric materials (as reported) were tabulated for the purpose of comparing with the results of our investigation in this research.

III. Results, Analysis and Discussion

The mean (with standard error) values of capacitance, loss angle, and dissipation factor at different frequencies deduced for the studied sample are shown in **Table 1**. It is evident in the expression that the capacitance of the sample decreases with increase in frequency.

Fig. 3 displays a linear relationship between the mean capacitance values and values of the sample's area at each frequency.

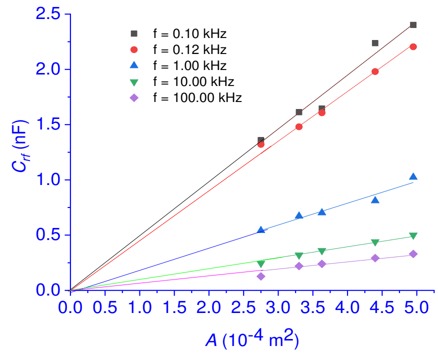

Figure 3. *Variation of Capacitance with the sample's area*

The values of dielectric permittivity were deduced from the slopes of the plots of mean capacitance at each frequency against area. The mean dielectric permittivity also decreases with increase in frequency. This is due to the fact that dipoles have less time (as the frequency progressively increases) to orient with the applied electric field resulting into decrease of real part of permittivity and hence the real part of capacitance. This is confirmed by equations (4) and (5). However, it has been observed that in some cases, dielectric permittivity values at frequencies below 1 kHz do not show significant variation from the values obtained at 1 kHz. This, essentially, means that there is no other dipolar relaxation process at a frequency below 1 kHz. As remarked by Halizan et al [23], good dielectric permittivity material has huge potential in capacitive energy storage devices for electronic applications. It can be clearly seen that loss angle values decrease with increase in frequency. The difference is very slight at frequency range below 1 kHz. It may not be wrong to aver that the value of loss angle is approximately constant for our test sample at a frequency range below 1 kHz.

The loss angle varies with frequency for our test sample. Values for dissipation factor (tan ∅) recorded for sample in **Table 1** reveal decreasing trend with increase in applied frequency. However, the decrease seems to be infinitesimal within the frequency bracket below 1 kHz. This relationship is illustrated using a log- log representation as shown in **Fig. 4**.

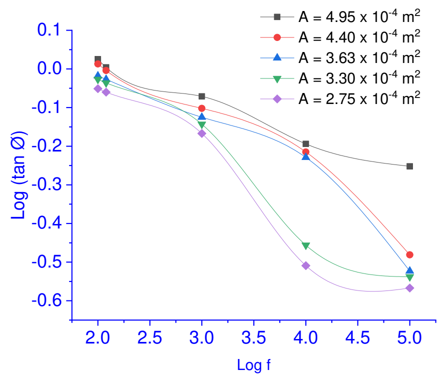

Figure 4. *Log-log representation of dissipation factor versus frequency*

Considering our research sample in terms of dissipation factor within the frequency range investigated, it is better at 100 kHz because the lower the dissipation factor, the better the dielectric is. Considering the trend, it is presumable that dissipation factor for this material will be lower at frequencies beyond 100 kHz, thus resulting in a better dielectric. The values of dielectric permittivity of our research sample at different frequencies are recorded in **Table 2**. It can be seen from the table that at the frequency of 1 kHz, the sample has a dielectric permittivity value of 11.14, but was greater at a lower frequency, thereby showing slight differences within the lower frequencies (below 1 kHz) bracket.

Table 3 shows the dielectric constant values reported in the literature for some commonly used dielectric materials. A dielectric permittivity value of 5.57 is recorded for our research sample at the frequency of 10 kHz. This value is slightly greater than the reported values for Mica (Muscovite) as 5.4; Bakelite as 5.0; Pyrex glass 3320, 7040, 7052, 7060, 7070, 7740, 7750, 7760, being 4.71, 4.65, 4.77, 5.07, 4.70, 4.0, 5.0 – 5.1, 4.28 and 4.5 respectively [24, 26, 28, 29] as seen in **Table 3**. At the frequency of 100 kHz, our investigated sample recorded 3.64 as the dielectric permittivity. This value is about the value of dielectric constant reported for paper (3.5), paper (bond) as 3.0, Mylar (3.2), rubber (3.0 – 4.0), plexiglass (3.4), titanium dioxide (3.0 – 4.0), Sulphur (sublimed) as 3.69 and PVC (3.18). Comparing the values of dielectric permittivity obtained for our chosen research sample within the radio frequency with the dielectric constant values of most of the commonly used dielectric materials as reported in the literature, it is correct to posit that our test sample exhibits a good and high ranking as a dielectric material. The manifestation of anomalous dielectric dispersion exhibited by our tests sample as clearly observed in **Fig. 5** has its support from the report of Vasudeva [24] and that of Salman [35] and Salman et al [36].

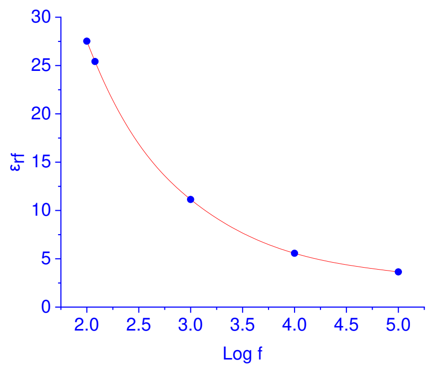

Figure 5. *Sample's dielectric permittivity versus log of frequency*

The value of dissipation factor obtained for the studied sample at the frequencies investigated follows the trend reported by Etuk et al [14] for some select eggshell membranes, which include those of eggs from Hen, Layers, Duck, Turkey, and Quail, which range between 0.173 and 0.350 at frequency of 100 kHz. It can be inferred that at frequency as high as 3 GHz, dissipation factor would also drop towards the range 0.002 to 0.005 even below as in the eggshell membrane. Values reported by Etuk et al [14] are approximately in the range reported by Fink and McKenzie [37] as (0.01 - 0.06), 0.04, (0.07 -0.028) 0.0011, and (0.0011 - 0.0025) for cellulose acetate, nylon 6, nylon 10, hard rubber, and glass mica respectively.

Table 1 *Results of capacitance, loss angle, and dissipation factor determinations for the studied sample*

$f\ (kHz)$	A = 4.95 x 10^{-4} m^2			A = 4.40 x 10^{-4} m^2			A = 3.63 x 10^{-4} m^2			A = 3.30 x 10^{-4} m^2			A = 2.75 x 10^{-4} m^2		
	$C_{rf}\ (nF)$	Ø (°)	Tan Ø	$C_{rf}\ (nF)$	Ø (°)	Tan Ø	$C_{rf}\ (nF)$	Ø (°)	Tan Ø	$C_{rf}\ (nF)$	Ø (°)	Tan Ø	$C_{rf}\ (nF)$	Ø (°)	Tan Ø
0.10	2.402 ± 0.006	46.90 ± 0.32	1.069 ± 0.012	2.237 ± 0.001	45.92 ± 0.04	1.033 ± 0.002	1.646 ± 0.003	44.10 ± 0.06	0.969 ± 0.002	1.612 ± 0.001	43.46 ± 0.02	0.948 ± 0.001	1.360 ± 0.003	41.86 ± 0.10	0.896 ± 0.003
0.12	2.204 ± 0.003	45.46 ± 0.04	1.016 ± 0.001	1.980 ± 0.004	44.94 ± 0.06	0.998 ± 0.002	1.607 ± 0.002	43.34 ± 0.06	0.944 ± 0.010	1.480 ± 0.002	42.80 ± 0.06	0.926 ± 0.002	1.321 ± 0.001	41.12 ± 0.02	0.873 ± 0.001
1.00	1.024 ± 0.002	40.56 ± 0.12	0.856 ± 0.004	0.811 ± 0.004	38.52 ± 0.16	0.796 ± 0.005	0.702 ± 0.002	37.18 ± 0.08	0.759 ± 0.002	0.672 ± 0.002	36.10 ± 0.12	0.729 ± 0.003	0.541 ± 0.002	34.32 ± 0.06	0.683 ± 0.001
10.00	0.500 ± 0.002	32.68 ± 0.06	0.642 ± 0.001	0.440 ± 0.002	31.76 ± 0.08	0.619 ± 0.002	0.360 ± 0.002	30.62 ± 0.08	0.592 ± 0.002	0.320 ± 0.003	19.62 ± 0.16	0.356 ± 0.003	0.245 ± 0.001	17.48 ± 0.04	0.315 ± 0.001
100.00	0.330 ± 0.002	29.34 ± 0.10	0.562 ± 0.002	0.292 ± 0.001	18.50 ± 0.04	0.335 ± 0.001	0.240 ± 0.001	17.14 ± 0.08	0.309 ± 0.007	0.220 ± 0.001	16.26 ± 0.06	0.292 ± 0.001	0.127 ± 0.001	15.20 ± 0.08	0.272 ± 0.001

Table 2 *Dielectric permittivity of the sample at different frequencies*

Frequency, f (kHz)	0.10	0.12	1.00	10.00	100.00
Dielectric permittivity, ε_{rf}	27.52	25.42	11.14	5.57	3.64

Table 3 *Distinctive values of dielectric constant of some commonly used dielectric materials as reported in the literature [14, 24, 25 – 34]*

Material	**Dielectric**	**Material**	**Dielectric**	**Material**	**Dielectric**
Rubber	3.0 – 4.0	Pyrex 7070	4.0	Polysulfones	3.13
Mylar	3.1	Pyrex 7720	4.5	Poly phenylene oxide	2.59
Bakelite	5.0	Pyrex 7740	5.0 - 5.1	Natural rubber	2.6
Paper (bond)	3.0	Pyrex 7750	4.28	Polychloroprene	6.6
Mica	3.0 – 8.0	Pyrex 7760	4.5	Polycrylonitrile	5.5
Paper	3.5	Vycor 7230	3.83	Glass bonded mica	6.3 – 9.3
Teflon	2.1	Vycor 7900	3.9	Soda lime glass	7.2
Air (1 atm)	1.00059 – 1.0006	Vycor 7910	3.8	Cordierite	4.02 – 6.23
Air (100 atm)	1.0548	Vycor 7911	3.8	Fluorocarbons	2.1 – 3.6
Vacuum	1.0	Germanium	16.0	Paraffin wax	2.0
Corning 8877	9.5	Porcelain	6.5	Poly vinylidene fluoride	12.2
Corning 0120	6.65	Plexiglass	3.4	Polymethyl methacrylate	3.12
Corning 0080	6.75	Polyethene	2.25 – 2.60	Polychlorotrifluoroehtyle	2.65
Corning 0010	6.32	Polyvinyl chloride	3.18 – 5.3	Polybutadiene	2.5
Glass	5.0 – 10.0	G.E. Clear (Silica	3.81	Sulphur (sublimed)	3.69 – 4.44
Mica (Canadian)	6.9 – 7.3	Quartz (Fused)	3.75	Polyceram 9606	5.57
Mica (Muscovite)	5.4 – 8.7	Titanium dioxide	3.0 – 4.0	Cellulose acetate	3.5 – 7.5
Pyrex 1710	6.0	Polypropylene	2.2	Alumina	8.0 – 10.0
Pyrex 3320	4.71	Neoprene	6.7 – 16.0	Polycarbonate	2.92
Pyrex 7040	4.65	ABC (Plastic)	2.4 – 3.8	Polyoxymethylene	3.8
Pyrex 7050	4.77	Barium titanate	5.0 - 450.0	Nylon 6 and nylon 10	3.5 – 3.6
Pyrex 7052	5.07	Forsterite	6.2 – 6.5	Borosilicate	4.1 – 4.9
Pyrex 7060	4.7	Hard rubber	2.95 – 4.80	Boron nitrite	4.15

IV. Conclusion

The dielectric permittivity of a material used for separating conductive plates of a capacitor determines the amount of energy that a capacitor can store when voltage is applied. A measure of loss-rate of energy known as dissipation factor of a dielectric material is another determining factor. This factor represents the tangent of the measure of current wave deviation from being 90o out of phase with voltage, designated loss angle.

The values of dielectric permittivity obtained for our study sample (*raphia* fiber from epidermis of young *Raphia vinifera* leaflet) in comparison with dielectric constant values of several already known and commonly used dielectric materials makes our investigated sample an alternative material of choice as dielectric material. The values obtained for the studied parameters give a very strong suggestion that the *raphia* fiber is a potential raw material for capacitor fabrication. *Raphia vinifera* young leaflet epidermis fiber is a biological membrane, though of plant kingdom. It grows well along creeks. The material is environmentally friendly and sustainable. Based on the afore-stated findings, it is highly recommended for electrical/electronic industry utilization. For future research, the influence of temperature on the investigated properties could be examined.

Author Contributions

S.E. Etuk: Conceptualization, Supervision, Writing – Original draft, review and editing.

S.S. Ekpo: Resources, Data curation, Writing - Review and editing.

U.W. Robert: Methodology, Investigation, Writing – Original draft, review and editing,

O.E. Agbasi: Visualization, Resources, Writing - Review and editing.

E.A. Effiong: Resources, Writing - Review and editing.

Disclosure Statement

We have no conflict of interest to declare.

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References

[1] Bonardd S, Moreno-Serna V, Kortaberria G, Díaz Díaz D, Leiva A, Saldías C, Dipolar Glass Polymers Containing Polarizable Groups as Dielectric Materials for Energy Storage Applications. A Mini review. Polymers 11 (2) (2019) 317. https://doi.org/10.3390/polym11020317

[2] Soccio M, Martínez-Tong DE, Guidotti G, Robles-Hernández B, Munari A, Lotti N, Alegria A, Broadband Dielectric Spectroscopy Study of Biobased Poly(alkylene 2,5-furanoate)s' Molecular Dynamics. Polymers 12 (6) (2020) 1355. https://doi.org/10.3390/polym12061355

[3] Bojovschi A, Quoc T, Trung H, Quang D, Le T, Environmental Effects on HV Dielectric Materials and Related Sensing Technologies. Applied Sciences 9 (5) (2019) 856. https://doi.org/10.3390/app905085

[4] Barber P, Balasubramanian S, Anguchamy Y, Gong S, Wibowo A, Gao H, Zur Loye HC, Polymer Composite and Nanocomposite Dielectric Materials for Pulse Power Energy Storage. Materials 2 (4) (2009) pp. 1697–1733. https://doi.org/10.3390/ma2041697

[5] Oliveira JGD, Pinto ENMG, Silva Neto VP, D'Assunção AG CSRR-Based Microwave Sensor for Dielectric Materials Characterization Applied to Soil Water Content Determination. Sensors 20 (1) (2020) 255. https://doi.org/10.3390/s20010255

[6] Dyre JC, The random free-energy barrier model for ac conduction in disordered solids. Journal of Applied Physics 64 (5) (1988) pp. 2456–2468. https://doi.org/10.1063/1.341681

[7] Tuan Naiwi T, Aung M, Ahmad A, Rayung M, Su'ait M, Yusof N, Wynn Lae K, Enhancement of Plasticizing Effect on Bio-Based Polyurethane Acrylate Solid Polymer Electrolyte and Its Properties. Polymers 10 (10) (2018) 1142. https://doi.org/10.3390/polym10101142

[8] Avella M, Buzarovska A, Errico M, Gentile G, Grozdanov A, Eco-Challenges of Bio-Based Polymer Composites. Materials 2 (3) (2009) pp. 911–925. https://doi.org/10.3390/ma2030911

[9] Etukudo I, Forest Our Divine Treasure, Dorand Publishers, Uyo, 2000.

[10] Van Wyk B, and Gericke N, People's Plants. A Guide to Useful Plants of Southern Africa, Briza Publications, Pretoria (2000) p. 352.

[11] Etuk SE, Akpabio LE, and Akpabio KE, Investigation of *Raphia hookeri* Trunk as a potential ceiling material for passively-cooled building design, Ghana J Sci. 43 (37) (2003).

[12] Child R, Coconut, 2nd edn., Longman, Harlow. 1974.

[13] Faba-Tendo J, Etape EP, Krause RWM, Namondo BV, Potential of blended biomass feedstock from species of raffia palm (*Raffia farinifera, Raffia hookeri, and Raffia vinifera*) and oil Palm Empty Fruit Bunch OPEFB from Cameroon. African Journal of Pure and Applied Chemistry 12 (4) (2018) pp. 25 – 33.

[14] Etuk SE, Robert UW, Emah JB, and Agbasi OE, Dielectric Properties of Eggshell membrane of some select Bird species, Arabian Journal for Science and Engineering (2020) https://doi.org/10.1007/s13369-020-04931-7

[15] Menkiti AI, Ifedili SO, Uwah EJ, Abumere OE, Awate IO, Advanced Practical Physics Manual, Nigerian University Physics Series, Spectrum Books Ltd (2010) p. 237.

[16] Anand MMS, Electronics Instruments and Instrumentation Technology, 7th edn., Ghosh K. Ghosh, New Delhi, 2009.

[17] Thereja BL, and Thereja AK, A Textbook of Electrical Technology, S. Chand, New Delhi (2000) p. 530.

[18] Sawhney AK, and Sawhney PA, A Course in Electrical and Electronic Measurements and Instrumentation, 19th edn., Gagan Kapur Dhampat Rai and Co (P) Ltd, Delhi (2011) pp. 170 – 172.

[19] Robertson CR, Fundamental Electrical and Electronic Principles, 3rd edn., Newnes, Elsevier, Amsterdam, (2008) pp. 101 – 102.

[20] Etuk SE, Akpabio LE, and Ekpe SD, Verification of Relationship between Relative Permittivity and Viscosity for determination of Adulteration and Grades of Engine Oil Samples, Global Journal of Pure and Applied Science 7 (3) (2001) pp. 579 – 584. https://doi.org/10.4314/gjpas.v7i3.16291

[21] Mee C, Grundell M, Arnold B, Brown W, International A/AS Level Physics, Endorsed by University of Cambridge International examinations, Hodder Education, Hachette Livre, UK (2011) pp. 295 – 296.

[22] Morris NM, Mastering electronic and Electrical Calculations, Macmillan, Hong Kong (1996) p. 8.

[23] Halizan MZM, Mohamed Z, Yahya AK, Understanding the structural, optical, and dielectric characteristics of SrLaLiTe1−xMnxO6 perovskites, Scientific Reports 11 (2021) 9744. https://doi.org/10.1038/s41598-021-89132-4

[24] Vasudeva AS, Modern Engineering Physics, 6th Edn., S. Chan & Co. Ltd, New Delhi, Part V, Chapter 4 (2013) pp. 63 – 83.

[25] Thereja BL, Basic Electronics-Solid State, 1st Multicolor Illustration edn., S. Chand & Company Ltd, Ram Nagar (2008) p. 63.

[26] Sears FW, Zemansky MW, Young HD, University Physics, 6th edn. Addison Wesley, 1982.

[27] Young HD, Freeman RA, and Ford AI, University Physics with Modern Physics, 12th edn., SEARS and ZEMANSKYS Pearson Addison Wesley, San Francisco (2008) pp. 828 – 829.

[28] Frederikse HPR, Dielectric constant of glass in CRC 12, CRC Press LLC (2000) pp. 48 - 58

[29] Lide DR, CRC Handbook of Chemistry and Physics, 8th edn., CRC Baco Raton (2005) pp.12–51.

[30] Anderson HL, A Physicist's Desk Reference, American Institute of Physics, New York, 1989.

[31] Brandup J, and Immergut EH, Polymer Handbook, 3rd edn., Wiley, Hoboken, 1989.

[32] Nelkon M, and Parker P, Advanced Level Physics, 5th edn., Heinemann Educational books Ltd, London (1982) p. 603.

[33] Young HD, and Federikse HPR, Compilation of the static dielectric constant of inorganic solids, J Phys Chem Ref. Data 2 (1973) p. 313. https://doi.org/10.1063/1.3253121

[34] Gray DE, American Institute of Physics Handbook, 3rd edn., McGraw-Hill, New York (1972) pp. 5 - 132.

[35] Salman F, AC Conductivity and Dielectric Study of chalcogenide glasses of Se-Te-Ge, Turk J Phys. 28 (1) (2004) pp. 41 – 48.

[36] Salman F, Aboelhssan S, Sheha E, Elmansy MK, Dielectric Properties and Conductivity of $KHCO_3$, Turk J Phys. 28 (1) (2004) pp. 57 – 63.

[37] Fink DG, and McKeenzie AA, Electronics Engineers' Handbook. McGraw-Hill Books, New York (1975) pp. 6 – 36.

ACTA TECHNICA JAURINENSIS
Vol. 15, No. 2, pp. 99-109, 2022
10.14513/actatechjaur.00636

A Review on Factors Affecting the Resilient Modulus of Subgrade Soils

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Submitted: 08/06/2021 Accepted: 19/04/2022 Published online: 25/05/2022

Abstract: The subgrade layer is the lowest pavement layer, which carries the loads transferred from the upper layers. Different researchers have studied the resilient modulus (Mr) of different subgrade soils for the fine-grained and coarse-grained soil types. The layer's resilient response mechanism was found to be different for those fine and coarse materials, and it is vital for improving the pavement performance and life constructed over it. The different parameters related to the soil that can affect the resilient modulus include moisture content, stress level, compaction degree, loading frequency, and matric suction characteristics. Due to the variability of the Mr result, a study is needed for each soil type and input parameter. The effects of these parameters on the Mr are reviewed and discussed in this paper. The results show that the water content beyond the optimum level and the increase in deviatoric stress decreased Mr. In contrast, the increase in confining stress, compaction degree, loading frequency, and matric suction was found to improve the Mr. During the wetting and drying of the soil, the Mr was improved in the drying process.

Keywords: Resilient modulus, Subgrade soils, Moisture content, Stress level, Loading frequency, Matric suction

I. INTRODUCTION

Pavement construction involves the construction of layers (subgrade, subbase, base, and surface layer). It needs analysis and design of each layer before the construction starts. Whether the pavement is flexible or rigid, it requires a solid base to securely withstand and transfer the load from the traffic and the layers above it. Subgrade soils are the foundation for the pavement structure. In the traditional method of design, the design parameter for pavements includes the California bearing ratio (CBR, a measure of a material's resistance to standard plunger penetration under controlled density and moisture conditions) and the static modulus (quantify the relationship between a change in stress and the resulting deformation) [1]. The CBR and static modulus values do not incorporate the traffic's dynamic and actual effects. The mechanistic pavement design method uses the mechanical characterization of unbound granular materials. These materials are characterized by a nonlinear elastoplastic behavior, which in turn is the Mr of the soil.

The Resilient Modulus (Mr) is a measure of subgrade material stiffness. The resilient modulus of the material is an estimate of its elasticity modulus (E) which often is determined based on the hysteresis loops obtained from cyclic triaxial tests. While the elastic modulus is stress divided by strain for a slowly applied load, this ratio is similar to the resilient modules for rapidly applied loads. It measures the stiffness of the subgrade soil or the actual estimate of the modulus of elasticity. The stress-strain behavior of subgrade soils under repeated traffic loading uses the determination of Mr [2]. The soil's resilient modulus, Mr, is calculated as the ratio of the deviator stress, q, to the recoverable axial strain ε_r .(see equation 1).

$$Mr = \frac{q}{\varepsilon_r} \quad (1)$$

The triaxial test of the soil determines the resilient modulus in the laboratory. The testing procedure uses a cylindrical test specimen, a repetitive axial cyclic stress of defined magnitude, load length, and cycle duration. A triaxial pressure chamber produces static confining stress when the sample is subjected to this complex cyclic stress. It is a cyclic version of a triaxial compression test, and the cyclic load application simulates the actual loading of traffic more accurately.

Since the subgrade's resilient characteristics affect the pavement's performance and service life, it is necessary to predict the resilient modulus as accurately as possible. It is also essential to study the contributing factors for the variation of the resilient modulus. Moisture content, stress level, compaction degree, loading frequency, and matric suction properties are some of the soil parameters that could affect the resilient modulus [3].

The amount of moisture inside the soil mass affects the structural response of the soil to any set of applied stresses. The stresses that occur on a given pavement are mainly from the traffic and other inter-layer stresses due to the self-weight of the pavement layers. The stress effect of the traffic is mainly a function of its magnitude, direction, and frequency.

Studies have been conducted to characterize Mr for different subgrade soil [1, 2, 4-7] and found different results for different soil types. Consequently, various studies discussed the effect of other parameters like the moisture content [1, 2, 8], matric suction [2, 8-10], confining stress [1, 2, 8, 11, 12], loading frequency, and compaction [1, 2, 8], and the wetting and drying history of the soil [2, 6] on the Mr. These studies try to model the relationship between these contributing factors and the Mr.

Researchers made an increasing number of efforts to predict the resilient behavior of subgrade soils for different scenarios [1-8, 11, 13, 14]. The proposed theoretical and experimental techniques add to the understanding of predicting the resilient response of subgrade materials and how that response evolves due to various contributing factors.

Although there is a fair amount of published information about the Mr of unstabilized and stabilized soils, most of the information is localized because of the use of natural soils as a subgrade and varies accordingly. The variation of the Mr concerning different soil state and stress state parameters initiates the author to review, discuss and summarize the behavior of soil's Mr concerning these parameters.

This paper summarizes factors that affect the resilient properties of subgrade soils. Moisture content, matric suction, confining and deviatoric stress, soil type, load frequency, and compaction degree, as well as the soil's drying and wetting history, are all parameters taken into consideration in this study. This paper looks into the elements that influence the Mr of subgrade soil by reviewing published research. The investigation is limited to the parameters that influence the Mr characteristic of subgrade soil for pavement foundation or subgrade purposes.

II. Materials and methods

Owing to the objective of this study, the data for analyzing the effect of the parameters on the Mr was reviewed from published studies (**Table 1 and 2**).

Table 1. *Summary of studies regarding the factors and number of soil types*

Author's name	*Parameters considered on each paper*							*No of the soil types tested*
	MC	*Matric suction*	*Compaction level*	*Stress level*	*Loading frequency*	*Soil type*	*Drying and wetting*	
X. Liu et al. [1]	+	+	+	+	+	+		6
X. Chu [2]	+	+	+	+	+	+	+	–
A. S. El-Ashwah et al. [4]	+			+		+		10
Y. Yao et al. [5]	+	+			+	+		1
K. Naji [6]	+					+	+	7
Y. J. Cui [7]						+		9
J. Zhang et al. [8]	+	+		+	+			22
C. E. Cary et al. [9]	+	+						2
H. Park et al. [10]		+		+				4
S. Jayakody et al. [11]	+		+	+				1

Table 2. *Summary of studies regarding the factors and number of soil types*

Author's name	***Parameters considered on each paper***							***No of the soil types tested***
	MC	***Matric suction***	***Compacti-on level***	***Stress level***	***Loading frequency***	***Soil type***	***Drying and wetting***	
N. Su et al. [12]	+			+	+			>6
J. H. Zhang et al. [13]		+		+				–
J. M. Rasul et al. [14]							+	3
X. R. Wu et al. [15]	+							5
R. Ji et al. [16]	+			+				6
F. Salour et al. [17]	+	+						2
X. R Wu et al. [18]	+		+					1
F. Salour et al. [19]	+	+		+				2
F. Achampong et al. [20]	+			+		+		2
A. Rahim et al. [21]				+		+		12
C. N. Khoury et al. [22]	+	+						>2

Among the 123 downloaded relevant and recent papers, 21 studies and two manuals were found close to the objective of this study and selected as a data source. The papers have much data related to the objective of this article. The papers are selected on a basis such that they contain more soil types and parameters concerning the Mr. This study summarizes the works done on more than 103 subgrade soils from different sources and a total of more than 1300 samples. The summary in Table 1 shows the factors considered for the analysis and the number of soils considered in each selected study.

The data for analysis were taken from the published papers, and values that were not found in tabular form were extracted from the figures using GetData Graph Digitizer software. The data collected using this software has 97% accuracy. The data and graphs chosen for each parameter considered in the study are carefully taken from the selected papers to represent the trend of the curves demonstrating the same parameter.

Table 3 presents the summary of the published works interms of the location of the soil samples , the soil classification, and the testing method employed by the respective authors. The AASHTOT307-99 and NCHRP 1-28A (2004) are widely used by the researchers. The soil classification manuals used in the study are mainly AASHTO [23] and USCS [24].

Data extracted from each paper were drawn into a scale for discussion and proving the scientific theories. The researchers utilized different techniques to determine the Mr values. Most of them employ the laboratory determination of Mr using the triaxial loading machine and plate load test for the field testing.

III. RESULTS AND DISCUSSION

Though the resilient modulus is the fundamental characteristic parameter, some factors influence its value. Those parameters that can change the subgrade resilient response and studied here are water content, matric suction, confining stress, soil type, load frequency, compaction degree, and soil drying and wetting history [1, 2, 4-8, 11, 14].

1. Moisture content

Due to seasonal environmental variations, the moisture content of unbound pavement layers continuously changes. Different studies stated the impact of this parameter on the resilient response of subgrade soils. For a naturally dried inorganic clay (CL) soil subjected to varying levels of moisture content (MC), the Mr tested and checked for MC levels of -2% of OMC, OMC, and +2% of OMC of the soil [1]. **Fig. 1/a** shows that by keeping the compaction degree to 96% and 1Hz frequency, the variation of the MC affects the soil's resilient response. The dynamic Mr increases with an increase in MC until the OMC level, and afterward, it decreases with an increase in MC [2, 6, 12]. The resilient modulus result of seven different soil samples also decreases with increasing the moisture contents and an increase with decreasing the moisture contents [6].

Table 3. *Summary of studies regarding the location, soil classification , and testing method*

Author's name	***Location***	***Classification***	***No of the soil types tested***
X. Liu et al. [1]	Tianjin, Shijiazhuang, Cangzhou, Xuanhua, Mohe, Nanjing	CL, SM, ML	AASHTOT307-99 (2012) Standard method of test for determining the resilient modulus of soils and aggregate materials. Washington, D. C. [25]
K. Naji [6]	Oklahoma and the State of Pennsylvania	Cl, SC, CH, SM	AASHTOT307-99 (2012) Standard method of test for determining the resilient modulus of soils and aggregate materials. Washington, D. C. [25]
C. E. Cary et al. [9]	Phoenix Valley, Arizona	A-1-a, A-4	NCHRP 1-28A (2004) protocol "Harmonized test methods for laboratory determination of resilient modulus for flexible pavement design" [26]
R. Ji et al. [16]	Indiana	A-4, A-6, A-7-6	AASHTOT307-99 (2012) Standard method of test for determining the resilient modulus of soils and aggregate materials. Washington, D. C. [25]
F. Salour et al. [17]	Northern and Southern Sweden	Two different silty sand subgrade materials (SM)	NCHRP 1-28A (2004) protocol "Harmonized test methods for laboratory determination of resilient modulus for flexible pavement design"
F. Salour et al. [19]	Northern and Southern Sweden	Two different silty sand subgrade materials (SM)	NCHRP 1-28A (2004) protocol "Harmonized test methods for laboratory determination of resilient modulus for flexible pavement design"
F. Achampong [20]		Two blended materials of low and high plasticity clay (CL and CH Soils)	An SBEL HX-100 Triaxial Cell/604 Servo system was used to perform the Mr testing. The AASHTO T-294 (1993) procedure for cohesive soils was followed in performing the Mr tests
A. Rahim et al. [21]	Mississippi (project)	A-4, A-6, A-7, A-2-4, A-2-6, A-3, and A-1-a	A Laboratory MR test, in accordance with the AASHTO TP46 protocol (1994), [27]
C. N. Khoury et al. [22]	Manufactured soil that consists of fine sand (48%), silt (46%), and clay (6%).		AASHTOT307-99 (2012) Standard method of test for determining the resilient modulus of soils and aggregate materials. Washington, D. C. [25]

The subgrade soil's resilient response will be low with increasing the MC above the OMC level [15, 16]. This variation becomes very large at lower moisture content levels [17]. For example, when the MC increases from -2% OMC to OMC level, the dynamic resilient modulus increases by an interval of 9% to 20%. However, it decreases by an interval of 24% to 30% for an increment of MC level from OMC to +2%OMC [1]. This happens because the MC that is higher than the OMC creates pore pressure and makes the moisture surround the soil particle surface and causes the soil to lose the cohesive behavior (binding force between soil particles) [19].

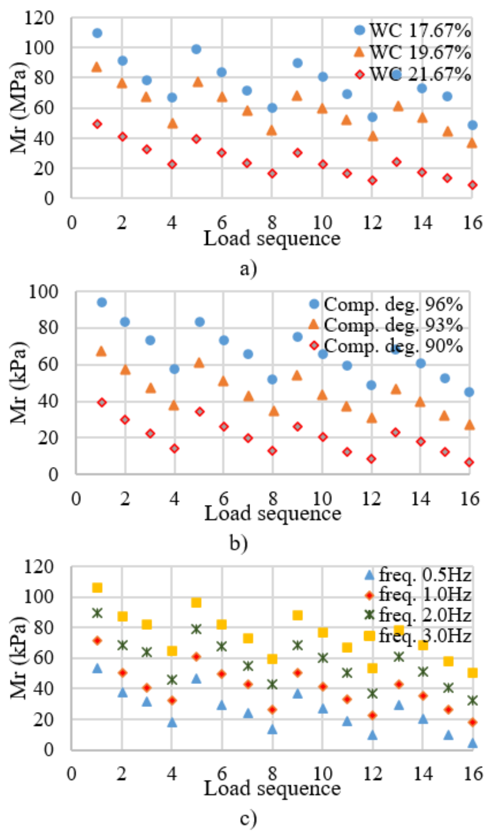

Figure 1. *Measured Mr at different a) water content, b) compaction degree, and c) loading frequency [1]*

Excess moisture in the pavement foundation decreases the subgrade bearing capacity and leads to pavement deterioration [2]. The moisture added will cause a lubrication effect on the soil [1]. Setting the MC level to the optimum value helps the soil to have an improved resilient response; hence it has better cohesion and shear resistance. A study by Wu & Zhu [18] also indicates that the Mr for a loess low liquid limit silt soil shows a variation while the water content changes. The Mr increases by 12.9% when the water content increases from 10.75% to 13.09% [18]. A study on silty sand subgrade soil of 42.2% and 27.4% fines for change in the degree of saturation from 30% to OMC level results in 51% and 48% reduction to the resilient modulus, respectively [19].

In the review by Chu [2], the moisture content variation within the subgrade soil arises from factors like precipitation, capillary action, flooding, and groundwater table variation. This moisture inside the soil induces positive pore water pressure and reduces the soil's load-carrying capacity, directly related to the Mr of the soil. Though the study is on recycled aggregates [11], the same pattern in the sample's resilient modulus occurs while increasing the degree of saturation. Increased moisture content, particularly at high saturation levels, has been demonstrated to result in a significant decrease in resilient modulus and Poisson's ratio [3].

2. Load frequency and compaction degree

The loading frequency, which is related to the vehicle speed, increases with the resilient modulus [1, 11]. **Fig. 1/c** shows an increase in load frequency (at 19.67% WC and 96% compaction level) from 0.5 Hz to 1.0 Hz and 1.0 Hz to 3 Hz improves the resilient modulus by 14%. The frequency dependency of the subgrade soil's resilient modulus is high at low-stress levels than at high-stress levels [1]. The Mr increases by a small amount at higher stress levels due to the soil's density at these stress levels. A study by Wu & Zhu [15] also shows that the five types of sandy silt soils subjected to varied compaction levels show varied levels of resilient modulus at a given moisture content level. For example, for sandy silt soil with an OMC of 9.3%, the Mr increases by 30.5% when the compaction level increases by 50% [15].

As shown in **Fig. 1/b**, for 19.67% WC and 1Hz load frequency, Mr increases by 26% and 24% when compaction degree increases from 90% to 93% and 93% to 96%, respectively. The level of compaction affects the percentage of voids in the soil so that the higher degree of compaction leads to a lower volume of voids, which has a positive impact on the resilient response of the subgrade soil. The decrease in the volume of voids allows the soil to occupy the space and become more denser and this mechanism with increasing the unit weight of the soil, it also increases the Mr.

3. Matric suction

An increase in matric suction results in a decrease in recoverable strain, which then improves resilient modulus. This parameter affects the soils' resilient property and the sensitivity of the resilient modulus to the bulk and octahedral shear stresses [18].

As pavement subgrade soils are exposed to varying levels of moisture due to the seasonal environmental variations, the stress developed in the layer is also affected. The stress which dominantly becomes pore pressure at higher degrees of saturation results in lower matric suction, and this is effect is high for fine grained soils [19]. Matric suction has been considered a vital stress variable in investigating the effects of moisture content on the mechanical behavior of unsaturated soils. It mainly consists of two components; osmotic and matric suctions [2]. The matric suction effect is more significant for unsaturated subgrade soils, and experiments show that the Mr is more related to this matric suction than the total suction [2]. Regarding the unsaturated state of the soil, matric suction has been a crucial stress variable in pavement structures with soil mechanics development. Due to the non-linearity of stress-strain parameters at higher matric suction levels, the variation of Mr is significant [17]. As per the study by Farhad et al. [19], the increase in the moisture content of soil materials corresponds to a decrease in the matric suction. It results in a significant reduction in the resilient modulus. **Fig. 2** presents the variation of Mr when the matric suction is changing, and it is seen that the suction increases with the Mr and vice-versa.

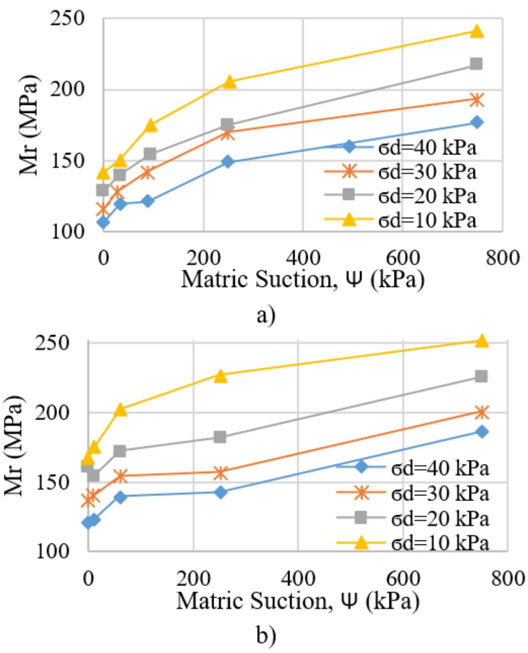

Figure 2. *Matric Suction (Ψ) vs. Resilient Modulus (Mr) at 120 kPa Minimum Bulk Stress: a) 95% Compaction, b) 100% Compaction [5]*

The resilient modulus increases with increasing matric suction at a certain compaction level [5, 17]. Yao et al. [5] report that, at a compaction level of 85% and deviator stress of 10 kPa, the resilient modulus increases from 107 MPa to 175 MPa when the matric suction increases from 31 kPa to 951 kPa. This result is uniform at each compaction and deviator stress level. For a silty sand subgrade soil of 42.2%, the reduction of the matric suction from 444 kPa to 7 kPa results in a 51% reduction in the resilient modulus. For the same soil type of 27.4% fines, the reduction of matric suction from 316 kPa to zero kPa results in a 48% reduction to the resilient modulus [19]. Moisture content differences in fine-grained unbound materials can modify stress by suction, changing material stiffness properties.

4. Confining Stress and Deviator Stress

For a constant MC, compaction degree, and frequency, the dynamic Mr increases with increasing the confining stress [1]. A study by Jayako et al. [11] shows that the resilient modulus increases with increasing confining stress along the constant principal axis. In other words, the deviatoric stress decreases with improving confining stress. Achampong, Usmen, & Kagawa [20] reported similar findings. The Mr increases with an increase in net bulk stress and decreases with increased deviator stress (octahedral shear stress). This effect is significant at higher matric suction values. Salour & Erlingsson [17] added that, at higher matric suction values, the variation of Mr at different stress levels is more significant.

Another study by Yao et al. [5] shows, for a weathered granite subgrade soil (sandy clay of a low liquid limit clay), the Mr significantly decreases with increasing the deviator stress at each compaction degree level. **Fig. 3** presents the result obtained for the variation of Mr concerning the deviatoric stress and cell pressure. It shows that the confining stress positively affects the Mr, while the deviatoric stress has a negative effect.

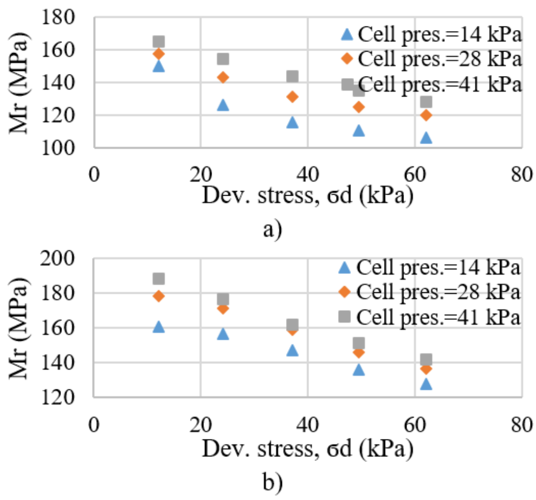

Figure 3. *The effect of cell pressure and deviatoric stress a) for fine-grained soil, b) for coarse-grained soil [21]*

Salour et al. [19] reported that resilient modulus increases with bulk stress. It decreases with the increase in octahedral stress (directly proportional to the deviatoric stress). It is presented that, at 120% OMC and 30 KPa minimum bulk pressure, as the deviator stress increases from 10 kPa to 40 kPa by intervals of 10kPa, the resilient modulus decreases by 20.7%, 13.0%, 19.7%, and 5.4% under a degree of compactions of 100%, 95%, 90%, and 85%, respectively [5]. Similarly, for the same soil type and condition at minimum bulk stress of 120 kPa, the resilient modulus decreases by 30.8%, 30.6%, 19.0%, and 11.8%. Rahim & George [21] also backed this idea in the study focused on the correlation between Mr and stress conditions for fine-grained and coarse-grained soil.

Densification of the soil material improves Mr and decreases the elastic strain of the soil. Similarly, the increase in the confining stress, since it confines the soil in all directions, is an addition to its shear strength. The increase in the deviator stress enhances the shear failure of the soil mass along the weak plane. Therefore, the confining stress increases the soil mass's resilient response while the deviator stress lowers this response mechanism [10].

5. Soil type and classification

Different soil types exhibit different characteristics as well as different response mechanisms. The resilient response mechanism of different soil samples is tested and found to be different [15]. Naji [6] shows different resilient modulus values for seven soil classes from two different regions, Oklahoma and Pennsylvania; namely, Kingfisher (CL), Binger (SC), Burleson (CH), Renfrow (CL), Stephensville (SM), Alloway Clay (CH), and Made Land (CL). Though the pattern of increase and decrease is similar for most soils, the degree of increase or decrease in Mr values is a function of soil type [6]. Farhad [19] also suggests that the resilient response is different even for the same soil type with different fine content. For example, the change in matric suction for two silty sand soils with 42.2% and 27.4% fine passing No.200 is different due to the moisture content variation from 30% to the OMC [19]. As a result, Mr also varies accordingly. Soils with less fine content tend to have less matric suction and a higher resilient modulus.

Another study by Rasul et al. [14] shows different Mr values for three different subgrade soil types (A-7-5, A-4, and A-6 soils [25]) found in Kurdistan. It is shown that the three different soils, whether treated or untreated by lime and or cement, the Mr remains different. For example, **Table 4** shows that the three soils subjected to equal level confining stress and deviator stress have different Mr values. The soil with more coarse soil content have the largest Mr value and vice-versa. The response of the finer soil classes to a given cyclic load is weak.

Table 4. *Resilient modulus values for soil A-4, A-6, and A-7-5 at unstabilized and stabilized state [14]*

Soil type	***Confining stress (kPa)***	***Deviator stress (kPa)***	***Resilient modulus (MPa)***	***Mr for cement treated 2% (MPa)***
A-4	41.4	12.4	117	131
	27.6	37.3	150	185
	12.4	62.0	165	222
A-6	41.4	12.4	96	139
	27.6	37.3	105	171
	12.4	62.0	100	196
A-7-5	41.4	12.4	74	76
	27.6	37.3	69	98
	12.4	62.0	57	117

The magnitude of the effect of the parameters like stress state, moisture content, and matric suction towards the materials' resilient response differs from the soil classification. Unsaturated subgrade soils with high fine content have the highest resilient response, or the magnitude of change of Mr for those soil types is much more significant than for saturated and less fine content soils [17]. The state of the soil, either drained or undrained, is also a significant contributing factor [9]. This factor becomes more substantial when the degree of saturation becomes higher.

Achampong et al. [20] reported that mineralogical composition has a marked effect on the Mr of cohesive soils. They found that soils with higher kaolinite clay minerals have higher Mr values than the soils with high montmorillonite clay minerals.

An indirect approach was employed by Rahim & George [21] and uses the ratio of deviator stress to confining stress for the fine-grained soils and the ratio of bulk stress to deviator stress for the coarse-grained soil samples. It is stated that the two parameters in the first ratio best capture the effect for the fine-grained soils, and the latter is found to best describe the effect for coarse-grained soils. The Mr increases with an increase in the ratio of deviator stress to confining pressure, and it has a reverse correlation for the ratio of coarse grain soil parameters. This pattern is due to fine- and coarse-grained soils' stress softening and hardening characteristics [21].

6. Drying and wetting history of the soil

Seasonal variation is one cause of subgrade soils' drying and wetting process. The effect becomes higher in regions where freeze and thaw actions are dominant. A study by Ji et al. [16] compared the resilient property of subgrade soils at different seasons of the year. The results obtained from this study show that the Mr measured by FWD in April, July, October, and December are 180 kPa, 190 kPa, 197 kPa, and 212 kPa, respectively. In other words, Mr increases as we approach the cold season (from October to January), and it will continue increasing until the soil reaches its OMC level. After reaching the OMC level and while the ice melts gradually (on March, April, and May), the Mr tends to decrease. The increase and decrease of the soil's moisture level due to the variation of the seasons in a given period causes the variation and lowering of the soil's cohesive and shear behavior. Moreover, it results in a decrease in the resilient modulus.

Table 5 shows that the drying and wetting process has different effects on the Mr. The drying process, which is the loss of moisture from the soil mass, shows the improvement of Mr value, and later, it decreases. At the same time, the soil is subjected to the wetting process. The latter pattern is more consistently shown in the characteristic of Mr in the process of drying and wetting. The primary drying and primary wetting are the states or complete cycles where the soil was subjected initially.

Table 5. *Effect of drying and wetting at confining stress of 41 kPa and deviatoric stress of 28 kPa [22]*

Condition	*Suction (kPa)*	*W (%)*	R^2	*Mr (kPa)*
Primary drying	8	17.2	0.90	28.1
	25	13.1	0.94	43.8
	50	9.6	0.92	71.6
	75	6.1	0.95	96.9
	100	4.3	0.96	114.1
Primary wetting	75	4.8	0.96	110.3
	50	5.9	0.94	99.5
	25	9.0	0.95	82.8
Secondary drying	25	11.0	0.95	71.2
	50	7.9	0.95	91.6
	75	5.7	0.97	110.3
	100	4.4	0.95	125.2
Secondary wetting	75	4.7	0.94	117.0
	50	5.7	0.94	100.7
	25	7.6	0.96	84.5

In contrast, the secondary drying and secondary wetting states are the second cycles that follow the first complete cycle. Khoury et al. [22] added that the hardening effect due to cyclic suction and the potential lubricant effect of the water content (at the same suction) is assumed to be the dominant cause for higher Mr on wetting relative to drying.

A study by Rasul et al. [14] on three different lime and cement stabilized subgrade soils to a different degree shows that the wetting and drying history of the soil affects its resilient response. The wetting and drying condition of the soil modeled in the lab uses entirely soaking the subgrade soil for 5 hrs at room temperature and letting it dry in an oven for around two days. For 25 cycles, the soil sample report shows that the soil becomes loess, and the volume changes. For example, the resilient modulus value for stabilized sandy clay soil (A-7-5) decreases up to 31% after the soil gets into the soaking and drying process beyond its optimum level. This is because the soil collapse as the wetting and drying condition continues. The study [14]suggests the same scenario of Mr happens for three soil samples (A-7-5, A-4, and A-6 soils [28]) in both treated and untreated conditions.

Another related factor to the soil's wetting and drying condition is climatic changes, which will lead to the build-up and breakdown of soil particles, and the aggregate stability inside the soil becomes negatively affected. On the review by Chu [2], the resilient modulus will increase slightly for lime-treated soils during the wetting and drying process, and the resilient modulus decreases for unstabilized soils. For soils compacted at their OMC level, the Mr decreases up to several times [2, 6].

IV. Conclusions

The parameters that affect the resilient modulus studied here are the stress state, matric suction, moisture content, soil type, wetting and drying history, and degree of compaction and loading frequency. Specifically, the review can be summarized as follows:

- Mr increases with increasing moisture content and matric suction. It keeps increasing up to the optimum moisture content level, and beyond the optimum point, the Mr will decrease.
- Mr increases with increased confining and net bulk stress and decreases with increased deviator stress (octahedral shear stress).
- Soils with more fine content have Mr values higher than the soil types with less fine content.
- Mr increases with the increase in loading frequency and compaction level. The

change in Mr becomes high at low-stress levels than high-stress levels.

- The seasonal temperature and climate fluctuation alter the Mr of subgrade soils. Mr increases in the drying process of the soil and vice versa.

Acknowledgement

The author would like to thank the Tempus Public Foundation of Hungary for awarding him a scholarship for the research and the Ph.D. study and Addis Ababa Science and Technology University for allowing him to study.

Author Contributions

M. D. Amare: Writing, Review and editing.

Z. Tompai: Writing, Review and editing.

Disclosure Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] X. Liu, X. Zhang, H. Wang, B. Jiang, Laboratory testing and analysis of dynamic and static resilient modulus of subgrade soil under various influencing factors, Construction and Building Materials 195 (2019) pp. 178–186. https://doi.org/10.1016/j.conbuildmat.2018.11.061

[2] X. Chu, A Review on the Resilient Response of Unsaturated Subgrade Soils, Advances in Civil Engineering (2020), 7367484 https://doi.org/10.1155/2020/7367484

[3] F. Lekarp, U. Isacsson, and A. Dawson, "State of the Art. I: Resilient Response of Unbound Aggregates," Journal of Transportation Engineering-asce - J TRANSP ENG-ASCE 126 (1) (2000) https://doi.org/10.1061/(ASCE)0733-947X(2000)126:1(66)

[4] A. S. El-Ashwah, A. M. Awed, S. M. El-Badawy, and A. R. Gabr, "A new approach for developing resilient modulus master surface to characterize granular pavement materials and subgrade soils," Construction and Building Materials 94 (2019) pp. 372-385.

[5] Y. Yao, J. Zheng, J. Zhang, J. Peng, and J. Li, "Model for predicting resilient modulus of unsaturated subgrade soils in south China," KSCE Journal of Civil Engineering 22 (6) (2018) pp. 2089-2098.

[6] K. Naji, "Resilient modulus–moisture content relationships for pavement engineering applications," Int. J. Pavement Eng. 19 (7) (2018) pp. 651-660.

[7] Y. J. Cui, "Mechanical behaviour of coarse grains/fines mixture under monotonic and cyclic loadings," Transportation Geotechnics, Review 17 (2018) pp. 91-97. https://doi.org/10.1016/j.trgeo.2018.09.016

[8] J. Zhang, J. Peng, L. Zeng, J. Li, and F. Li, "Rapid estimation of resilient modulus of subgrade soils using performance-related soil properties," Int. J. Pavement Eng. (2019) pp. 1-8.

[9] C. E. Cary and C. E. Zapata, "Resilient modulus for unsaturated unbound materials," Road Materials and Pavement Design 12 (3) (2011) pp. 615-638.

[10] H. Park, G. Kweon, and S. R. Lee, "Prediction of resilient modulus of granular subgrade soils and subbase materials using artificial neural network," Road Materials and Pavement Design 10 (3) (2009) pp. 647-665.

[11] S. Jayakody, C. Gallage, and J. Ramanujam, "Performance characteristics of recycled concrete aggregate as an unbound pavement material," Heliyon, Review 5 (9) (2019), Art no. e02494 https://doi.org/10.1016/j.heliyon.2019.e02494

[12] N. Su, F. Xiao, J. Wang, and S. Amirkhanian, "Characterizations of base and subbase layers for Mechanistic-Empirical Pavement Design," Construction and Building Materials, Review 152 (2017) pp. 731-745. https://doi.org/10.1016/j.conbuildmat.2017.07.060

[13] J. H. Zhang, J. H. Peng, and J. L. Zheng, "Progress and Prospect of the Prediction Model of the Resilient Modulus of Subgrade Soils," Zhongguo Gonglu Xuebao/China Journal of Highway and Transport, Review 33 (1) (2020) pp. 1-13. https://doi.org/10.19721/j.cnki.1001-7372.2020.01.001

[14] J. M. Rasul, G. S. Ghataora, and M. P. Burrow, "The effect of wetting and drying on the performance of stabilized subgrade soils," Transportation Geotechnics 14 (2018) pp. 1-7.

[15] X. R. Wu and L. L. Zhu, "Analysis of the influence of water content on shanxi loess CBR and rebound module," in H. Abbas and T. K.

Hwee Eds., Advanced Materials Research. Durnten-Zurich: Trans Tech Publications Ltd 919-921 (4) (2014), pp. 820-823.

[16] R. Ji, N. Siddiki, T. Nantung, and D. Kim, "Evaluation of resilient modulus of subgrade and base materials in Indiana and its implementation in MEPDG," The Scientific World Journal 2014 (2014).

[17] F. Salour and S. Erlingsson, "Resilient modulus modelling of unsaturated subgrade soils: laboratory investigation of silty sand subgrade," Road Materials and Pavement Design 16 (3) (2015) pp. 553-568.

[18] X. R. Wu and L. L. Zhu, "Study on the Relations of Strength control indicators of road subgrade in shanxi loess region," in H. Abbas and T. K. Hwee Eds., Advanced Materials Research. Durnten-Zurich: Trans Tech Publications Ltd 919-921 (2014) pp. 1160-1163.

[19] F. Salour, S. Erlingsson, and C. E. Zapata, "Modelling resilient modulus seasonal variation of silty sand subgrade soils with matric suction control," Can. Geotech. J. 51 (12) (2014) pp. 1413-1422.

[20] F. Achampong, M. Usmen, and T. Kagawa. Evaluation of resilient modulus for lime- and cement-stabilized synthetic cohesive soils, Transportation Research Record (1997) pp. 70-75.

[21] A. Rahim and K. George, "Models to estimate subgrade resilient modulus for pavement design," Int. J. Pavement Eng. 6 (2) (2005) pp. 89-96.

[22] C. N. Khoury, N. N. Khoury, and G. A. Miller. Effect of cyclic suction history (hydraulic hysteresis) on resilient modulus of unsaturated fine-grained soil, Transportation Research Record (2011) pp. 68-75.

[23] AASHTO, "AASHTO M 145 (1991), AASHTO Standard Specification for Classification of Soils and Soil–Aggregate Mixtures for Highway Construction Purposes," 1991.

[24] A. C. D.-o. Soil and Rock, Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System) 1. ASTM international, 2017.

[25] AASHTO, "AASHTO T 307-99 (2007), AASHTO Standard method of test for determining the resilient modulus of soils and aggregate materials, Washington D.C.," 2009.

[26] T. R. Board, E. National Academies of Sciences, and Medicine, Laboratory Determination of Resilient Modulus for Flexible Pavement Design. Washington, DC: The National Academies Press (in English), 2004.

[27] AASHTO, "AASHTO T 274 (1994), AASHTO Standard Method of Test for Resilient Modulus of Unbound Granular Base/Subbase Materials and Subgrade Soils - SHRP Protocol P46," 1994.

[28] ASTM, "ASTM D 559-96, (2003), Standard test method for wetting and drying of compacted mixture, ASTM International, Pennsylvania, USA."

ACTA TECHNICA JAURINENSIS
Vol. 15, No. 2, pp. 110-116, 2022
10.14513/actatechjaur.00657

Investigating the temperature field distribution over transport structures' metal corrugated construction surface under temperature influences

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Submitted: 29/03/2022 Accepted: 16/04/2022 Published online: 25/05/2022

Abstract: The experimental studies results of temperature distribution over metal corrugated sheet structure surface at positive and negative ambient temperatures are presented. It is established that the temperature is distributed unevenly over the sheet surface along its plane. An analytical method for calculating the temperature field from a fragment of a structure metal sheet in the case of setting the temperature at the sheet area boundaries is presented. The calculation of the temperature field distribution on the metal sheet of the structure with the setting of the temperature along the contour of the sheet is performed. As a result, it is established that at the metal sheet boundaries there is a temperature difference, which can cause the occurrence of temperature stresses and deformations.

Keywords: metal corrugated structure; ambient temperature; temperature field; finite difference method

I. INTRODUCTION

Transport structures made of metal corrugated structures (hereinafter MCS) are related to the most progressive and promising types of transport structures that are built on highways and railway tracks [1-2]. They consist of a multi-dimensional closed loop structure assembled from individual corrugated sheets of a given radius and bolted together [3] However, during operation, MCS structures are damaged by cracking the corrosion-resistant zinc coating, etc. (**Fig. 1**).

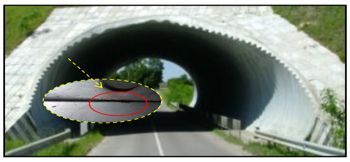

Figure 1. *Damage to zinc coating of metal corrugated structure in operation*

One of the reasons for this damage is the level of the temperature field at the steel–zinc or steel–zinc–soil borders. The high level of the temperature field, and therefore of stresses, can be caused by the fact that in the summer the metal structure on the outer part is heated to high temperatures due to the significant thermal fluxes passing through the inner part of the structure. The basis of this calculation is the prediction of the temperature field using mathematical modeling.

In this regard, the problem of studying the temperature field of metal corrugated structures that are under the influence of variable heat fluxes of the environment is relevant. Such studies, along with studying the impact of static and transport loads, are the basis for assessing the load-bearing capacity and reliability of transport structures with MCS when calculating the effect of climatic temperature influences. In work [4] it is indicated that such studies will allow engineers of various organizations at the stage of project work for constructing transport structures with MCS to take into account the influence of temperature changes on the stress-strain state of metal corrugated structures. This will make it possible to make design decisions to reduce this impact on the thermoelastic state of these structures by selecting materials that can withstand the specified temperature influences under operating conditions.

II. Analysis of Literature Data and Problem Statement

In work [5] it is noted that the general stress state of transport structures depends on both the action of the transport load and the influence of climatic temperature changes in the environment.

To correctly determine the temperature distribution over the structures' surface, a one-dimensional calculation is not enough, it is necessary to use more complex models (two-dimensional or three-dimensional).

However, in practical calculations design engineers take into account simplified calculation methods when studying temperature effects on bridge structures [6, 7] that is insufficient to correctly take into account the temperature distribution over the structures' surfaces.

In works [8, 9], it was established that uneven temperature distribution over the surfaces of transport structures causes the development of structural structures' stresses and deformations. It is recommended that their values should be taken into account at operating transport loads.

In the regulatory document DBN v. 2.3-14 [10], it is indicated that the standard temperature and climatic influences should be taken into account when calculating the limit state of the second group for bridges of all systems. At the design calculation, the operating temperature value should be determined by the maximum temperatures recorded in the area where the structure is in operation.

In the AASHTO standards [11] for different types of bridges, the maximum values of high and low temperatures, which must be taken into account when designing bridge structures, are given. However, the standards [12] recommend taking into account the temperature unevenly in the vertical direction of bridge structures, which most accurately reflects the real influence of ambient temperatures on the stress state of bridge structures.

The standards En -1991-1-5-2009 [12] they require calculating the thermal stress state of bridges under the action of maximum and minimum recorded ambient temperatures.

Studying the temperature distribution in a reinforced concrete superstructure is given in work [13]. And in works [14, 15] it was established that temperature fluctuations cause asphalt subsidence on road bridges.

In work [16], the temperature distribution in the cross-section of elements of superstructures, taking into account the uneven temperature distribution in the vertical direction of the structure, is studied.

When calculating the stresses of transport structures in work [17], it is established that the temperature distribution in the structures of such bridges should be taken into account while designing structures with taking into account the most heating side of the bridge superstructure.

In work [18], it was found that the temperature difference between the lower and upper surfaces of the bridge box beam can be up to 24 °C

In work [19, 20], it is noted that the distribution of the temperature field along the bridge beams is influenced by weather and climatic conditions. The calculations of temperature gradients showed that the temperature is unevenly distributed along the guide section in the vertical direction of the beam.

It was found in [21] that to describe the general stress state of metal corrugated structures, it is necessary to take into account the effect of climatic temperature differences on metal corrugated 143 structures.

The study of the influence of ambient temperature on the thermal stress state of repaired reinforced concrete pipes with metal corrugated structures was carried out in [22]. It is obtained that at the contact of concrete and metal shells there is a significant jump in temperature stresses, which can lead to premature failure of structures.

The authors studied in [23] the influence of temperature on the dynamic characteristics of the railway ballast. As a result, it was found that the dynamic characteristics of the ballast in the frozen state dramatically change the dynamic characteristics of the track.

In [24-25], the authors conducted a study of the stability of the seamless track, taking into account temperature effects. It is shown that the stability of the track significantly depends on the action of temperature.

In [24], a study of the temperature effect depending on the distribution of moisture on the surface of the material. It is established that moisture has a significant effect on the temperature distribution of the surface.

In [25] the influence of metal oxide on thermal radiation and heat generation of metal structures was carried out.

The surface coating effect of temperature on structures is demonstrated in [26] for the improvement of structures in terms of thermal properties by applying nanoparticles. A study of changes in the structure of wood at elevated temperatures is produced in [27].

In [28], the influence of the thermal cycle of welding on the structure and properties of the metal of the thermal impact zone for steel C460M was studied. The results of the experimental data relate to the values of static strength, ductility and toughness at the level of the parent metal, as well as structural changes in the weld.

A method for investigation of the ballast material deformations, that could be potentially useful for monitoring of metal corrugated construction is presented in [29]. The paper [30] presents the Concrete Canvas a promising material for application in many civil engineering fields.

From the research projects' analysis, it was established that studying the temperature distribution on the metal sheets surfaces of transport structures were not carried out. Although the structures made of metal corrugated structures are intensively introduced into the practice of the road industry. And in a short service life, they have damage in the form of peeling off the zinc coating, etc. That can cause premature decommissioning of such structures. The novelty of the present paper is the assessment of the temperature field in the metal corrugated construction surface of soil-filled structures.

III. Purpose and objectives

The study's objective is to determine the influence of climatic temperature changes on the distribution of the temperature field over the metal corrugated structures' surfaces of transport structures.

To achieve this object, the following tasks were set:

- to conduct experimental measurements of the temperature distribution on the surfaces of a metal corrugated sheet at positive and negative ambient temperatures;
- to improve the model for estimating the temperature distribution over the surface of the structure metal sheet;
- to study the temperature field distribution by a structure metal sheet when setting the measured temperatures along the contour of a metal corrugated sheet.

IV. Studies' results of the temperature field distribution over the surface of a structure metal sheet

1. Experimental measurements of the temperature distribution on the surfaces of structural sheets

To determine the heat fluxes acting on metal structures of structures in operation, the temperature distribution over metal corrugated structures' surfaces of transport structures was measured. Full-scale experimental measurements of the temperature distribution were measured on a transport structure made of metal corrugated structures, which is shown in **Fig. 1**. Temperature was measured with a pyrometer. The results of the temperature distribution over the surface of a structure metal sheet fragment are shown in **Table. 1**.

The diagram of coordinates for measuring the temperature distribution of the surface of the construction sheet is shown in **Fig. 2**.

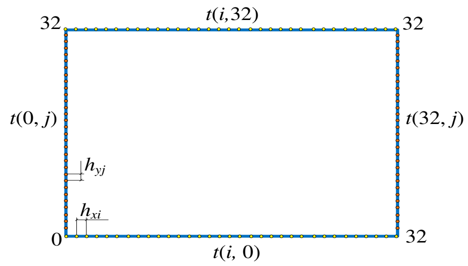

Figure 2. *Coordinate diagram of measuring the temperature distribution on the surface of the metal sheet of the structure*

From the experimental studies, the maximum positive value of the surface temperature of the structure metal corrugated sheet was recorded at +38.7 °C, and the minimum negative value was – -27.5 °C.

It is established that the temperature is distributed unevenly over the surface of the corrugated structure sheet. There is a fluctuation in temperature in the vertical direction. The difference in the distribution of positive temperatures along the vertical of the sheet is 2.3 ºC, and the negative values of temperatures – -3.7 ºC.

The experimental measurements of the surface temperature of the structure metal sheet showed that the temperature changes slightly in the longitudinal direction and over time (over a short period).

2. The mathematical model for estimating the thermal conductivity process of metal corrugated sheets

Let's assume that the cross-section of the structure sheet occupies the area

$$(P) = \{(x, y) : 0 \le x \le a, 0 \le y \le b\}, \qquad (1)$$

where x, y are the coordinates of a rectangular Cartesian system.

In the model let's assume that the temperature field distribution does not depend on time. Then the equation of thermal conductivity in the two-dimensional case will be [20]. The coordinates of the points where the temperature was measured are shown in **Fig. 2**.

$$\frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial y^2} = 0 \qquad (2)$$

here t – the temperature value is measured at a specific point in the contour of the sheet.

Table 1. *The results of experimental measurements of the temperature distribution over the surface of the structure sheet*

i	$t_{i,0}, ^\circ C$		$t_{i,32}, ^\circ C$		j	$t_{0,j}, ^\circ C$		$t_{32,j}, ^\circ C$	
	Positive temperatures	**Negative temperatures**	**Positive temperatures**	**Negative temperatures**		**Positive temperatures**	**Negative temperatures**	**Positive temperatures**	**Negative temperatures**
0	31.8	-27.8	35.4	-20.5	0	32.7	-27.1	31.7	-27.5
1	32.4	-27.4	36.2	-20.2	1	32.8	-27.4	33.1	-27.2
2	32.8	-26.5	35.2	-20.4	2	32.0	-26.4	34.5	-27.1
3	32.3	-26.3	37.3	-20.5	3	33.2	-26.8	34.5	-26.2
4	31.3	-27.4	38.5	-21.7	4	33.4	-26.8	35.2	-26.0
5	31.5	-27.4	38.0	-20.4	5	33.7	-26.5	35.5	-26.1
6	31.0	-26.5	38.4	-21.5	6	33.7	-24.2	35.4	-26.5
7	32.2	-26.5	35.2	-21.4	7	33.5	-25.5	35.5	-25.4
8	32.1	-26.4	34.2	-21.9	8	34.2	-25.7	35.8	-25.3
9	32.2	-26.4	35.5	-20.5	9	35.8	-25.9	36.5	-25.7
10	32.3	-25.1	36.4	-21.7	10	34.8	-25.4	36.4	-25.1
11	32.5	-26.4	37.2	-21.5	11	34.4	-24.6	36.2	-25.2
12	33.4	-26.4	36.8	-20.2	12	35.8	-24.4	36.5	-25.1
13	33.7	-26.1	38.2	-20.1	13	36.8	-24.5	36.2	-24.1
14	33.7	-26.8	37.4	-20.1	14	35.8	-23.5	36.0	-23.7
15	33.8	-26.4	37.4	-20.2	15	35.8	-23.5	36.7	-23.6
16	33.2	-26.8	37.2	-21.4	16	36.7	-23.7	36.9	-22.5
17	32.5	-27.1	37.4	-20.1	17	36.3	-23.4	37.4	-22.4
18	32.2	-26.2	37.1	-21.1	18	36.4	-23.4	37.8	-22.4
19	32.6	-27.1	37.1	-21.0	19	36.4	-21.4	37.9	-22.8
20	31.2	-26.8	37.7	-21.7	20	36.9	-22.5	38.5	-22.5
21	31.2	-26.1	38.8	-21.8	21	37.9	-21.9	38.1	-22.4
22	31.5	-26.4	38.7	-20.7	22	37.9	-22.3	37.8	-21.2
23	31.6	-26.4	38.4	-20.4	23	37.5	-21.4	38.1	-20.4
24	32.5	-25.4	38.1	-20.2	24	37.2	-21.3	38.0	-21.5
25	32.0	-25.4	38.5	-21.5	25	38.5	-20.7	37.9	-21.9
26	32.0	-25.6	38.4	-21.4	26	37.9	-20.5	38.1	-21.8
27	31.2	-25.4	37.5	-20.7	27	38.4	-20.4	37.2	-20.7
28	31.5	-24.1	37.8	-20.8	28	37.4	-20.1	37.4	-20.4
29	31.5	-24.4	38.5	-20.4	29	38.1	-20.4	37.5	-20.5
30	32.0	-24.7	37.5	-21.2	30	38.4	-20.3	37.2	-19.5
31	32.3	-24.5	36.5	-21.2	31	38.4	-20.4	37.2	-19.3
32	32.4	-24.4	37.4	-21.2	32	38.5	-21.0	38.4	-20.2

Let's find a solution of the differential equation (3.32) that would satisfy the boundary conditions

$$t\big|_{x=0}=t_1(y),\ t\big|_{x=a}=t_2(y),\ t\big|_{y=0}=t_3(x),\ t\big|_{y=b}=t_4(x). \quad (3)$$

Here $t_1(y), t_2(y),\ t_3(x),\ t_4(x)$ are the temperature values at the boundaries of the region (*P*), which were obtained in the experimental studies (**Table 1**) and measured at a specific time of day.

To solve the boundary problem (2), (3) the method of finite differences are used. To do this, let's apply the uniform grid with steps (*P*) to the area

$$h_x = \frac{a}{m} \quad (4)$$

$$h_y = \frac{b}{m} \quad (5)$$

$$x_i = \frac{ai}{m} \ \ (i = 0,1,2, ...,m), \quad (6)$$

$$y_j = \frac{bj}{m} \ \ (j = 0,1,2, ...,m). \quad (7)$$

Function value $t(x, y)$ at the nodal point of the grid (x_i; y_j) will be denoted $t_{i,j}$. The other derivatives of the function t will be approximated by finite differences [25]. Let's assume that

$$\left(\frac{\partial^2 t}{\partial x^2}\right)_{i,j} = \frac{t_{i+1,j} - 2t_{i,j} + t_{i-1,j}}{\left(h_x\right)^2}, \quad (8)$$

$$\left(\frac{\partial^2 t}{\partial y^2}\right)_{i,j} = \frac{t_{i,j+1} - 2t_{i,j} + t_{i,j-1}}{\left(h_y\right)^2}. \quad (9)$$

Taking into account the expressions (8) and (9), for each internal node point (x_i; y_i) the Differential Equation (1) is replaced by the finite difference equation

$$t_{i+1,j} - 2t_{i,j} + t_{i-1,j} + \left(\frac{a}{b}\right)^2 \left(t_{i,j+1} - 2t_{i,j} + t_{i,j-1}\right) = 0. \quad (10)$$

At the boundary nodal points, the temperature has the value

$$t_{0,j} = t_1\left(y_j\right),\ t_{m,j} = t_2\left(y_j\right),\ t_{i,0} = t_3\left(x_i\right),\ t_{i,m} = t_4\left(x_i\right) \quad (11)$$

Thus, using equation (10), let's determine the temperature distribution over the surface of a structure metal sheet fragment.

3. Results of calculating the temperature field over the surface of a structure metal sheet

Numerical studies of the temperature field are performed based on the of the parameters' values a=2000 mm; b=280 mm; m=32 and temperature values obtained during experimental measurements of the temperature distribution and given in **Table 1**. It should be noted that in our studies we use only the maximum and minimum temperature values obtained in the experiment. It should be noted that the magnitude of stresses that occur at maximum and minimum temperature values is not always the highest. High tension spikes can cause significant temperature differences at adjacent points on the surface of the metal structure.

The results of calculating the temperature field by the finite difference method in the Mathcad 14 software package at positive ambient temperatures are shown in **Fig. 3**, and for negative values – in **Fig. 4**.

From the studies of the temperature distribution over the structure metal sheet surface, it was found that at positive values of sheet temperatures (**Fig. 2**) on the lower surface of the sheet, the temperature varies from +32.1 °C to +33.7 °C. On the upper edge, the temperature ranges from +35.5 °C to +38.7 °C.

At negative sheet temperatures (Fi**g. 3**) on the lower sheet surface the temperature varies from -27.5 ºC to -25.4 ºC. On the upper edge, the temperature ranges from - 21.2 °C to - 20.0 °C.

It is established that in the vertical direction of the sheet, the temperature changes unevenly. In the bottom-up direction, the temperature of the metal sheet changes to values from +32.1 °C to +38.7 °C at added temperatures, and from - 27.5 °C to-20.0 °C at negative temperature values.

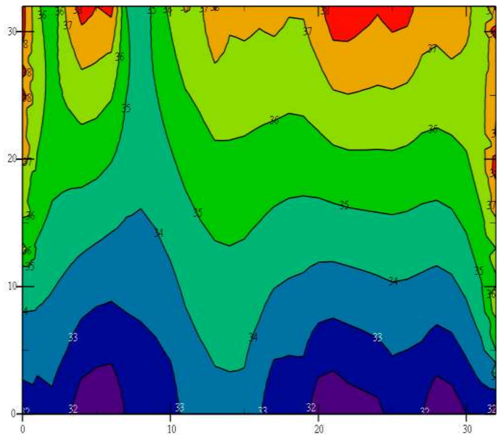

Figure 3. *The results of calculating the temperature field by the finite difference method at positive values of metal sheet surface temperatures*

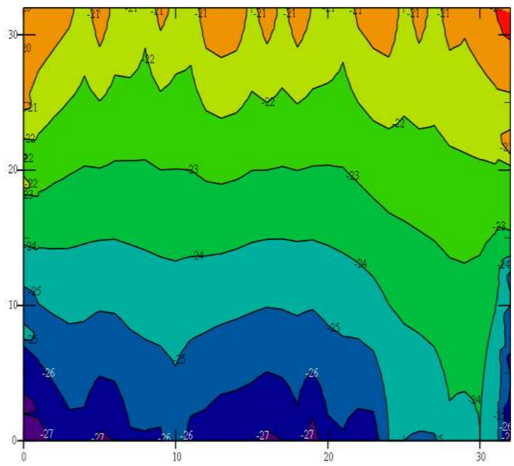

Figure 4. *The results of calculating the temperature field by the finite difference method at negative values of metal sheet surface temperatures*

It should be noted that the assessment of the temperature field is the first step in solving the temperature problem. In the following research works, studies of the thermostressed state of metal structures will be carried out, taking into account the uneven temperature distribution of the sheet surface.

Conclusions

1. From the experimental measurements of the temperature distribution over the surface of the metal sheet fragment of a transport structure, it is established that the temperature is distributed unevenly over the surface of the corrugated structure sheet. In addition, the temperature changes slightly in the longitudinal direction and over time (over a short period). The maximum positive temperature value recorded on the surface of the metal corrugated structure sheet was +38.7 °C, and the minimum negative value was -27.5 °C.

2. It is established that in the vertical direction of the corrugated metal structure sheet, the temperature changes unevenly. In the bottom-up direction, the temperature of the metal sheet at the added temperatures changes to values from +32.1 °C to +38.7 °C, and from - 27.5 °C to-20.0 °C at negative temperatures.

ACKNOWLEDGEMENT

The authors express their sincere gratitude to the Laboratory of Research and Prevention of Railway Accidents of the Ukrainian State University of Science and Technology for assistance in the equipment for measuring the temperature distribution on the surfaces of corrugated metal strucktures.

AUTHOR CONTRIBUTIONS

Vitalii Kovalchuk: Conceptualization, Writing, Theoretical analysis, Review and editing.

Ivan Kravets: Experiments.

Olga Nabochenko: Conceptualization, Writing, Supervision, Review and editing.

Oleksiy Petrenko: Experiments.

Andriy Milyanych: Theoretical analysis.

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REFERENCES

[1] V. Kovalchuk, J. Luchko, I. Bondarenko, R. Markul, B. Parneta. Research and analysis of the stressed-strained state of metal corrugated structures of railroad tracks. Eastern-European Journal of Enterprise Technologies. – Kharkov – 6/7 (84) (2016) pp. 4–10. http://dx.doi.org/10.15587/1729-4061.2016.84236

[2] V. Kovalchuk, R. Markul, O. Bal, A. Milyanych, A. Pentsak, B. Parneta, O. Gajda. The study of strength of corrugated metal structures of railroad tracks. Eastern-European Journal of Enterprise Technologies. – Kharkov. – 2/7 (86) (2017) pp. 18–25. http://dx.doi.org/10.15587/1729-4061.2017.96549

[3] V. Kovalchuk, R. Markul, A. Pentsak, B. Parneta, O. Gajda, S. Braichenko. Study of the stressstrain state in defective railway reinforcedconcrete pipes restored with corrugated metal structures. Eastern-European Journal of Enterprise Technologies. – Kharkov, 5/1 (89) (2017) pp. 37–44. http://dx.doi.org/10.15587/1729-4061.2017.109611

[4] B. Gera, V. Kovalchuk. A study of the effects of climatic temperature changes on the corrugated structure of a culvert of a transportation facility. Eastern-European Journal of Enterprise Technologies. – Kharkov, 3/7 (99) (2019) pp. 26–35. http://dx.doi.org/10.15587/1729-4061.2019.16826

[5] Mangerig I. Klimatische Temperatur-beanspruchung von Stahl- und Stahlverbundbrucken. Inst. für Konstruktiven Ingenieurbau, Ruhr-Univ., 1986, p. 143.

[6] Y. Y. Luchko, V. V. Kovalchuk. Vymiriuvannia napruzheno-deformovanoho stanu konstruktsii mostiv pry zminnykh temperaturakh i navantazhenniakh: monohrafiia. – Lviv: Kameniar, 2012, p. 235.

[7] J. Luchko, Y. Hnativ, V. Kovalchuk. Method of calculation of temperature field and deflected mode of Bridge structures in software environment NX Nastran. Theoretical Fuundations of Civil Engineering. 21 (2013) pp. 107–114.
Dilger W. H., Ghali A., Chan M., Cheung M. S., Maes M. A. Temperature Stresses in Composite Box Girder Bridges. Journal of Structural Engineering 109 (6) (1983) pp. 1460–1478. https://doi.org/10.1061/(asce)0733-9445(1983)109:6(1460)

[8] M. J. N. Priestley, I. G. Buckle. Ambient Thermal Response of Concrete Bridges. Bridge Seminar 2 (1978).

[9] DBN V.2.3-14: 2006. Sporudy transportu. Mosty ta truby. Pravyla proektuvannia. K., 2006, p. 359.

[10] AASHTO Guide specifications: Thermal effects in concrete bridge superstructures. Washington, DC: American Association of State Highway and Transportation Officials, 1989.

[11] Luchko J. J. Modeling of thermal conductivity of thin slabs with multilayer coating. Diagnosis, durability and reconstruction of

bridges and building structures. – Lviv: Kamenyar 6 (2004) pp. 65–70.

[12] Kovalchyk Ya. I. Rekomendatsii z proektuvannia ta tekhnolohii zvedennia monolitnykh poperedno napruzhenykh zalizobetonnykh prohonovykh budov mostiv. SWorld, 2016.

[13] M. F. Dmytrychenko, M. M. Dmytriiev, O. B. Derkachov. Teplova diahnostyka (osnovy teorii ta praktyky zastosuvannia): monohrafiia. – K.: NTU, 2012, 168 p.

[14] T. Feng, S. Feng. A Numerical Model for Predicting Road Surface Temperature in the Highway. Procedia Engineering 37 (2012) pp. 137–142. https://doi.org/10.1016/j.proeng.2012.04.216

[15] Design Criteria Skyway Structures. San Francisco-Oakland Bay Bridge East Span Se ismic Safety Project, 2001, p. 91.

[16] V. Z. Stankevych, I. O. Butrak, V. V. Kovalchuk. Cracks Interaction in the Elastic Composite under Action of the Harmonic Loading Field. 2018 XXIIIrd International Seminar/Workshop on Direct and Inverse Problems of Electromagnetic and Acoustic Wave Theory (DIPED), 2018. https://doi.org/10.1109/diped.2018.8543323

[17] De Backer H., Outtier A., Van Bogaert Ph. Numerical and experimental assessment of thermal stresses in steel box girders. Civil Engineering Department, Universiteit Gent, Gent, Belgium NSCC, 2009, pp. 65–72.

[18] Burdet O. L. Thermal Effects in the Long-Term Monitoring of Bridges. IABSE Symposium Report 97 (19) (2010) pp. 62–68.

[19] Y. Y. Luchko, Yu. M. Hnativ, V. V. Kovalchuk. Doslidzhennia temperaturnoho polia ta napruzhenoho stanu prohonovoi budovy stalezalizobetonnoho mosta. Visnyk Ternopilskoho natsionalnoho tekhnichnoho universytetu 2 (70) (2013) pp. 29 – 38.

[20] Vitalii Kovalchuk, Yuri Kovalchuk, Mykola Sysyn, Volodymyr Stankevych, Oleksiy Petrenko. Estimation of carrying capacity of metallic corrugated structures of the type multiplate mp 150 During interaction with backfill soil. Eastern-European Journal of Enterprise Technologies. – Kharkov.: 1/1 (91) (2018) pp. 18–26. http://dx.doi.org/10.15587/1729-4061.2018.123002

[21] Vitalii Kovalchuk, Yuriy Hnativ, Joseph Luchko, Mykola Sysyn. Study of the temperature field and the thermos-elastic state of the multilayer soil-steel structure. Roads and Bridges – Drogi i Mosty. – 19 (1) (2020) pp. 65–78. http://dx.doi.org/10.7409/rabdim.020.004

[22] J. Liu, Z. Liu, P. Wang, L. Kou, M. Sysyn. Dynamic characteristics of the railway ballast bed under water-rich and low-temperature environments. Engineering Structures, 2022, 252, 113605.

[23] Mehdi Moslemi, Kourosh Javaherdeh, Hamid Reza Ashorynejad. Temperature Effect on Moving Water Droplets at the Channel of PEMFC by Multi-component Multiphase Lattice Boltzmann Method. Journal of Applied and Computational Mechanics. – J. Appl. Comput. Mech. http://dx.doi.org/10.22055/JACM.2021.39023.3332

[24] Sharma R. P., Mishra S. R. Metal and Metallic Oxide Nanofluid over a Shrinking Surface with Thermal Radiation and Heat Generation/Absorption, J. Appl. Comput. Mech. 8 (2) (2022) pp. 557–565. https://doi.org/10.22055/JACM.2020.32813.2085

[25] Akinshilo A.T., Davodi A., Ilegbusi A., Sobamowo G. Thermal Analysis of Radiating Film Flow of Sodium Alginate using MWCNT Nanoparticles, J. Appl. Comput. Mech. 8 (1) (2022) 219–231. https://doi.org/10.22055/jacm.2020.33386.2218

[26] Bragov A. M., Iuzhina T. N., Lomunov A. K., Igumnov L. A., Belov A. A., Eremeev V. A. Investigation of Wood Properties at Elevated Temperature, J. Appl. Comput. Mech. 8 (1) (2022) pp. 298–305. https://doi.org/10.22055/JACM.2021.38486.3239

[27] Zavdoveev A., Rogante M., Poznyakov V., Heaton M., Acquier P., Kim H. S., Baudin T., & Kostin V. (2020). Development of the PC-GMAW welding technology for TMCP steel accordance with welding thermal cycle, welding technique, structure, and properties of welded joints. Reports in Mechanical Engineering 1 (1) (2020) pp. 26-33. https://doi.org/10.31181/rme200101026z

[28] Szalai S., Eller B., Juhász E., Movahedi M. R., Németh A., Harrach D., Baranyai G., & Fischer S. (2022). Investigation of deformations of ballasted railway track during collapse using the Digital Image Correlation Method (DICM). Reports in Mechanical Engineering 3 (1) (2022) pp. 258-282. https://doi.org/10.31181/rme20016032022s

[29] Eller B., Movahedi M. R. & Fischer S. Laboratory Tests and FE Modeling of the Concrete Canvas, for Infrastructure Applications. Acta Polytechnica Hungarica 19 (3) (2022) pp. 9-20.

ACTA TECHNICA JAURINENSIS
Vol. 15, No. 2, pp.117-124, 2022
10.14513/actatechjaur.00658

Determination of the type and the length for the transition curves on the directions of high-speed train operation

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Submitted: 05/04/2022 Accepted:19/04/2022 Published online: 2505/2022

Abstract: In many countries around the world, a cubic parabola is used as transition curves in a simplified form. Today, the properties of many mathematical curves are well studied, which can be used as transition curves. The object of research is the process of restructuring transition curves when organizing high-speed trains operation. The use of modern means of mathematical modelling allows to add a number of dynamic characteristics for evaluation parameters of motion in the curved sections of the tracks. Thus, with an increase in speed for transition curves, both the values of unbalanced acceleration and its change in time, and also the velocity attenuation of oscillations of rolling stock when moving from a transition curve to a circular curve or to a direct section. On the basis of the conducted research, it has been found that when increasing the speed of the vehicle movement in the range from 120 to 200 km/h, the length of the stabilization section increases at the output of the curvature by an average of 20 m for every 40 km/h. The analysis showed that with correctly set parameters of transition curves, which correspond to the maximum speed of movement and radius of a circular curve, the strength and reliability of the bearing elements in the structure of the permanent way and the travel comfort are fully ensured.

Keywords: High-speed train; Railway; Railway curve; Transition curves

I. INTRODUCTION

Before the beginning of the twentieth-century transition curves on the railways in some countries were not foreseen, although then the maximum speeds reached 100 versts per hour (107 km/h), and only since 1912, the arrangement of transition curves has become one of the main requirements. Transition curves were arranged at a radius of 500 sazhens (1067 m) and less. The speed for calculation was taken 60 versts per hour (64 km/h), the transition curve parameter was determined as $C = Rl = 12300$ m^2.

Since the middle of the twentieth century, transition curves should be arranged at a radius of less than 2000 m. In subsequent normative documents of most European countries, transition curves were begun to apply on all curves, radius up to 4000 m inclusive.

In many countries around the world, a cubic parabola is used as transition curves in a simplified form. The transition of such types does not meet all the established requirements [1, 2].

Today, the properties of many mathematical curves are well studied, which can be used as transition curves: the clothoide (also known as Euler spiral or Cornu's spiral), Bernoulli's lemniscate, a cubic parabola, quartic parabola, a high-speed curve, a majorant curve, a minorant curve, etc.

Here are the most common of them with the corresponding curvature equation in **Table 1**.

Thus, in work [3], an overview of the current state of transient curves is given. It is shown that adopted rational parameters of transition curves facilitate the safe and comfortable motion of vehicles for transportation of passengers and cargoes, leading to a decrease in the wear of the permanent way and wheels of rolling stock, which is economically in terms of maintenance. The article defines the objectives of the study related to the geometric continuity of the curve and the dynamics of a transport vehicle for ensuring the smoothness of movement.

It is known that the use of clothoide as a transition curve has become widely applied in many countries of the world. However, a linear curvature is not a sufficient parameter to provide all the requirements of high-speed train traffic. The main results presented in the article [4] are related to the use of new types of transition curves, which turned out to be smoother than clothoide. The proposed method allows to improve the geometry of the existing railways without the need to introduce significant changes in the restructuring of the railway track. In order to eliminate the problems associated with the dynamics of vehicles traffic at high speeds along the transition curves in the form of clothoide, the article [5] analyzes the possibility in the use of the sinusoid as transition curves, which is a diagram of the ideal curvature.

Table 1. *Types of transition curves*

Title	***Equation***
High-speed curve	$k = \cos\beta\sqrt{\frac{2\beta}{C}}$
Quartic parabola	$k = \sqrt[3]{\frac{9}{C}tg^{2/3}\beta cos^3\beta}$
Majorant curve	$k = 2\sqrt{\frac{tg\beta/2}{C}}$
Minorant curve	$k = \sqrt{\frac{2sin\beta}{C}}$
Bernoulli's lemniscate	$k = \frac{1}{\sqrt{C}}\frac{cos^{2/3}\beta}{\sqrt{3sin^{2/3}\beta}}$
Elastic line	$k = \frac{\sqrt{2Csin\beta}}{C}$
Sinusoidal curve	$k = \frac{2\pi l - Lsin\left(\frac{2\pi l}{L}\right)}{2\pi LR}$
Cosinusoidal curve	$k = \frac{1 - cos\left(\frac{\pi l}{L}\right)}{2R}$
Half-sinusoidal curve	$k = \frac{\frac{1}{2R}[1 - cos\beta]}{\left[1 + \left(\frac{l}{2\pi R}[\beta - sin\beta]\right)^2\right]^{\frac{3}{2}}}$
Bloss's curve	$k = \frac{3l^2}{RL^2} - \frac{2l^3}{RL^3}$
Dunin's curve	$k = \frac{1}{R}(3\sigma^2 - 2\sigma^3)$
Shakhuniants's curve	$k = \frac{1}{R}\left(\sigma - \frac{sin2\pi\sigma}{2\pi}\right)$
Minorskyi's curve	$k = \frac{8 - 9cos\pi\sigma + cos3\pi\sigma}{16R}$
Koziichuk's curve	$k = \frac{1}{R}sin^2\frac{\pi\sigma}{2}$
Lokhtman and Rote curve	$k = \frac{1}{R}(10\sigma^3 - 15\sigma^4 + 6\sigma^5)$

In the table: R – radius of the circular curve; l and L – respectively current and full length of the transition curve; $\sigma = \frac{l}{L}$; k –the curvature; β – angle of rotation; $C = Rl$.

Also, there is a transition curve "Wiener Bogen" considering the center of gravity of the vehicle [6, 7]

$$k = k_1 + (k_2 - k_1)f(l) - h(\psi_2 - \psi_1)\frac{d^2f}{dl^2}$$

where k_1 and k_2 are the curvature at each end, ψ_1 and ψ_2 are the cant values at each end, h is the height to the center of gravity and $f(l)$ is the cant shaping function (chosen among 6 types, of which the most common is a seventh degree polynomial) [8].

In works [9, 10] there are difficulties upon the practical realization and further maintenance of very small horizontal ordinates of the transition curve on the initial section. A new form of a transitional curve is proposed, which, unlike the conventional clothoide, is characterized by a gentle bend in the zone of entry into a circular curve. The apparent advantage of this curve from the viewpoint of its implementation is shown compared to Bloss's graduated transition curves.

In the article [11], the results of optimization of curves are presented through the use of polynomials of the 9th and 11th degrees. The authors use a model of a two-axle rail vehicle in combination with mathematical methods of optimization. The assessment criterion is passengers' comfort. The results obtained for curves, the length of which exceeds 150 m, show that the curve used in the form of the parabola of the 3rd degree is not always optimal. In such cases, the transition curves of the 9th and 11th degrees will be the rational decision.

The article [12] describes the analysis of the results of transitional curves continuation, depending on the track control and modernization of railways. The analysis is based on numerical calculations of a wide range of parameters describing a typical geometric scheme of the railway with transition curves. The radius impact and angle of rotation of the curve on the process of transition curves continuation are considered. On the basis of theoretical assumptions, an effective numerical algorithm of comparative analysis for options of transition curves continuation was developed.

The theoretical foundations in the choice of a rational form of the transition curve developed by Academician V. A. Lazarian are an example of a strict statement of the problem in determining the form of the transition curve, which connects two sections of different curvature, which have a common tangent in the connection point [13].

The authors imply a transitional curve with a limited second derivative of the curvature as the rational form, for which the requirements for angular acceleration, unbalanced acceleration, its changes and steepness of right-of-way for the elevation of an outer rail.

Later, the analytical expressions of the transition curve curvature of the rational form were obtained by V. V. Lahuta under Professor A. A. Bosov [14].

Based on the analysis of graphs for the transition curves curvature in [13], it is possible to conclude that some of them, for example, the curve of V. A. Lazarian, quartic parabola and some others are focused on performing dynamic requirements for angular acceleration in the initial and end points of the transition curve. This condition is quite important for railways, especially for high-speed networks.

Papers [15, 16] deals with the comparative of transition curves used in Hungary are determined. In these works approves that the usability of the clothoide in the Hungarian regulations is unnecessarily restricted for the speeds 120 km/h.

Today, various options of transition curves offered by different scientists are used.

Clothoide, in view of the linear character of a graph of its curvature ($k = \frac{x}{C}$) (**Fig. 1**), is the shortest transition curve, which ensures continuity of the curvature function with the minimum possible rate of change of the curvature for this length ($\frac{dl}{dk}$), and, accordingly, with a minimum rate of growth of centrifugal force at a constant velocity of movement on it.

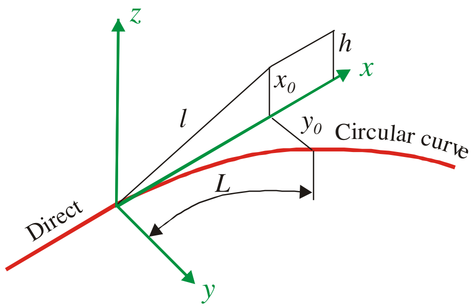

Figure 1. *Image of the transition curve in two planes*

All other curves, equal to clothoide by the extreme value of the rate of curvature change for these curves, will either be longer clothoide, or have sections with greater than in a clothoide rate of curvature change and, accordingly, with a higher rate of growth of centrifugal for the same constant velocity of motion, that along the clothoide.

It should be noted that the practical application of new types of transition curves, which have a number of excellent properties compared to clothoide, is complicated due to the unresolved issues of normalization of their parameters and support of the horizontal track geometry [17, 18]. Thus, the normalization of the lengths of transition curves depending on the radius that is included in the state-building norms of Ukraine SBN B.2.3-19:2018 [19], can only be applied to clothoide, and only in cases of a connection of direct with circular curves. The normalization of only length is clearly not enough both for the same clothoide, and other transition curves with a nonlinear nature of the change in the curvature. In the publication [20] upon this problem, the authors substantiated the general method of normalizing parameters of any type of transition curves, based on the analysis of the intensity of changing their curvature. This method can be used to clothoide because it does not contradict the theoretical bases of their normalization by parameter $A = \sqrt{C}$. Clothoide parameter C is the magnitude of the inversely proportional rate of changing its curvature over the length, that is $\frac{dl}{dk} = \frac{l}{C} = \frac{l}{RL}$.

Completing the brief overview in the developmental history of the theory of transition curves and the practice of their application, it should be noted that transition curves can be used with regard to the regulatory requirements of safety and smoothness of movement. The very latter circumstance requires a scrupulous analysis in the application of the transition curve in each particular case.

II. Methods

The object of research is the process of restructuring transition curves when organizing high-speed trains.

The transition curve is a spatial curve, in which the curvature both in-plane and in profile smoothly changes (**Fig. 1**). In order to simplify the calculations and break the transition curves, the spatial curve is replaced by a curve of variable curvature only in-plane (**Fig. 2**).

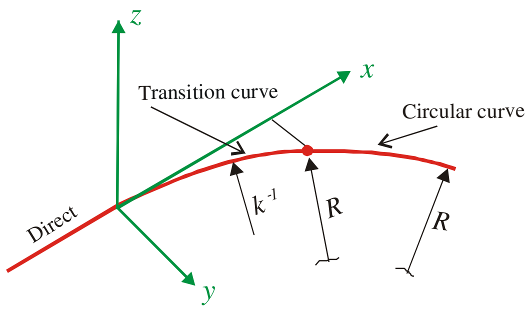

Figure 2. *Connection of a transition curve with a circular*

As a rule, the transition curve used on the railways of most countries is designed with a linear change of both a radius and elevation of the outer rail. A right-of-way of elevation is determined by the speed of lifting the wheel on it, and the right-of-way of the curvature by the rise speed of a transverse unbalanced acceleration. Such a right-of-way (**Fig. 1**) is easy to arrange and maintain, so it is very common on the railways of many countries. But the transitions of these types do not meet the requirements:

$$\frac{dk}{dL} = 0; \frac{dh}{dL} = 0; \frac{d^2k}{dL^2} = 0; \frac{d^2h}{dL^2} = 0, \quad (1)$$

where k and h – accordingly, the curvature and elevation of outer rail at the beginning and at the end of the transition curve.

So, for a cubic parabola at the point of connection with a circular curve, we have

$$\frac{d^2k}{dL^2} = \frac{2}{dL^2} \neq 0. \quad (2)$$

However, neglecting conditions (1) at the beginning and at the end of the transition curve should be compensated by the proper choice of the length for the transition curve to limit the emerging forces and accelerations.

In this paper, creating a new type of transition curves was not a task. Analysis of existing types of transition curves proposed by Shakhuniants, Minorskyi, Dunin, and other scientists (**Fig. 3**) shows that all of them considerably in the initial part has small ordinates and it is difficult to keep them in the correct position on existing lines with the modern design of the upper structure of the track [1].

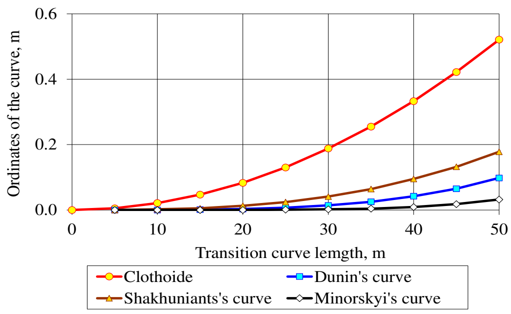

Figure 3. *Changing ordinates along the curve for different types of transition curves*

It is expedient to choose the type of transition curve, that is, function $k = f(l)$, associated with the study of dynamic conditions in the vehicle movement. The analysis showed that sinusoidal curves have good dynamic characteristics for velocities more than 200 km/h [5].

In each case, the type of curve, its length and parameters depend on local relief and situational features and determining conditions of movement.

There is a correct question, whether it is necessary to perform the restructuring of transition curves in order to elongate them, which would meet all necessary requirements at sections of transport corridors, where modernization of the track and artificial structures are carried out in connection with the introduction of high-speed trains movement.

III. Modeling the passenger car movement in the curve of complex outline

Currently, experimental trips with a speed of more than 200 km/year in Ukraine are impossible due to the lack of appropriate rolling stock, and therefore the identification of parameters in designing the plan is based on the modeling the movement of a high-speed car on the curves of a real outlines.

Many works of famous authors are devoted to mathematical modeling of the oscillations of rail vehicles. Such models of rolling stock and track interaction are a system of differential Lagrange equations of the second kind, which describe linear and angular oscillations of the bodies system. As a rule, a local coordinate system is used, that is, a car (locomotive) seems to fluctuate in the same spot under the impact of external forces that show movement. This simplifies some mathematical calculations and increases the accuracy of solving equations (numerical values of oscillations of all bodies are small and approximately the same in all directions). To simulate the movement in the curve, a centrifugal force is applied to the system, which is calculated analytically, based on the curvature of the track under the car. If the curvature is described by complex dependencies or set deterministically with regard to the real outline of the track, the analytically determined definition of centrifugal force is impossible. In such cases, a global coordinate system is used, which allows you to directly specify the coordinate outline of the track and receive the results of centrifugal forces actions as a consequence of the wheels trajectory change which are directed by the positions of rails.

As the basic, the authors accept a model of spatial oscillations of a high-speed passenger car, which was adapted to solve the set problem, including with the implementation in the transition to the global coordinate system [1].

The use of modern means of mathematical modeling allows to add a number of dynamic characteristics for evaluation parameters of motion in the curved sections of the tracks. Thus, with an increase in speed for transition curves, both the values of unbalanced acceleration and its change in time, and also the velocity attenuation of oscillations of rolling stock (updating of a steady motion) when moving from a transition curve to a circular curve or to a direct section. Examples of lateral oscillations damping for the body of the passenger car in the output of the transition curve are shown in **Fig. 4**.

On the basis of the conducted research, it has been found that when increasing the speed of the vehicle

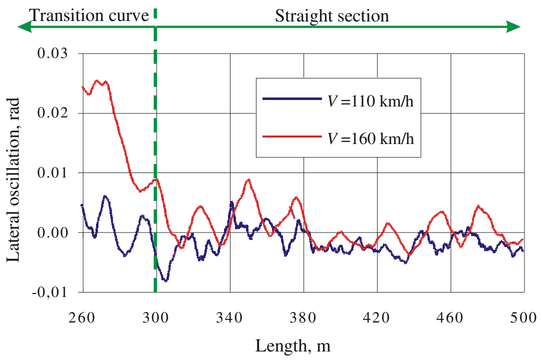

Figure 4. *Lateral oscillation of the car body during the movement along the transition curve*

movement in the range from 120 to 200 km/h, the length of the stabilization section increases at the output of the curvature by an average of 20 m for every 40 km/h.

IV. Determination of the transition curves length in the directions of the introduction of high-speed trains operation

In order to prevent operational and technical problems associated with the possibility of disorders of the permanent way, violations of smoothness and travel comfort in the implementation of the accelerated train movement, the specialization of routes of passenger and freight traffic, taking into account domestic and international needs in transportation is expedient.

Under the conditions of stability, strength and reliability in operation of the track and travel comfort, the structure of the train flow and distribution in it, the categories of trains should be appointed depending on the classification of directions of trains movement [21, 22]. **Table 2** shows characteristics for the direction of high-speed trains traffic. The recommended values of the unbalanced acceleration and its change per unit time are given in **Table 3**.

Table 2. *Characteristics of the direction by categories of trains and the structure of the train flow*

Direction characteristic	***Maximum speed, km / h***	***Categories of trains and the structure of the train flow***	***Maximum load on the axis, kN / axis***
High-speed passenger traffic	$161 < V_{\max pass} \leq 200$	- high-speed passenger trains (85-75%); - accelerated passenger trains (10-15%); - accelerated suburban train (5-10%).	- locomotives of high-speed passenger trains 215; - cars of accelerated passenger trains 180/215; - cars of suburban trains 160.

Table 3. *Security criteria, smoothness and travel comfort*

Direction characteristic	***Maximum permissible unbalanced acceleration α, m / s²***	***Maximum permissible change of the unbalanced acceleration per unit time ψ, m / s³***	***Maximum permissible speed of the wheel elevation on the right-of-way of elevation of outer rail f_v, mm / s***	***Maximum permissible steepness of the right-of-way for elevation of outer rail i, ‰***
High-speed passenger traffic	$\alpha = 0.7$	$\psi = 0.4$	$f_v = 28 \ldots 30$	$i = 0.5 \ldots 0.6$

In the zone of transition curves, the speed of trains is limited by the permissible speed of lifting wheels on the right-of-way for elevation of the outer rail f_v, unbalanced acceleration α and speed of its change in time ψ. And the length of the transition curve is established provided that: the right-of-way for elevation of the outer rail, determined by the speed of the wheel elevation on the right-of-way of outer rail f_v by the equation (3) – condition 1; the right-of-way for the curvature determined by the rate of increase of transverse unbalanced acceleration ψ by the equation (4) – condition 2.

$$l = \frac{hV_{max}}{3.6[f_v]} \tag{3}$$

$$l = \frac{\alpha V_{max}}{3.6[\psi]} \tag{4}$$

Regulatory values $[f_v]$ and $[\psi]$ are accepted by **Table 3**.

In order to calculate the length of the transition curve by the equation (3), it is necessary to set the elevation of outer rail. For high-speed purely passenger traffic

$$\mathrm{h} = \frac{S}{g}\left(\frac{V_{max}^2}{3.6^2 R} - \alpha\right) \qquad (5)$$

where S – distance between the axes of the rails; g – acceleration of gravity.

By the equation (5), minimum elevations of the outer rail are calculated, h_{min} in curves for maximum movement speed of high-speed passenger train (**Table 4**).

If the minimum elevation of the outer rail h_{min} in curves of large radii (see **Table 4**) is zero, then the length of the transition curve, in any case, is arranged as necessary for the right-of-way of the curvature (equation 4). The greater value of the transition curve of two obtained by equations (3) and (4) is taken as final. The results of calculations for the following analysis are given in **Table 5** and in **Fig. 5**.

Table 4. *Minimum elevation of outer rail in curves for the direction high-speed traffic*

Radius, m	***Elevation of the outer rail in curves (mm) at the maximum movement speed (km / h)***				
	161	***170***	***180***	***190***	***200***
1400	130	145			
1600	100	115	140		
1800	75	90	110	140	
2000	55	70	90	115	140
2200	40	50	70	90	115
2400	30	35	55	75	95
2600	20	25	45	60	80
2800	10	15	30	50	65
3000	0	5	20	35	55

Table 5. *The length of the transition curves at the maximum speed of the passenger train movement and the radius of the circular curve (direction high-speed traffic, $\alpha = 0.7\ m/s^2$)*

Radius, m	***Maximum speed of passenger train movement, km / h***				
	161	***170***	***180***	***190***	***200***
1400	170				
1600	120	170			
1800	90	130	180		
2000	70	100	150	200	
2200	50	80	120	160	
2400	50	60	90	130	180
2600	50	50	70	110	150
2800	50	50	60	80	120
3000	50	50	60	70	100

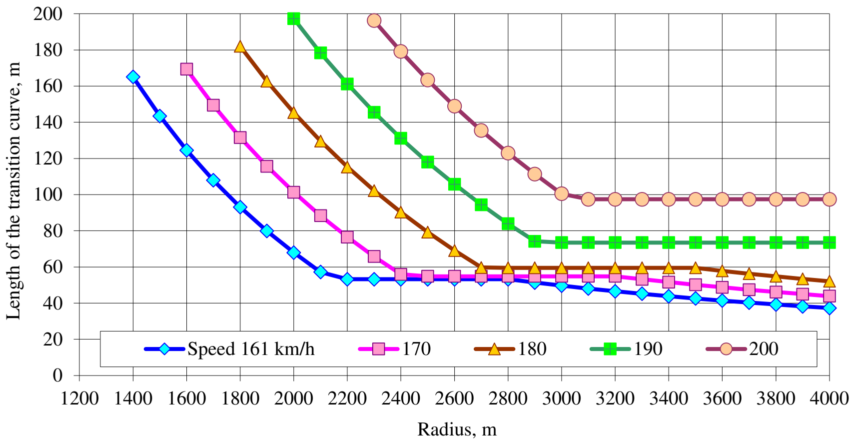

Figure 5. Dependence of the transition curve length from the radius of the curve and the maximum speed of movement in the direction high-speed traffic

The authors offer the unbalanced acceleration to take differentially depending on the distance. This approach allows us to more rationally take into account the need and possibility of restructuring the railway plan when increasing the speed of trains movement. The use of higher values of the unbalanced acceleration makes it possible to realize a higher speed in curves of the average radius (1500-2000 m). For example, at a speed of 161-200 km/h, the required length of the transition curve is reduced by 20-30 m when increasing α from 0.7 m/s^2 to 0.8 m/s^2. When applying α = 0.9 m/s^2 instead of 0.7 m/s^2 the length of the transition curves can be reduced by 40-60 m, and at α = 1.0 m/s^2 the length of the transition curves can be reduced by 50-70 m depending on the maximum speed level.

V. Conclusions

The conducted research showed that the orientation to define the length of the transition curve by the value of the calculated increase, which is determined by the weighted average speed for the train flow, should not be taken on high-speed traffic sections.

The length of the transition curve is determined by the speed of the wheel elevation on the right-of-way of the outer rail f_v (condition 1) and increasing speed of the transverse unbalanced acceleration ψ (condition 2), therefore, there is no clear dependence between the length of the transition curve and the radius of the curve. So, for example:

- at V_{max}=160 km/h the transition curve length l decreases from 170 metres at =1400 m up to 50 metres at R=2200 m (condition 1); in the range R=2200-3300 m, the transition curve length is constant and equal to l=50 m, in the range R=3400-4200 m l=40 m, in the range R=4300-5000 m l=30 m (condition 2);
- at V_{max}=180 km/h the transition curve length l decreases from 180 metres at R=1800 m up to 60 metre at R=2700 m (condition 1); in the range =2700-3700 m the transition curve length is constant and equal to l=60 m, in the range R=3800-4600 m l=50 м , in the range R=4700-5000 m l=40 m (condition 2);
- at V_{max}=200 km/h the transition curve length l decreases from 200 metres at R=2300 m up to 100 metre at R=3000 m (condition 1); in the range R=3000-4500 m the transition curve length is constant and equal l=100 м, in the range R=4500-5000 m l=90 m (condition 2).

The analysis showed that with correctly set parameters of transition curves, which correspond to the maximum speed of movement and radius of a circular curve, the strength and reliability of the bearing elements in the structure of the permanent way and the travel comfort are fully ensured.

AUTHOR CONTRIBUTIONS

All authors made a substantial, direct, and intellectual contribution to this work. The manuscript was written through the contribution of all authors. All authors discussed the results, reviewed and approved the final version of the manuscript.

Disclosure Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] M. B. Kurhan, D. M. Kurhan. Theoretical basis for the introduction of high-speed trains in Ukraine, Dnipro, Ukraine, 2016, 283 p. ISBN 978-966-8471-78-0, in Ukrainian.

[2] S. Fischer. Comparison of railway transition curves, MSc. thesis, Széchenyi István Egyet (2007), in Hungarian. https://doi.org/10.13140/RG.2.1.3943.1845

[3] T. F. Brustad, R. Dalmo. Railway Transition Curves: A Review of the State-of-the-Art and Future Research, Infrastructures 5 (5), 43 (2020). https://doi.org/10.3390/infrastructures5050043

[4] T. F. Brustad, R. Dalmo, R. Exploring Benefits of Using Blending Splines as Transition Curves, Applied Sciences 10 (12), 4226 (2020). https://doi.org/10.3390/app10124226.

[5] A. Pirti, M. A. Yücel, T. Ocalan. Transrapid and the transition curve as sinusoid, Technical Gazette 22 (6) (2015). https://doi.org/10.17559/TV-20140217144435.

[6] R. Wojtczak. Charakterystyka krzywej przej´sciowej Wiener Bogen®, Publishing House of Poznan University of Technology: Poznan, Poland, 2017.

[7] S. Fischer. Comparison of Railway Track Transition Curves in consideration of clothoid, cosine and Wiener Bogen transition curves in the respect of the ENV 13803-1, the ÖBB

standard and the Hungarian railway design regulations (TADR, NRR) in the interval of V=120…160 km/h for normal track gauge, Fourth International PhD&DLA Symposium (2008). https://doi.org/10.13140/RG.2.1.4046.6089.

[8] T. Fossli Brustad, R. Dalmo. Railway Transition Curves: A Review of the State-of-the-Art and Future Research, Infrastructures 5(5):43 (2020) https://doi.org/10.3390/infrastructures5050043

[9] W. Koc. Smoothed transition curve for railways, Transportation Overview - Przeglad Komunikacyjny 7 (2019) pp. 19-31. https://doi.org/10.35117/A_ENG_19_07_03.

[10] W. Koc. Transition Curves on Railway Roads in Terms of Feasibility, Problemy Kolejnictwa - Railway Reports (2019) pp.125-137.

[11] K. Zboinski, P. Woznica. Optimum Railway Transition Curves—Method of the Assessment and Results, Energies 14 (13), 3995 (2021). https://doi.org/10.3390/en14133995.

[12] P. Chrostowski, W. Koc, K. Palikowska. Prospects in elongation of railway transition curves, ICE Proceedings Transport 173 (5) (2017). https://doi.org/10.1680/jtran.17.00097.

[13] V. A. Lazaryan. On the shape of the transition curve, Vehicle dynamics (1985) pp. 10-24, in Russian.

[14] Lahuta V. V. Improving the design of railway curves in the plan, Ph.D. thesis, Dnipro National University of Railway Transport named after Academician V. Lazaryan (2002), in Ukrainian.

[15] S. Fischer. Comparison of railway track transition curves, Pollack Periodica 4 (3) (2009) pp.99-110 https://doi.org/10.1556/Pollack.4.2009.3.9.

[16] S. Fischer. Compatibility of the HungarIan railway design guideIlnes with the European standards, közúti és mélyépítési szemle 58 (2008), pp. 30-35, in Hungarian.

[17] M. Przybyłowicz, M. Sysyn, U. Gerber, V. Kovalchuk, S. Fischer. Comparison of the effects and efficiency of vertical and side tamping methods for ballasted railway tracks, Construction and Building Materials 314 (Part B):125708 (2022). https://doi.org/10.1016/j.conbuildmat.2021.125708.

[18] S. Fischer. Investigation of the Horizontal Track Geometry regarding Geogrid Reinforcement under Ballast, Acta Polytechnica Hungarica 19 (3) (2022), pp. 89-101. https://doi.org/10.12700/APH.19.3.2022.3.8.

[19] State building norms of Ukraine. Transport facilities. Railway track 1520 mm. Design standards, SBN B.2.3-19:2018, Kyiv, Ukraine, 2018, 129 p., in Ukrainian.

[20] G. Velichko. Properties Study of the Harmonized Shape Transition Sections of the Railway Track Curves, Proceedings of the 25th International Scientific Conference, Transport Means 2021, pp. 16-21.

[21] Instructions on the arrangement and maintenance of the railway track of Ukraine, CP-0269, Kyiv, Ukraine, 2012, 456 p., in Ukrainian.

[22] M. Kurhan, D. Kurhan, M. Husak, N. Hmelevska. Increasing the Efficiency of the Railway Operation in the Specialization of Directions for Freight and Passenger Transportation, Acta Polytechnica Hungarica 19 (3) (2022), pp. 231-244. https://doi.org/10.12700/APH.19.3.2022.3.18.