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Selected implications of a hyper-connected world on pavement engineering

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Abstract

The world is becoming a hyper-connected environment where an abundance of data from sensor networks can provide continuous information on the behaviour and performance of infrastructure. The last part of the 3rd Industrial Revolution (IR) and the start of the 4th IR gave rise to a world where this overabundance of sensors, and availability of wireless networks enables connections between people and infrastructure that was not practically comprehensible during the 20th century. 4IR supports the datafication of life, data science, big data, transportation evolution, optimization of logistic and supply chains and automation of various aspects of life, including vehicles and road infrastructure. The hyper-connected 4IR environment allows integration between the physical world and digital and intelligent engineering, increasingly serving as the primary lifecycle management systems for engineering practitioners. With this background, the paper evaluates a few concepts of the hyper-connected pavement environment in a 4IR Digital Twin mode, with the emphasis on selected applications, implications, benefits and limitations. The hyper-connected world can and should be managed in the pavement realm to ensure that adequate and applicable data are collected regarding infrastructure, environment and users to enable a more efficient and effective transportation system. In this regard, and planning for future scenarios where the proliferation of data is a given, it is important that pavement engineers understand what is possible, evaluate the potential benefits, conduct cost / benefit evaluations, and implement appropriate solutions to ensure longevity and safety of pavement infrastructure.

Keywords: Hyper-connected pavement; Digital twins; Intelligent infrastructure

1. Introduction and background

Over the last two decades the world became an increasingly connected place, with hosts of devices and networks that connect infrastructure, people and devices. The last part of the 3rd Industrial Revolution (IR) and the start of the 4th IR gave rise to a world where the overabundance of sensors, and availability of wireless networks (including Wi-Fi, 3-, 4-, 5-G mobile, Bluetooth®, LoRAWAN®, SigFOX®, etc.) enables connections between people and infrastructure that was not practically comprehensible during the 20th century. It is estimated that there are around 20.8 billion connected devices currently, and expectations are that the number of Internet of Things (IOT) devices will grow to more than 1 trillion in the foreseeable future [1].

Schwab [2] introduced the term 4IR as a phase of industrial development characterized by a more ubiquitous and mobile Internet, smaller, cheaper and more powerful sensors, and artificial intelligence and machine learning, leading to a world with intertwined virtual and physical systems. 4IR supports the datafication of life, data science, big data, transportation evolution, optimization of logistic and supply chains and automation of various aspects of life, including vehicles and road infrastructure. The hyper-connected 4IR environment allows integration between the physical world and digital and intelligent engineering [3,4]. This fusion of reality and virtual environments (Digital Twins) span across disruptive transportation systems, and smart and intelligent infrastructure [5]. Through these systems, prodigious quantities of data can be characterized by the 5 Vs - velocity, variety, veracity, value and volume [6].

Digital Twins (DT) can be defined as “an integrated multi-physics, multiscale, and probabilistic simulation of a complex product and uses the best available physical models, sensor updates, etc., to mirror the life of its corresponding twin” [7]. Cyber-physical data systems and Big Data implementations increasingly serve as the primary lifecycle management systems for engineering practitioners, particularly in a 4IR environment [6]. Applications of DT implementations can provide for improved lifecycle management of infrastructure and assets, specifically when operated in a continuous data mode.

A further feature of the hyper-connected 4IR environment is the continuous availability and collection of data. Where traditional

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data collection efforts (specifically related to road pavement infrastructure) often consisted of sporadic data collections with long intervals (typically annual), the current environment enables an unceasing flow of sensor data with an almost uninterrupted indication of infrastructure response and behaviour to internal and external stimuli. Such continuous data-flows require specific techniques to effectively manage and analyse the data [8,9].

With this background, the paper evaluates a few concepts of the hyper-connected pavement environment in a 4IR DT mode, with the emphasis on selected applications, implications, benefits and limitations. It is highly appreciated that in such a developing field new insights occur at a quick pace, and therefore these thoughts are offered as guidelines for further investigation and reflection.

2. Hyper-connections in pavement engineering

The focus of this paper is a hyper-connected pavement environment. This includes the pavement structure, materials, environment, and traffic. It can be expanded to include laboratory derived data on materials as well as databases of collected information where such information can continuously and without undue hindrance be incorporated into a DT of the infrastructure. The main objective of such a hyper-connected DT environment for a pavement is the continuous monitoring of demand and supply. Demand being defined as the requirements placed on the pavement by the traffic loads and environment, and supply being the inherent properties of the pavement to cope with such demands. In this context, when demand is less than supply, the pavement should function well, while a situation with supply being less than demand leads to premature failures.

2.1. Hyper-connected structure

A hyper-connected pavement structure consists of a structure that incorporates sensors that communicate continuously through a network to a central hub where data are collected and analysed. Such analyses should preferably run on a continuous basis with flags that can be activated whenever a selection of the monitored properties exceed stated values. Data being continuously stored in this warehouse enables a historical database to be generated that becomes part of the standard Pavement Management System (PMS) operations of the road owner. Parameters that are typically monitored in this structure can include temperature, moisture, accelerations, deformation etc. [10,11]. Selection of appropriate sensors depends partly on the pavement structure (rigid / flexible), materials incorporated (temperature / moisture sensitivity), environment and traffic.

2.2. Hyper-connected materials

A hyper-connected pavement structure database is only valuable if details regarding the materials inside the pavement are available. This enables decisions to be made regarding the experience of the various materials / layers in the pavement, and decisions regarding possible over-stress / -strain conditions that requires a flag to be raised. The hyper-connected materials database typically consist of a database of laboratory-generated materials properties for the specific materials used in the pavement structure. It can also incorporate materials databases where typical values under stated conditions, as well as variations in such parameters are defined. The outputs of a reference laboratory can typically play a major role in developing such materials databases that can be centrally linked to the network with pavement structure data [12].

2.3. Hyper-connected environment

Environmental conditions play a major role in the behaviour and performance of any pavement structure. This includes temperature, humidity, Ultraviolet radiation, rainfall, air quality, etc. [13]. Weather station data are typically easily available in developed areas, however, in rural areas such data may be less available. The effect of micro-environments on pavement behaviour should also be incorporated in the collection and analysis of environmental data. Shadows cast by road furniture or vegetation can for instance change the microclimate significantly, causing localised failures [14-16]. Online availability of cloud-based environmental data are becoming a viable alternative to obtain local environmental conditions [17].

2.4. Hyper-connected traffic

Vehicle technologies are advancing to incorporate various connectivity options (Vehicle to Vehicle (V2V), Vehicle to Infrastructure (V2I), Vehicle to Everything (V2X)), depending on the availability of networks to carry the data from the sensors incorporated in the vehicles [18]. Hyper-connected traffic systems include not only data generated from vehicles, but also information such as traffic classification, counting and speed, based on Artificial Intelligence (AI) camera-linked networks that can provide accurate indications of the traffic stream (demand) on a road. Initial evaluation of such a system on the Engineering 4.0 DT facility showed counting accuracy of 5 % compared to actual traffic counts.

2.5. Hyper-connected pavement engineering

Merging of the data originating from the hyper-connected pavement structure, materials, environment and traffic brings together and generates a DT of the complete pavement environment (road furniture and structures are excluded in this paper, but obviously form a large portion of the bigger DT of the infrastructure environment) which can be utilized for improved road infrastructure management and maintenance. The concept is shown in a simplified schematic in Fig. 1.

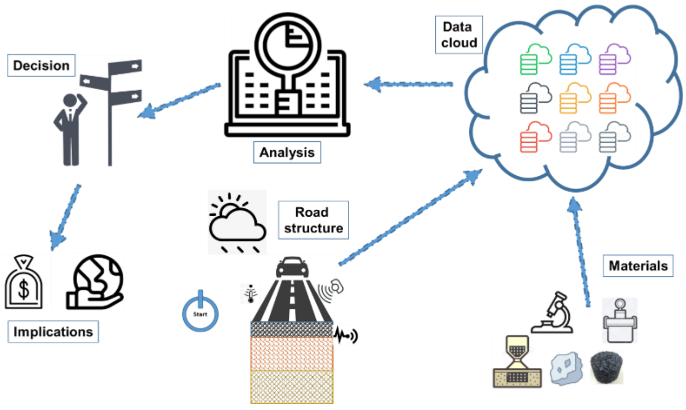

Fig. 1. Schematic of a hyper-connected pavement digital twin.

3. Application example

Discussing concepts without actual data can be beneficial for a thought experiment to reflect on potential future environments. However, actual data are useful in demonstrating the potential of such environments with initial inferences regarding the potential benefits of such hyper-connected DT concepts. In some initial experiments incorporated into a DT of a campus environment as well as an agricultural transportation environment, actual data collections already provide some inferences on the potential benefits of continuously collected data.

3.1. *Digital twin infrastructure*

The Innovation Africa (IA) campus of the University of Pretoria is situated on the eastern edge of the main campus. It consists of 146 ha of original experimental agricultural fields that are currently being redeveloped to enable smart agricultural, infrastructure and transportation research. The Engineering 4.0 facility is one of the latest additions to this campus. It consists of a combination of a national road materials reference laboratory, training laboratory, concrete and related materials laboratory, Accelerated Pavement Testing (APT) track and an active traffic lane on the adjacent highway [19]. Engineering 4.0 is the hub of a LoRAWAN network on this campus from where a host of mostly environmental data are currently collected [20], forming the basis of a DT of this campus.

From a pavement engineering viewpoint the DT incorporates asphalt temperature and base moisture condition data, as well as an AI traffic count and classification facility for the adjacent highway.

As an example of the application of DT data from the pavement, Fig. 2 indicates the process of tracking asphalt surfacing data through to expected life effects on the asphalt layer. Fig. 2 starts (left top) with the actual measured temperature inside the 50 mm asphalt layer (constructed on top of a deep granular base layer). A rainfall event suddenly causes a decrease in asphalt temperature from 47°C to 31°C. This causes a change in the modulus of the asphalt of around 62 % (top right) which leads to a 24 % increase in vertical stress at the interface between the asphalt and the granular base (bottom right) and a resultant decrease in asphalt life of around 55 % (bottom left).

Although this is just one example (and obviously dependent on specific environmental data and materials), it highlights the benefit of having access to continuous data from the DT of the pavement, as it can emphasise the effects of sudden environmental changes on the behaviour and expected performance of the pavement structure. This simple example needs to be incorporated into a more complex model where the full history of the pavement structure, also combined with the actual traffic loading on the pavement during the various environmental events, are incorporated. This will lead to a much more comprehensive understanding of the continuous influences of environmental and traffic demands on the pavement behaviour and performance.

This process can be expanded to any road network where the appropriate sensors are available. This gives rise to a DT management tool for the pavement.

3.2. *Digital twin agricultural transportation*

In the hyper-connected agricultural logistics example, a DT is being developed of the transportation process of tomatoes and avocados from the field to the market. Through development of smart fruits [21-23], the experience of the transported fruits can be tracked continuously, providing a clear indication of any locations during the transportation process where stressors (e.g. low riding quality, unmaintained vehicle suspension, etc.) potentially causes damage to the transported goods. Linking this into a road

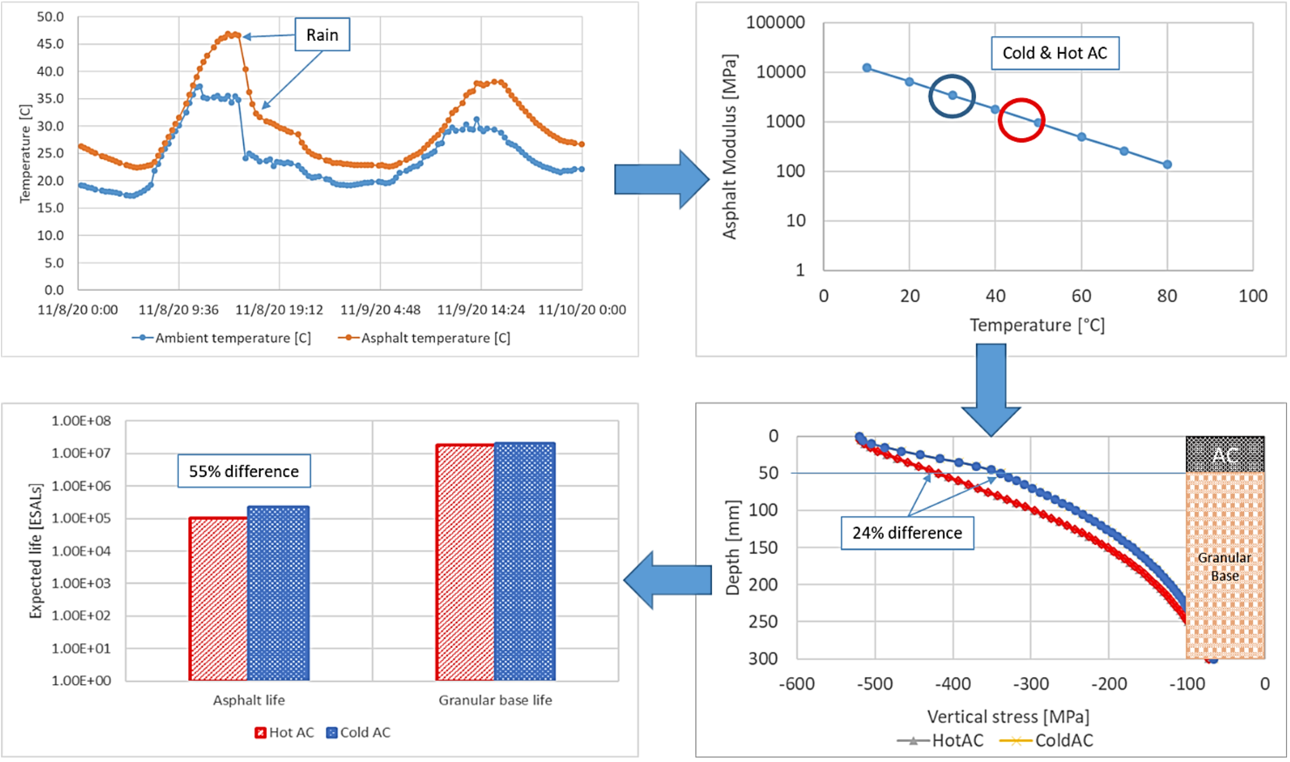

Fig. 2. Sequence of effects of change in Asphalt surfacing temperature change due to rainfall event.

maintenance management system [24] leads to an always-on DT of the transportation and the maintenance processes. The process delivers continuous information such as kinetic energy experienced by the transported produce, allowing identification of stress locations in the network (Fig. 3).

This information can significantly affect the management process of the infrastructure on which the produce is transported, as well as issues such as route optimization for low-damage transportation. It directly affects the agricultural economic value chain, demonstrating the benefit of access to real-time infrastructure information [22].

4. Implications for pavement engineering

The proliferation of sensors and networks is leading to a situation where continuous data regarding the behaviour and performance of pavements as well as factors affecting this behaviour can be collected. This situation allows for various challenges and benefits. These challenges and issues for reflection with the hyper-connected pavement networks include:

1. Sensor maintenance: The nature of a road pavement is that there are constant traffic loading applying stresses onto the materials, as well as exposure to the external environment. Sensor design should enable pavement, environmental and traffic sensors to withstand these stresses, and a process of ongoing maintenance and replacement when needed is required. This may affect the condition of the pavement at the time of maintenance or replacement;
2. Sensor energy management: Energy management includes the selection of appropriate power sources for the sensors. Many IOT devices operate on very low energy requirements, and examples of energy resource management that limits energy use, as well as extraction of energy from the immediate environment are already cited [25-27];
3. Compatibility with pavement environment: The influence of the sensor on the surrounding materials (especially when embedded inside the pavement structure) should be quantified. With miniaturisation of sensors, this effect is diminishing. However, it is advisable to conduct evaluations comparing the behaviour of sections of pavement with and without the embedded sensors to ensure that sensor influence on the surroundings does not influence behaviour and data significantly;
4. Data storage: Decisions need to be made regarding the actual data to be collected and what needs to be stored. Much space can be saved through truncated storage of main parameters. Such a process, however, limits later analysis of the collected data and should probably be discouraged, as this does lead to inability to replicate the conditions under which data were collected entirely. Mobile Edge Computing (MEC) is one possible solution to some of the data storage and transfer issues [28];
5. Data analytics: Development of data analytics procedures to effectively and efficiently analyse the continuous, large data sets that are available, and to ensure the correct inferences based on not only a statistically correct analysis of the data, but also a deep understanding of the fundamental pavement / environment / traffic relationships that define such possible inferences, are required;
6. Implications of outputs on pavement engineering: A clear understanding is required to be developed on the implications of continuous data on pavement, environment and traffic behaviour on general pavement engineering. Questions such as “how quickly should the pavement engineer react to changes in data from the pavement?”, “What level of changes constitute a need for action regarding maintenance?”, etc. needs to be clarified. The current operational model is that surveys are conducted on at best an annual basis, with maintenance actions probably only conducted around 18 months after the initial survey was done (except for emergency maintenance). The availability of continuous data can affect this model significantly, and reflection is required on whether or not this will really lead to improved and more cost-effective road networks;
7. Numbers of sensors and placement: With low-cost miniature sensors operating in a wireless mode, a swarm of sensors inside and adjacent to a pavement becomes possible. However, an optimal number of sensors will exist for the adequate and efficient collection of data that are required to manage the pavement, and this optimum should be defined for different types of sensors (pavement, materials, environment and traffic), without flooding the environment with an overabundance of sensors, but also without missing significant localized areas where behaviour may be significantly different to the remainder of the pavement evaluated in the DT model.

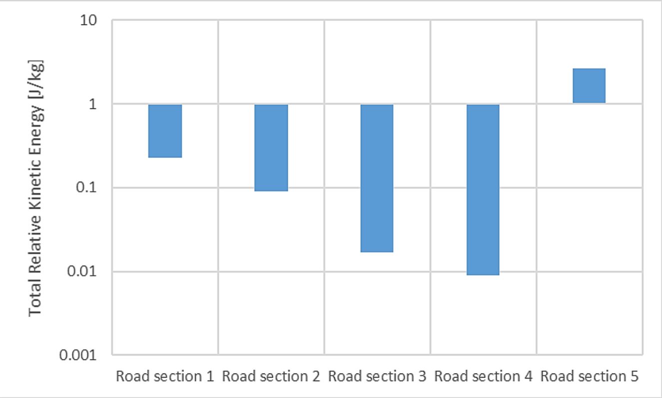

Fig. 3. Example of kinetic energy experienced by agricultural produce transportation collected through DT modelling.

The overall beneficial implication to pavement engineering of a hyper-connected pavement environment, should be a continuous understanding of infrastructure condition, leading to timeous decision-making. Examples such as autonomous road maintenance based on continuous data collection will have a significant beneficial effect on service levels and infrastructure management [24]. This should also lead to more cost-effective pavement infrastructure.

5. Conclusions

The world is becoming a hyper-connected environment where an abundance of data from sensors networks can provide continuous information on the behaviour and performance of infrastructure. Such a hyper-connected world can and should be managed in the pavement realm to ensure that adequate and applicable data are collected on the infrastructure, environment and users to enable a more efficient and effective transportation system to users. In this regard, and planning for future scenarios where the proliferation of data is a given, it is important that pavement engineers understand what is possible, evaluate the potential benefits, conduct cost /

benefit evaluations, and then implement appropriate solutions to ensure longevity and safety of pavement infrastructure.

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