ASTM INTERNATIONAL

Journal of Testing
and Evaluation

Wynand JvdM Steyn[1] and André Broekman[2]

DOI: 10.1520/JTE20210043

Development of a Digital Twin of a Local Road Network: A Case Study

Journal of Testing and Evaluation

doi:10.1520/JTE20210043 available online at www.astm.org

Wynand JvdM Steyn[1] and André Broekman[2]

Development of a Digital Twin of a Local Road Network: A Case Study

Reference

W. JvdM Steyn and A. Broekman, "Development of a Digital Twin of a Local Road Network: A Case Study," *Journal of Testing and Evaluation* https://doi.org/10.1520/JTE20210043

ABSTRACT

Virtual replicas of infrastructure can be used to run simulations and optimize the construction, management, and maintenance of such assets throughout their entire lifecycle. These digital twins (defined as integrated multi-physics, multiscale, and probabilistic simulations of a complex product) mirror the behavior and environmental responses of its corresponding twin. Digital reconstruction techniques using optical sensor technologies and mobile sensor platforms are providing viable, low-cost alternatives to develop digital twins of physical infrastructure. In previous work, the digital twinning of asphalt pavement surfacings using visual simultaneous localization and mapping and the initiation of a digital twin of a local road network were investigated and successfully demonstrated. In this article, the further development of the concept, incorporating road surface temperatures collected over a 1-month period, as well as potential inferences based on these data, in the micro- and macro-twinning of a local road, are discussed. Light detection and ranging, unmanned aerial vehicles, and traffic counting artificial intelligence allows for quantification of the road geometry and infrastructure utilization over large areas (macro-twinning), whereas the photogrammetric reconstruction technique based on a neural network, a proprietary environmental condition sensor (SNOET, or SNiffing Omgewing / Environmental Tester) and commercial temperature sensors were used to acquire the surface texture and environmental conditions respectively (micro-twinning), as well as surface temperatures at four locations and different surfacing materials. The combination of advanced environmental monitoring data, physical data, and surface temperature data provide management data that can assist in the maintenance of such roads. This article expands (with the permission of the conference organizers) on a GeoChina 2021 article through the addition of further temperature data collected on the discussed digital twin, with substantial additional data analysis and discussion.

Manuscript received January 22, 2021; accepted for publication April 5, 2021; published online xxxx xx, xxxx.

[1] Department of Civil Engineering, Engineering Built Environment and IT (EBIT), University of Pretoria, Private Bag X20, Lynnwood Rd., Hatfield 0083, South Africa (Corresponding author), e-mail: wynand.steyn@up.ac.za, https://orcid.org/0000-0001-5893-3733

[2] Department of Civil Engineering, Engineering Built Environment and IT (EBIT), University of Pretoria, Private Bag X20, Lynnwood Rd., Hatfield 0083, South Africa, https://orcid.org/0000-0002-3368-2947

Keywords

digital twin, local roads, light detection and ranging, long range, wide area networking protocol, transportation engineering, civiltronics

Introduction and Current Understanding

Tao et al.[1] defines a digital twin 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." For engineering practitioners, cyber-physical data better serve the lifecycle management of infrastructure and assets. These cyber-physical systems and Big Data implementations (Núñez et al.[2]) increasingly serve as the primary lifecycle management systems for engineering practitioners, particularly during the 4th Industrial Revolution. These digital twins are underpinned by powerful and intelligent sensor platforms alongside network connectivity at the physical edge of the sensor platform. Improved wireless sensor capabilities, decreasing power consumption and costs drive the accelerating adoption of such sensor platforms.

Various entities have started to experiment with the concept of digital twins of campuses and road infrastructure, although most of the digital twin work in the built environment focuses on actual building infrastructure (e.g., Ruohomäki et al.[3]). In Qiuchen et al.,[4] the development of such a digital twin on the west Cambridge campus in the United Kingdom is discussed, with a major emphasis on the importance of the data on which any digital twin is based. This is an essential issue, as the architecture and systems for a digital twin merely provide the platforms for the data to be connected. Without active and relevant data, a digital twin cannot operate. Machl et al.[5] discussed the use of digital twins in the development of an agricultural road network, modeling the infrastructure as well as operations on such a network. Liu et al.[6] concludes that a digital twin essentially is an individualized (one-to-one with individual physical twin), high-fidelity (simulate behavior as exact as possible), real-time (response with relatively low latency), and controllable (changes on one twin control the other twin) system that aims to realize digital-physical convergence.

This fusion of electronic engineering, information technology, materials science, and computer science—together with traditional civil engineering theory—is collectively referred to as civiltronics (Steyn and Broekman[7]). Intricate engineering challenges benefit from this transdisciplinary approach and revolutionary new technologies supporting the seamless integration of cyber-physical systems. Examples include the development of a three-dimensional (3-D) printed ballast particle (Kli-Pi) that can measure the in situ, three-dimensional acceleration and rotation characteristics of a discrete particle (Broekman and Gräbe[8,9]). This contrasts with traditional instrumentation techniques that consider only the macroscopic response of the track structure, ignoring the driving mechanism of permanent settlement on a mesoscale (discrete) level.

This article evaluates a case study of the development of a local road network digital twin, discussing the micro- and macro-twinning concepts, with additional data regarding road surface temperature and potential applications of such data in a digital twin.

It is believed that the type of digital twin discussed and proposed in this article will lead to an improvement in provision of smart and green infrastructures with optimum life cycle, as continuous monitoring of road infrastructure condition provides for early warning and indication of potential distress. This provides the opportunity of early remedial action before expensive deterioration and subsequent repairs are needed on the infrastructure. Further, it allows for more appropriate maintenance budget allocations.

Quantification of Road Performance and Surface Textures

Pavement roughness is defined as the irregularities of a pavement surface as measured over a fixed distance between two points in space (Sayers and Karamihas[10]). This affects long-term vehicle maintenance and operating costs and fuel consumption. The development of comparatively accurate laser-based scanning systems automated the process of measuring pavement surface texture (Sengoz et al.[11]). During the last decade, low-cost tri-axis acceleration sensor platforms were employed, notably in the agricultural sector in South Africa, for collection of pavement roughness data. The data-driven approach for road maintenance improves the operational efficiencies through optimized blading of unpaved roads when riding quality deteriorates below a certain threshold (Pretorius and Steyn[12]). Telematics devices in vehicles can be exploited for the same application, alongside existing communications infrastructure that relays the data to a centralized storage, processing, and visualization service (Wessels and Steyn[13]). This methodology uses calibrated response type algorithms to provide class 3 road roughness classification continuously. Additionally, the measurements are independent of the vehicle dimensions and suspension characteristics, speed, and operation conditions (Wessels and Steyn[13]). Even though these devices provide an approximated geolocation alongside a quality classification and failure identification of short sections of roadway, poor signal coverage and obstructions in rural areas provide limited definition and resolution of the in situ road geometry.

On a much smaller dimensional scale, existing measurement techniques of the pavement surface texture are qualitative and prone to operator bias. The methods for determining the mean profile depth and mean texture depth are clearly defined (ASTM E1845-15, *Standard Practice for Calculating Pavement Macro-Texture Mean Profile Depth*[14]; ASTM E965-96, *Standard Test Method for Measuring Pavement Macro-Texture Depth Using a Volumetric Technique*[15]; Van Zyl and Van der Gryp[16]). Execution of these processes lends itself to digital collection and analysis. Experimental evidence supports the notion of obtaining quality measurements surpassing that of the traditional sand patch method when employing laser-based 3-D scanning techniques (Sengoz et al.[11]). Steyn et al.[17] detail the methodology required to digitize small areas of in situ pavements using a digital scanner. Although the areas are small when compared to the size of the road, the calibrated accuracy of 10–15 µm is unparalleled. Significantly, digitization of a defined section of the road serves as data input into a digital twin to measure the progressive interparticle orientation and settlement as influenced by traffic loading. This can be applied in a normal trafficked situation, or in an experimental accelerated pavement testing application (Jordaan et al.[18]). Changes in the micro-twinning data can be described statistically using a probability mass function for the roughness and curvature properties.

Autonomous and Dynamic Road Maintenance

An online digital twin of a road section serves as the necessary interface to implement dynamic maintenance schemes. In these schemes, autonomous and dynamic scheduling is supported by a continuous stream of road condition data from a variety of sources (Steyn[19,20]). This can range from more complex, sparsely implemented continuous vehicle response tracking, to automatic vehicle counting and classification measuring the traffic load over a defined section of road. Automation of mining haul road monitoring and maintenance, confined to a more controlled environment, has successfully demonstrated automatic road grading systems with improvements tied to the adoption of ever-more accurate and sophisticated technology (Heikkilä and Jaakkola[21]; Thompson et al.[22]). Through incorporating existing mine communications and assets management systems, the autonomy of dispatching maintenance equipment to priority areas, and therefore urgency and completion of maintenance actions to near real-time implementation has been achieved (Marais et al.[23]). Regression models combining road roughness, maintenance history, and historical rainfall data have been used to successfully model the deterioration of unpaved agricultural road networks (Swanepoel et al.[24]). As indicated by Quichen et al.,[4] continuous data are essential for the operation and functionality of any digital twin, and therefore, the current expansion of Internet of Things (IoT) devices and coverage networks in rural areas support the development and implementation of real-time maintenance and asset management systems on even smaller local road networks.

Methodology

Digital twinning can be subdivided into macro-twinning and micro-twinning applications. For macro-twinning, the geometry of the road and road utilization is considered using two optical instrumentation systems.

High-accuracy light detection and ranging (LiDAR) and photogrammetry using an unmanned aerial vehicle/drone are used for the geometry, whereas video media acquired with the drone were used for traffic counting applications (road utilization). The latter can also be collected using various types of fixed camera systems connected to a network. For micro-twinning applications, a novel three-dimensional neural network (NN) reconstruction technique is investigated alongside environmental and air quality measurements that are indicative of factors that affect the surrounding roads. The digitization process of the digital twins (micro- and macro-) was divided into three steps. These are sample preparation or identification, data acquisition, and digital processing (in conjunction with interpretation). **Figure 1** provides a reference map of the Engineering 4.0 campus (located in Pretoria, South Africa), highlighting the location of the various points of interest mentioned in the article. It shows locations of the central receiving antenna, as well as locations where data were collected that are discussed in the article. Road surfacing temperatures were collected for four different road surfacing types, over a period of 1 month since initialization. The surfaces included an asphalt (in direct sun and in shade), concrete block paving, concrete and graded aggregate.

MACRO-TWINNING

In macro-twinning, the article evaluates a concept where the LiDAR, SNOET (or SNiffing Omgewing / Environmental Tester), photogrammetry, and traffic artificial intelligence (AI) work are done on a wider scale on the specific campus. The objective of this work is to incorporate the entire 106 ha campus inside the digital twin. This is followed by more frequent micro-twinning steps using selected sensors, as well as additional photogrammetry techniques. An overall schematic of the process is shown in **figure 2**.

An example of the LiDAR imaging of the first section of road is shown in **figure 3**. LiDAR data consist of a point cloud indicating the physical infrastructure that was scanned. The data are converted into standard computer-aided design packages to become part of the digital model. The photogrammetry reconstruction is currently based on a drone scan using high-resolution photographs of the buildings and features of the campus (**fig. 4**). Both the LiDAR and photogrammetry scans can be combined in the digital twin to ensure that not only high-quality data clouds with better than 50-mm accuracy are available for detailed analysis but also 3-D imaging information.

SNOET is a proprietary multicomponent sensor platform that was developed as a proof-of-concept prototype, integrating available sensor breakout boards that could be commercially sourced with a low-cost

FIG. 1

Overview of Engineering 4.0 and various data collection locations and infrastructure.

FIG. 2 Overall schematic indication of digital twinning process for local road application.

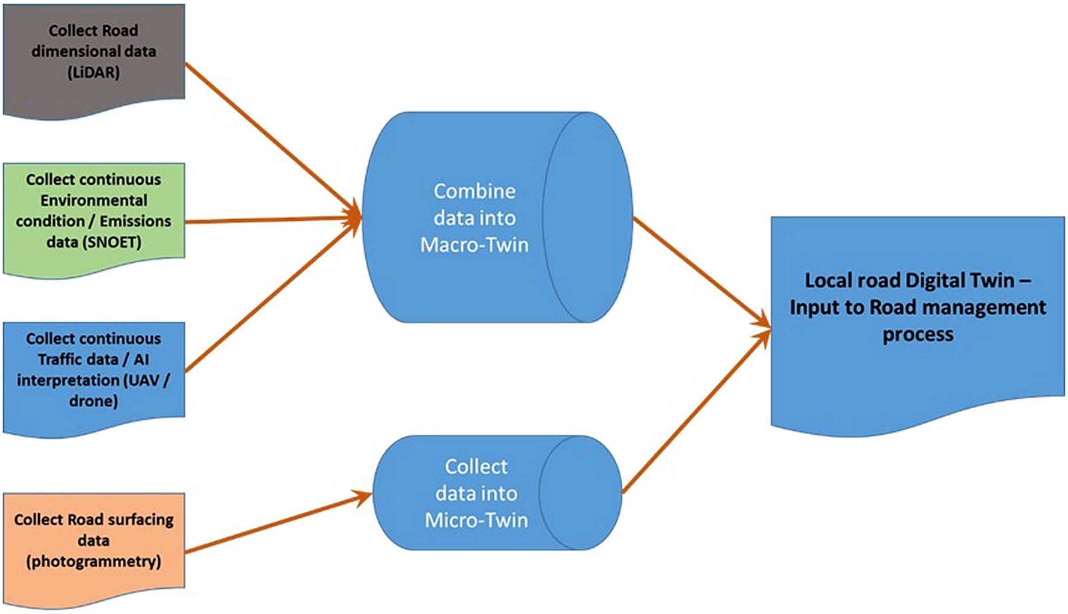
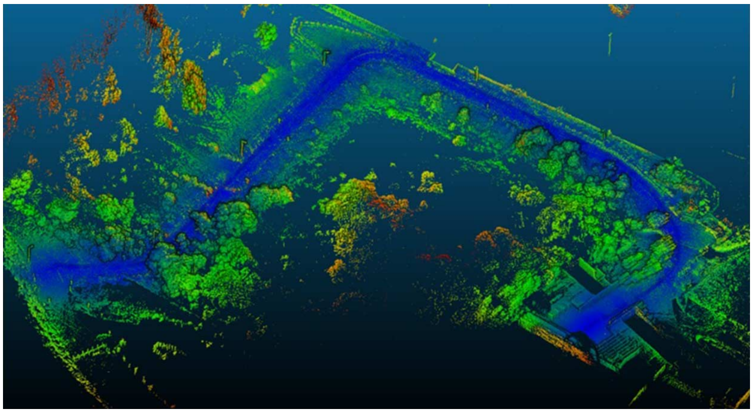


FIG. 3

LiDAR captured macro-twinning road details.



microcontroller based on the Arduino architecture. The measurement parameters include temperature, relative humidity, barometric air pressure, total volatile organic compound (TVOC) concentration, carbon dioxide (CO_2) concentration, air quality, geolocation, infrared temperature, light intensity, and ultraviolet radiation. On the macro-twinning model, SNOET surveys are conducted using mobile options along the roads and paths on the campus (**fig. 5**). This provides for accurate environmental data at various times of the day along these routes. These data are combined with a static network of devices where continuous data are collected to develop environmental reference timelines. This static network communicates using a LoRaWAN (long range, wide area networking protocol) network to enable continuous and current data in the central data repository.

As the traffic data source for the digital twin, the OpenDataCam open source real-time analysis framework is trialed as a potential low-cost, readily scalable solution to count and classify vehicles along the highway using

FIG. 4

Photogrammetry reconstruction of storage building.

FIG. 5

SNOET-based TVOC and CO_2 data collected using mobile options on selected roads.

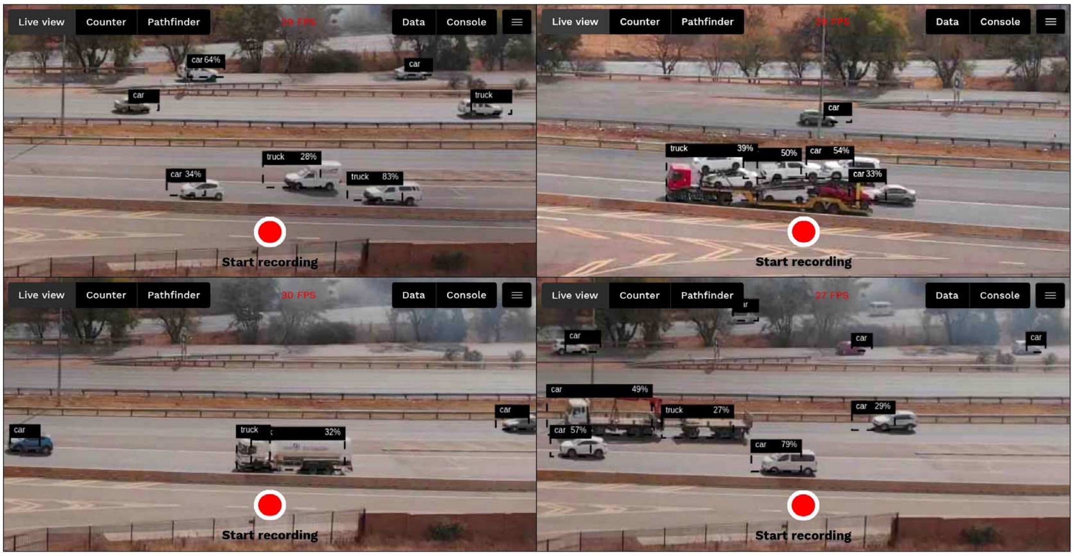
lightweight, pretrained NNs. It is specifically designed for deployment on power efficient, edge processing hardware that feature real-time inference capabilities, negating the need to store the large quantities of data for post-processing. Screenshots of the analysis indicate the observations with identification of the various vehicle classes (fig. 6). A counting accuracy of 5% was realized compared to ground truth traffic counts. Average speed could be approximated as the geometric scale of the road is known between predefined counting stations.

MICRO-TWINNING

NNs are ideal for applications where programming rules and algorithms are impossible to define explicitly. Current photogrammetric pipelines are computationally expensive, particularly for the dense 3-D point reconstruction and meshing components. Multi-view stereo network (MVSNet) (Yao et al.[25]) was developed as a deep learning architecture for depth map inference from unstructured multiview images. The network is pretrained on calibrated datasets (e.g., Broekman and Gräbe[26]). It accelerates the depth map inference with sufficient accuracy when provided with a minimum of three images, each with known intrinsic and extrinsic camera properties. In this article, a section of road on the local road network with visible signs of damage and deterioration to the seal was selected. A total of 45 photographs were captured on a Samsung Galaxy S9 cellphone in a circular pattern from three different heights.

Thereafter, the structure-from-motion was computed (using COLMAP) from the photographs to calculate the relative orientation and location of the cameras. The camera properties, together with the photographs, where

FIG. 6 OpenDataCam interface illustrating real-time object detection and inference confidence scores.



processed through the MVSNet NN. Although the image resolution (768 by 576 pixels) and depth map resolution (384 by 288 pixels) are limited, the reconstruction is accomplished in less than 1 s when executed on a workstation computer. **Figure 7** illustrates the depth map (**fig. 7**, top) and point cloud (**fig. 7**, bottom) generated from only three input images provided (**fig. 7**, right), each captured from a slightly different perspective. The metal pins serve as a scale, with the pins spaced 2.54 mm (0.1 in) apart.

FIG. 7

MVSNet generated depth map and point cloud generated from cellphone photographs.

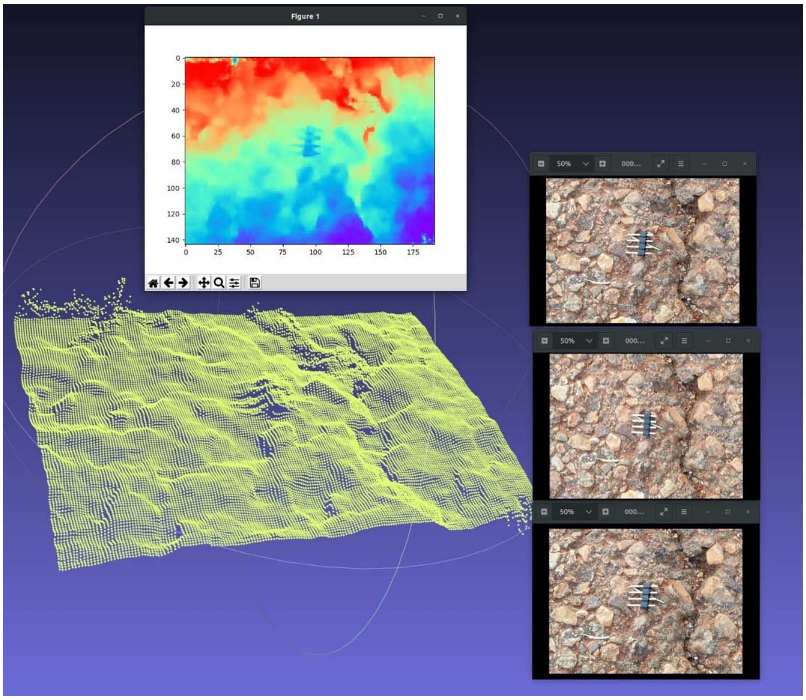


FIG. 8

SNOET prototype installed adjacent to the N4 freeway.

SNOET was installed around various locations on the Engineering 4.0 campus (**fig. 8**), adjacent to the freeway (**fig. 1**). Of interest are the TVOC concentration, CO_2 emissions, and air quality that are all associated with vehicle traffic. Clear patterns could be observed during peak morning and afternoon traffic (**fig. 9**), where concentrations increased above the background levels that were recorded during the night and over weekends.

The SNOET prototype has been improved significantly since its inception, with the construction of four additional, identical sensor platforms. The new generation of Arduino MKR1310 microcontrollers used for SNOET include a LoRaWAN radio module that sets the standard for low-power wide-area IoT networks. More specifically, LoRaWAN uses a media access control protocol to establish wide area networks, allowing low-powered devices to communicate securely with Internet-connected applications over long-range, low-bandwidth wireless connections. These devices communicate with a dedicated router (gateway) installed on the Engineering 4.0 campus (**fig. 1**), with the network traffic sent to The Things Network (TTN). TTN uses an open source, decentralized network to exchange data with applications. These applications receive the data payloads, decode them, and route the formatted data to third-party service providers such as Google Cloud or Ubidots (**fig. 10**) for long-term storage, analysis, and visualization.

FIG. 9 Air pollution and organic molecule concentrations measured by SNOET.

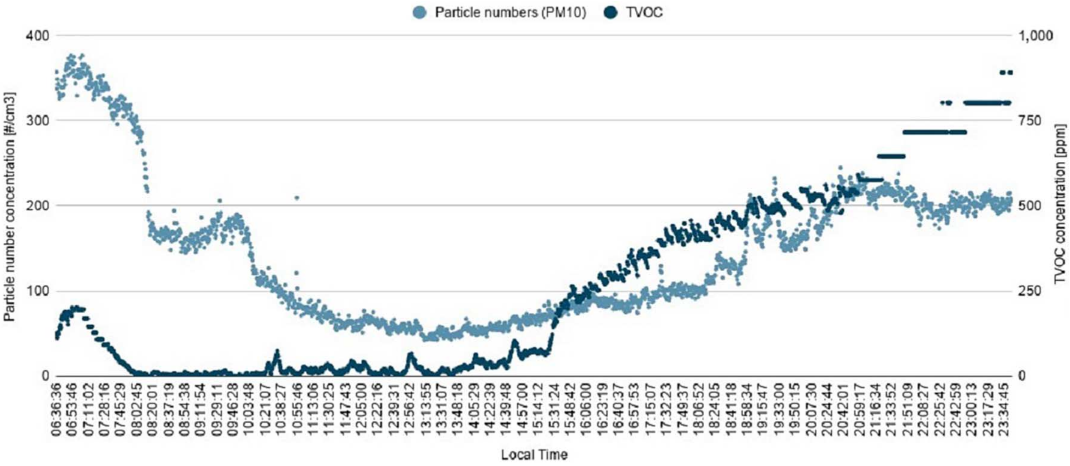
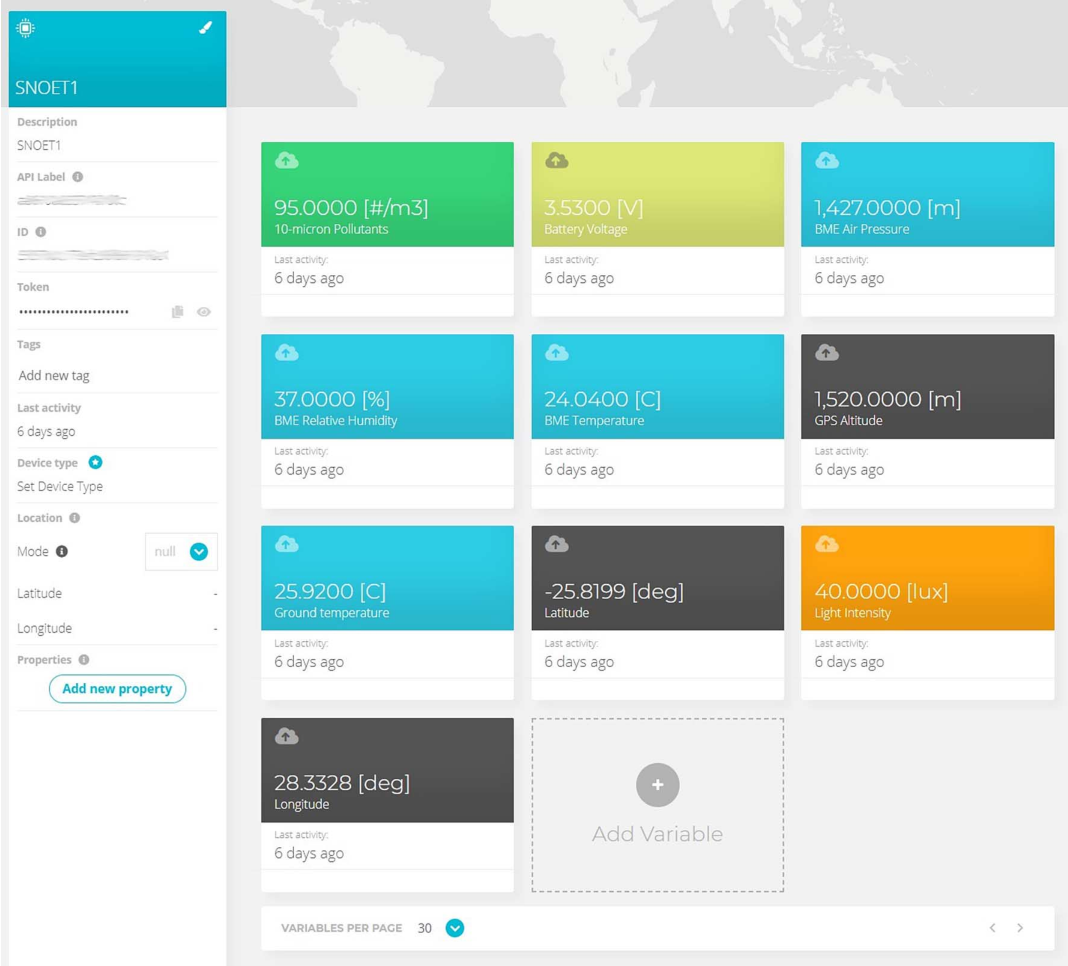


FIG. 10 Ubidots dashboard backed of SNOET1 illustrating the sensor measurements.



SNOET1

Description
SNOET1

API Label
[redacted]

ID
[redacted]

Token
••••••••••••••••••••••••

Tags
Add new tag

Last activity
6 days ago

Device type
Set Device Type

Location

Mode: null

Latitude -

Longitude -

Properties

95.0000 [#/m3]
10-micron Pollutants
Last activity:
6 days ago

3.5300 [V]
Battery Voltage
Last activity:
6 days ago

1,427.0000 [m]
BME Air Pressure
Last activity:
6 days ago

37.0000 [%]
BME Relative Humidity
Last activity:
6 days ago

24.0400 [C]
BME Temperature
Last activity:
6 days ago

1,520.0000 [m]
GPS Altitude
Last activity:
6 days ago

25.9200 [C]
Ground temperature
Last activity:
6 days ago

-25.8199 [deg]
Latitude
Last activity:
6 days ago

40.0000 [lux]
Light Intensity
Last activity:
6 days ago

28.3328 [deg]
Longitude
Last activity:
6 days ago

VARIABLES PER PAGE 30

Road Temperature Data

Road temperature data are a significant parameter in pavement analysis, especially for temperature-sensitive materials such as bitumen and asphalt. Knowledge of the effects of temperature changes on the stiffness and behavior of asphalt is well described in the literature, and not repeated here. Suffice to say, as background, that asphalt stiffness increases at lower temperatures and decreases at higher temperatures, significantly affecting the structural and load-bearing properties of the material, and thereby the pavement in a very short time span (Steyn[27]).

In the initialization of the local road network digital twin on the Engineering 4.0 campus, monitoring of pavement surface temperatures is one of the initial and simpler parameters to collect continuously. This is done using commercially available sensors that monitor temperature using a probe, as well as accurate weather and atmospheric conditions obtained from a nearby weather station, which also feed continuous data into the data repository (**fig. 11**).

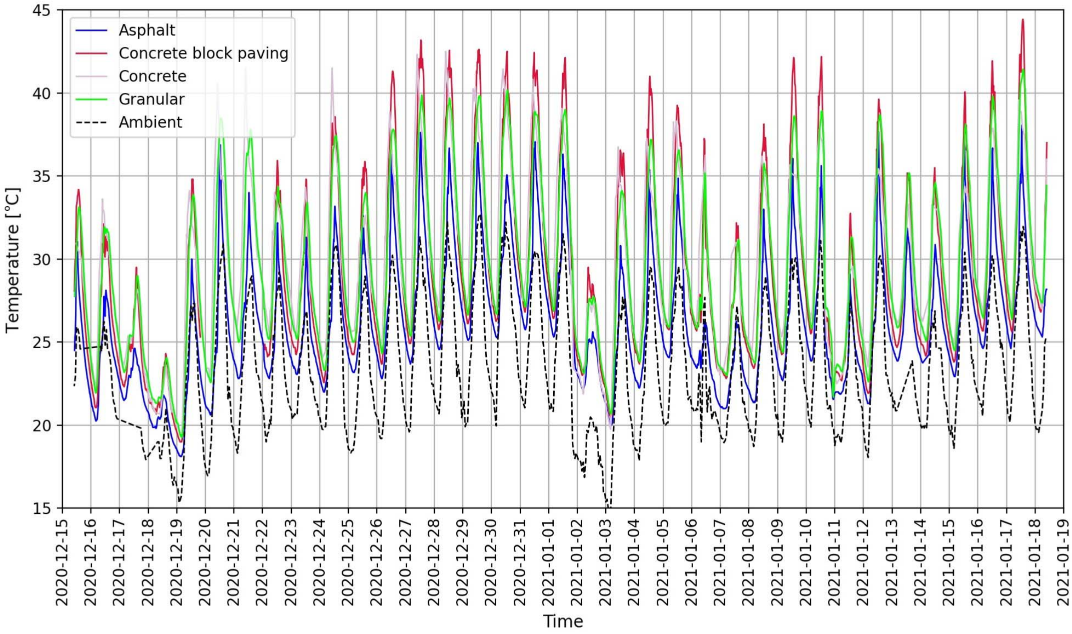
On the Engineering 4.0 campus, there is a small network of roads with various surfacing types. These include asphalt, concrete, concrete block paving, and aggregate. Although it is known that the properties of aggregate and concrete are less affected by temperature than for asphalt, an initial installation of temperature probes was done in

FIG. 11 IoT sensors for asphalt (top-left), concrete block paving (top-right), concrete (bottom-left), and granular (bottom-right) pavement surfacing temperature measurement.

each of these surfacings. These collections have been running for 1 month at the time of writing this article (20-min data intervals), and therefore the focus is on this initial data (15 December 2020 at 10:00 UTC to 18 January 2021 at 10:00 UTC). The weather station is used as the true ambient air temperature because of its superior design to eliminate self-heating effects. For a full digital twin, and interpretations and applications of these data, a dataset spanning one complete year will be preferable and applicable to account for seasonal variations.

Figure 12 illustrates the time history of temperature sensor measurements alongside the ambient air temperature measurements from the weather stations. As expected, the ambient air temperature remains below the pavement temperature throughout, owing to the large amount of thermal radiation associated with the sun positioned at the zenith during the December summer (southern hemisphere). The markedly cooler asphalt temperature—which would be expected to be one of the warmest samples—can be explained by the ample shadow

FIG. 12 Time history of the temperature sensor and ambient air temperature measurements.



coverage provided throughout the day by the large number of trees, orientated parallel to the pavement shoulder in a north-south direction. If the temperature of the pavement is considered as a function of the air temperature (**fig. 13**), a similar pattern emerges compared to the time history (**fig. 12**). The asphalt exhibits the smallest increase in temperature for every unit of temperature the ambient air increases (0.8714°C/°C), compared to the concrete block paving with a notably larger gradient of (1.3051°C/°C). Despite these large differences, it is interesting to note that the y-intercepts (denoted *a* in **fig. 13**) of all the samples are also grouped close to 0°C when the ambient air temperature approaches 0°C. This extrapolation of the observed linear behavior could be indicative of the much larger thermal mass of the granular material compared to the air, leading to temperature inversion close to freezing conditions, reversing the thermal strain profile of the pavement in the process. It will be observed in detail during the coming winter season.

Figure 14 (left) illustrates the distribution of the temperature data over the observation period, together with the rate of change of the temperature (**fig. 14**, right). The temperature distributions can be considered a normal distribution from the shape, with a characteristic skewness toward higher temperatures. The change in temperature is not mirrored along the zero line because of the different mechanisms adding and removing energy from the pavement. The narrower distribution on the negative scale is indicative of the large thermal mass providing greater resistance to the removal from energy. In contrast, the temperature increases much more readily as a result of the proximity of the temperature sensor to the surface of the material. The most surprising results are related to outliers associated with temperature changes. The largest negative and positive rate of temperature change was calculated to be −17.1°C/h for the concrete and −8.89°C/h for the asphalt, respectively (visible as a distinctive vertical tangent in **fig. 13**). The granular material (−14.1°C/h), concrete block paving (−10.98°C/h), and asphalt recorded reduced temperature variation extremes as a result of different material characteristics and lower in situ

FIG. 13

Scatter plot of temperature sensor measurements as a function of the ambient air temperature.

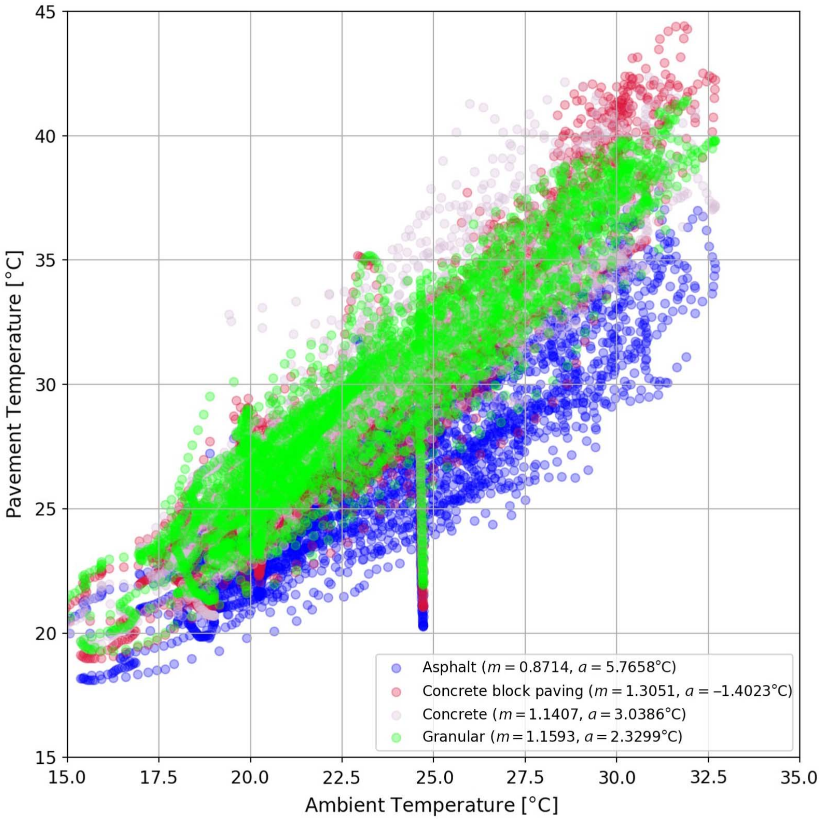
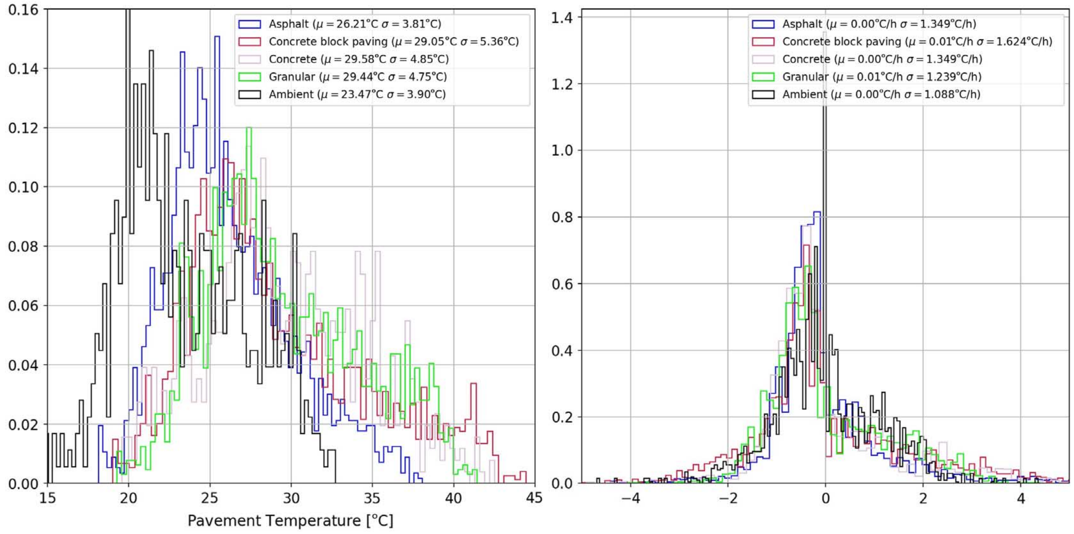


FIG. 14 Distribution of temperature sensor measurements (left) and the rate of temperature change (right).



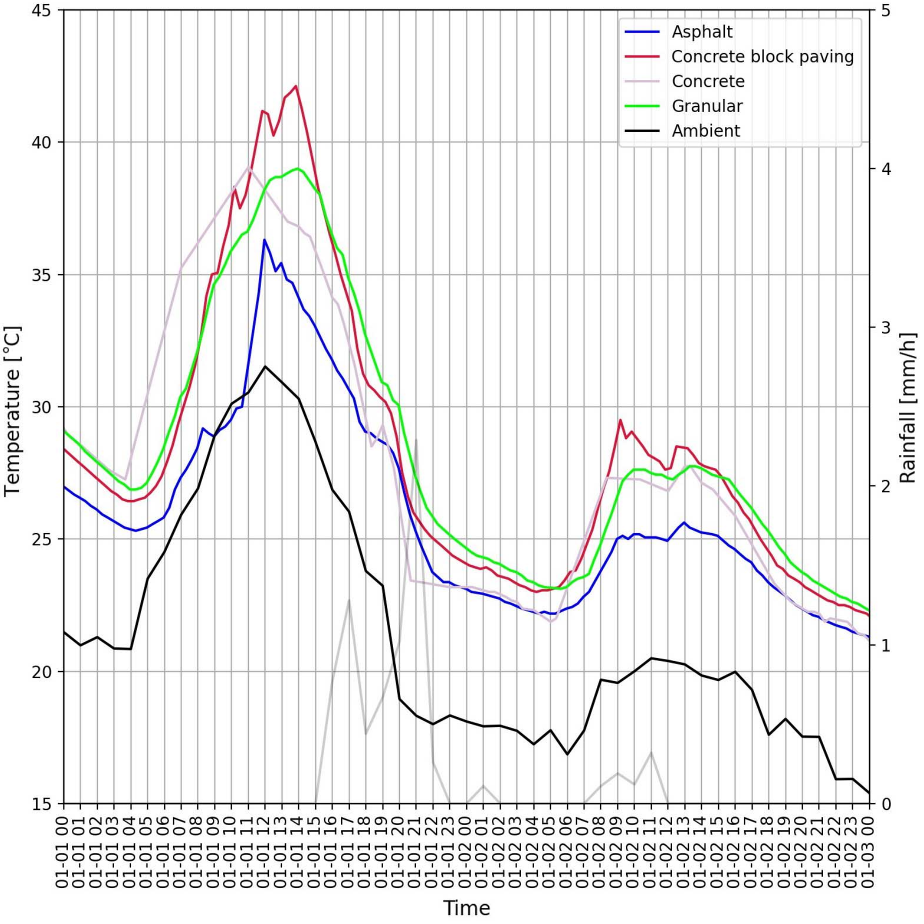
temperature. The rapid reduction in temperature of the concrete coincides with extreme rainfall events experienced in the area with above-average rainfall for the summer season. Similar behavior was observed in the initial (November 2020) data collected on the asphalt sections that were exposed to direct sunlight throughout the day (Steyn[27]). The prolonged rainfall and cloud cover combines the different pavement temperatures to that of the ambient air temperature, reducing both the amplitude and variation of the observed temperatures (**fig. 15**).

Applications

The article describes the process of collecting infrastructure and operational condition data of a local road to develop a digital twin of the scenario. The objective of such a digital twin is to improve the management process of local (and by extension any other) roads through a combination of detailed infrastructure information (LiDAR scans) and continuous data emanating from the local road (environmental and traffic data). Such a road management process means that the road owner does not have to wait for a typical 1-year snap-shot dataset regarding the conditions on the road, but that continuous data submission to the model can improve the continuous management and maintenance of the road. Through such continuous monitoring, local instantaneous changes in aspects such as traffic levels and emissions, or pavement conditions (e.g., asphalt temperature) can be incorporated into the road condition models to improve the maintenance expectations and planning for future actions on the specific road. Although the analysis of cost-effectiveness is outside of this initial evaluation of the system, indications are that the overall cost of delivering a digital twin model of a local road network will provide substantial cost savings, because of the reduced manpower requirements for monitoring of the infrastructure, and savings in road deterioration and subsequent rehabilitation costs, as deterioration will be identified earlier, and be able to be rectified at a lower cost.

Data analysis of the temperature data obtained from the four pavement surfacings focused on the differences in the temperature responses between the various surfacings that are all in close proximity to each other in the same geographic area. Data were collected over a period of a month during the rainy summer season summer. Although this represents a short window into the life of a pavement surfacing, the objective of the article and the initial project is to demonstrate a working implementation of a digital twin of a local road network that can survive the expected extreme operating conditions and demonstrate the large number of variables associated with the pavement performance. Extreme variations in pavement temperature, environmental effects that are

FIG. 15 Influence of rainfall and overcast weather on temperature data over a 48-h period.



due to shading, hysteresis associated with diurnal and seasonal variations, and the potential for rapid temperature inversion all affect the structural strength profile throughout the depth of the engineered material, which is typically based on a number of simplified assumptions that mostly do not account for these observations and extreme variations. The intention is thus to continue with the data collection, quantify the statistically significant distribution with cognizance of increasingly severe climatic conditions, and start to build up a continuous understanding of these temperature relationships. Such a history can then be applied in advanced pavement analysis, both offline during design and testing phases and online for existing infrastructure, especially in regions where surfacing material properties are highly temperature dependent.

Conclusions

The article shares some of the potential benefits of generating a macro- and micro-twin of physical infrastructure available. These digital twins can seamlessly integrate with the pavement / building management system of an infrastructure owner, providing continuous and objective data regarding the physical condition and environmental elements around the infrastructure. This can support continuous management decisions in an objective way. Theavailability of continuous road condition data supports efficient and timeous remedial and maintenance planning with subsequent potential benefits in improved sustainability and life cycle costs.

The implementation of OpenDataCam's AI-assisted traffic counting proved effective to deploy a low-cost traffic quantization solution. With the addition of a dedicated internet protocol-camera, the system will soon record the traffic of the adjacent freeway on a permanent, real-time basis for longer-term trend monitoring, improving existing design guidelines through this data-driven approach. Significant improvement exists for the classification of vehicles, particularly for public transportation vehicles such as minibus taxis. The aggregation of data from SNOET and vehicle statistics on a single data repository provides additional insight into interrelated variables.

Compared to traditional 3-D scanners, AI-assisted reconstruction techniques have the benefit of operating in nearly any illumination condition with significantly faster processing capabilities and at a lower cost. With the implementation of more accurate geolocation services, these platforms can be integrated with geospatial macro-twin for long-term monitoring of the pavement surface texture. This approach is simple enough for autonomous robotic systems that could perform the task, independent of human operators. Additional experiments are underway to determine the viability of integrating SNOET with asset management systems of unpaved roads. The air quality measurements associated with dust in the air could be used for dynamic blading maintenance. The addition of LoRaWAN capabilities could see the installation of such miniaturized devices on vehicles themselves that continuously traverse the same section of a road in parallel to the large-scale deployment of low-cost, versatile sensors.

ACKNOWLEDGMENTS

The authors thank Prof. Liesl Dyson and David Jean du Preez from the University of Pretoria's Department of Geography, Geoinformatics and Meteorology for maintaining and sharing the weather station data included in the analysis of the road temperature phenomena.

This article expands (with the permission of the conference organizers) on Steyn and Broekman[28] through the addition of further temperature data collected on the discussed digital twin, with substantial additional data analysis and discussion.

References

1. F. Tao, K. Cheng, Q. Qi, M. Zhang, H. Zhang, and F. Sui, "Digital Twin-Driven Product Design, Manufacturing and Service with Big Data," *The International Journal of Advanced Manufacturing Technology* 94 (2018): 3563–3576, https://doi.org/10.1007/s00170-017-0233-1
2. A. Núñez, J. Hendriks, Z. Li, B. De Schutter, and R. Dollevoet, "Facilitating Maintenance Decisions on the Dutch Railways Using Big Data: The ABA Case Study" (paper presentation, IEEE International Conference on Big Data, Washington, DC, October 27–30, 2014): 48–53, https://doi.org/10.1109/BigData.2014.7004431
3. T. Ruohomäki, E. Airaksinen, P. Huuska, O. Kesäniemi, M. Martikka, and J. Suomisto, "Smart City Platform Enabling Digital Twin" (paper presentation, Ninth IEEE International Conference on Intelligent Systems (IS), Funchal, Madeira, Portugal, September 25–27, 2018): 155–161, https://doi.org/10.1109/IS.2018.8710517
4. V. Q. Lu, A. K. Parlikad, P. Woodall, G. D. Ranasinghe, and J. Heaton, "Developing a Dynamic Digital Twin at a Building Level: Using Cambridge Campus as Case Study" (paper presentation, International Conference on Smart Infrastructure and Construction, Churchill College, Cambridge, United Kingdom, July 8–10, 2019): 67–75, https://doi.org/10.1680/icsic.64669.067
5. T. Machl, A. Donaubauer, and T. H. Kolbe, "Planning Agricultural Core Road Networks Based on a Digital Twin of the Cultivated Landscape," *Journal of Digital Landscape Architecture* 4 (May 2019): 316–327, https://doi.org/10.14627/537663034
6. M. Liu, S. Fang, H. Dong, and C. Xu, "Review of Digital Twin About Concepts, Technologies, and Industrial Applications," *Journal of Manufacturing Systems* 58 (January 2021): 346–361, https://doi.org/10.1016/j.jmsy.2020.06.017
7. W. J. vdM. Steyn, and A. Broekman, "Civiltronics: Fusing Civil and elecTronics Engineering in the 4IR Era," *Magazine of the South African Institution of Civil Engineering* 28, no. 1 (January/February 2020): 24–28.
8. A. Broekman and P. J. Gräbe, "Development and Calibration of a Wireless, Inertial Measurement Unit (Kli-Pi) for Railway and Transportation Applications" (paper presentation, 37th Annual South African Transport Conference, Pretoria, South Africa, July 9–12, 2018): 329–339.
9. A. Broekman, and P. J. Gräbe, "Analysis, Interpretation and Testing of Mesoscale Ballast Dynamics using Kli-Pi" (paper presentation, International Heavy Haul Association Conference, Narvik, Norway, June 12, 2019): 151–157.
10. M. W. Sayers, and S. M. Karamihas, *The Little Book of Profiling: Basic Information about Measuring and Interpreting Road Profiles* (Ann Arbor, Michigan: The Regents of the University of Michigan, 1998).
11. B. Sengoz, A. Topal, and S. Tanyel, "Comparison of Pavement Surface Texture Determination by Sand Patch Test and 3D Laser Scanning," *Periodica Polytechnica Civil Engineering* 56, no. 1 (2012): 73–78, https://doi.org/10.3311/pp.ci.2012-1.08

12. C. J. Pretorius and W. J. vdM. Steyn, "Quality Deterioration and Loss of Shelf Life as a Result of Poor Road Conditions," *International Journal of Postharvest Technology and Innovation* 6, no. 1 (2019): 26–45, https://doi.org/10.1504/IJPTI.2019.104178
13. I. Wessels and W. J. vdM. Steyn, "Continuous, Response-Based Road Roughness Measurements Utilizing Data Harvested from Telematics Device Sensors," *International Journal of Pavement Engineering* 21, no. 4 (2020): 437–446, https://doi.org/10.1080/10298436.2018.1483505
14. *Standard Practice for Calculating Pavement Macro-Texture Mean Profile Depth*, ASTM E1845–15 (2001) (West Conshohocken, PA: ASTM International, approved May 1, 2015). https://doi.org/10.1520/E1845-15
15. *Standard Test Method for Measuring Pavement Macrotexture Depth Using a Volumetric Technique*, ASTM E965–96 (Superseded) (West Conshohocken, PA: ASTM International, approved November 10, 1996). https://doi.org/10.1520/E0965-96
16. A. Van der Gryp and G. Van Zyl, "Variability and Control of Gravel Road Visual Assessments," *Journal of the Transportation Research Board* (January 2007), https://doi.org/10.3141%2F1989-70
17. W. J. vdM. Steyn, G. J. Jordaan, A. Broekman, and A. Marais, "Evaluation of Novel Chip Seals Applications During Periods of Low Temperatures" (paper presentation, 12th Conference on Asphalt Pavements for Southern Africa, Sun City, South Africa, October 13–16, 2019).
18. G. Jordaan, A. Kilian, L. Du Plessis, and M. Murphy, "The Development of Cost-Effective Pavement Design Approaches Using Mineralogy Tests with New Nano-Technology Modifications of Materials" (paper presentation, 36th Southern Africa Transportation Conference, Pretoria, South Africa, July 10–13, 2017).
19. W. J. vdM. Steyn, "Intelligent Infrastructure and Data Science in Support of Road Maintenance" (paper presentation, Advances in Materials and Pavement Performance Prediction, Doha, Qatar, April 16–18, 2018).
20. W. J. vdM. Steyn, "Optimization of Gravel Road Blading," *Journal of Testing and Evaluation* 47, no. 3 (2019): 2118–2126, https://doi.org/10.1520/JTE20180022
21. R. Heikkilä and M. Jaakkola, "The Efficiency of a 3-D Blade Control System in the Construction of Structure Layers by Road Grader Automated Design - Build of Road Construction in Finland" (paper presentation, 19th International Symposium on Automation and Robotics in Construction, Gaithersburg, MD, September 23–25, 2002): 475–480, https://doi.org/10.22260/ISARC2002/0074
22. R. Thompson, R. Peroni, and A. T. Visser, *Mining Haul Roads: Theory and Practice* (Boca Raton, FL: CRC Press, 2019).
23. W. J. Marais, R. J. Thompson, and A. T. Visser, "Managing Mine Road Maintenance Interventions Using Mine Truck On-Board Data", (paper presentation, Seventh International Conference on Managing Pavement Assets, Calgary, Alberta, Canada, June 23–28, 2008).
24. T. Swanepoel, J. W. Maina, and W. J. vdM. Steyn, "Deterioration Trends of Unpaved Roads from Real Data," *Journal of the South African Institution of Civil Engineering* (in press).
25. Y. Yao, Z. Luo, S. Li, T. Shen, T. Fang, and L. Quan, "Recurrent MVSNet for High-Resolution Multi-View Stereo Depth Inference" (paper presentation, IEEE Conference on Computer Vision and Pattern Recognition, Long Beach, CA, June 16–20, 2019): 5525–5534, https://arxiv.org/abs/1902.10556
26. A. Broekman, and P. J. Gräbe, "PASMVS: A Perfectly Accurate, Synthetic, Path-Traced Dataset Featuring Specular Material Properties for Multi-View Stereopsis Training and Reconstruction Applications," *Data in Brief* 32 (October 2020): 106219, https://doi.org/10.1016/j.dib.2020.106219
27. W. J. vdM. Steyn, "Selected Implications of a Hyper-Connected World on Pavement Engineering," *International Journal of Pavement Research and Technology* 13 (January 2020): 673–678, https://doi.org/10.1007/s42947-020-6012-7
28. W. J. vdM. Steyn, and A. Broekman, "Process for the Development of Multi-Scale Digital Twins of Local Roads—A Case Study" (paper presentation, GeoChina 2021 Conference Theme: Civil and Transportation Infrastructures: From Engineering to Smart and Green Life Cycle Solutions, NanChang, China, September 18–19, 2021).