The current issue and full text archive of this journal is available on Emerald Insight at:
https://www.emerald.com/insight/2634-2499.htm

Received 5 July 2023
Revised 1 December 2023
Accepted 25 January 2024

Operator guidance systems in road construction: a technological mediation perspective

Hans Voordijk, Seirgei Miller and Faridaddin Vahdatikhaki
Department of Civil Engineering, University of Twente, Enschede, Netherlands

Abstract

Purpose – Using real-time support systems may help operators in road construction to improve paving and compaction operations. Nowadays, these systems transform from descriptive to prescriptive systems. Prescriptive or operator guidance systems propose operators actionable compaction strategies and guidance, based on the data collected. It is investigated how these systems mediate the perceptions and actions of operators in road pavement practice.

Design/methodology/approach – A case study is conducted on the specific application of an operator guidance system in a road pavement project. In this case study, comprehensive information is presented regarding the process of converting input in the form of data from cameras and sensors into useful output. The ways in which the operator guidance systems translate data into actionable guidance for operators are analyzed from the technological mediation perspective.

Findings – Operator guidance systems mediate actions of operators physically, cognitively and contextually. These different types of action mediation are related to preconditions for successful implementation and use of these systems. Coercive interventions only succeed if there is widespread agreement among the operators. Persuasive interventions are most effective when collective and individual interests align. Contextual influence relates to designs of the operator guidance systems that determine human-technology interactions when using them.

Originality/value – This is the first study that analyzes the functioning of an operator guidance system using the technological mediation approach. It adds a new perspective on the interaction between this system and its users in road pavement practice.

Keywords Real-time support systems, Technological mediation, Operators, Road pavement, Interventions

Paper type Research paper

1. Introduction

Currently, hot mix asphalt (HMA) is the most dominant material being used as road surfacing layer in most countries around the world. The compaction process of these layers is influenced by numerous factors (Makarov *et al.*, 2021). These include design (e.g. asphalt mix type), logistics (e.g. the asphalt temperature at the time of delivery), construction (e.g. compaction uniformity) and environmental conditions (e.g. ambient weather condition). It is important that compaction is carried out within an appropriate temperature range to avoid over- or under-compacting the asphalt layer (Bijleveld, 2015). To cope with this complex and dynamic process, asphalt machine operators rely on their implicit knowledge, craftsmanship, experience and rule-of-thumb approaches based on tradition and custom (Ranasinghe *et al.*, 2023; Zhang *et al.*, 2019). A distinct absence of method-based approaches and a reliance on tacit knowledge create high variability in the overall quality of asphalt layers constructed (Bijleveld, 2015; Sivagnanasuntharam *et al.*, 2023).

Disclosure statement: No potential conflict of interest was reported by the authors.

Frontiers in Engineering and Built Environment
Vol. 4 No. 2, 2024
pp. 116-129
Emerald Publishing Limited
e-ISSN: 2634-2502
p-ISSN: 2634-2499
DOI 10.1108/FEBE-07-2023-0031

Given the unique circumstances of a road construction project (e.g. mix type, weather conditions and temperature of the delivered asphalt), using the real-time support systems may help operators improve paving and compaction operations. Asphalt machine manufacturers have of late, designed support systems in the form of separate dashboards that descriptively present real-time date, i.e. they provide information regarding the temperature and compaction status of the asphalt layer. In turn, machine operators monitor and track the visuals presented on dashboards and then convert them into actionable strategies. Given that compaction is case-dependent, operators must complement the data visualizations with crucial process information such as mix type, weather and asphalt temperature, to ascertain the optimal actions for compaction. This complexity adds an extra cognitive burden on machine operators.

Transferring tasks of data collection, visualization and most importantly, interpretation to operator support systems, can result in lessening the cognitive burden for operators. These support systems have the potential to be transformed from descriptive to prescriptive systems. Descriptive systems only provide data needed for planning compaction strategies and hence, may lead to cognitive overload. Prescriptive systems on the other hand, propose actionable strategies and guidance, based on the compaction data collected.

Transitioning to operator guidance systems that offer prescriptive and user-friendly guidance for roller operators requires a comprehensive approach to paving and compaction operations. This entails leveraging innovative techniques and methods (e.g. the Internet of Things) to integrate road design, asphalt production, transport logistics and real-time sensory data (e.g. GPS and temperature sensors) collected from the asphalt paving team (paver and roller compactors). Consequently, operator guidance systems not only collect and analyze real-time temperature and compaction of the asphalt but also translate this information into actionable guidance for operators by prioritizing compaction on various sections of the asphalt mat. Consequently, the operator guidance systems not only collect and analyze real-time temperature and compaction data of the asphalt but also translate this information into actionable guidance for operators by prioritizing compaction on various sections of the asphalt mat.

The ways in which the operator guidance systems translate data into actionable guidance for operators can also be analyzed from the technological mediation perspective (Ihde, 2009; Verbeek, 2015). Technological mediation assumes that technologies play a role in human interpretation of reality (Rosenberger and Verbeek, 2015a, b): humans do not experience the world in a direct manner; instead, their perception is always influenced by some form of intermediate technology. The way humans perceive and interact with their surroundings is inevitably shaped and altered to some extent by the presence of various technologies (Voordijk, 2019).

Based on this perspective, this study aims to explore the mediating functions of the operator guidance systems between their users and the roads to be paved. The major question driving this research is focused on understanding how operator perceptions and behaviors are mediated by operator guidance systems. How and where does such a system engage with its users? In answering this question, the well-known typology on human–technology relations of Ihde is used first. Ihde (2012) examines various relationships between humans and technology that are dependent on the specific contexts. Each of these relationships explores a distinct manner in which technologies act as intermediaries, shaping human perceptions of the world (Rosenberger and Verbeek, 2015a, b). The hermeneutic and, based on this, the composite intentionality and digital materials relationships are the focus of our study. Secondly, the approach of technological mediation is translated to practice by using the framework developed by Dorrestijn (2017). This framework offers deeper insights into how operator guidance systems shape users' actions and behaviors.

Initially, we delve into the technological mediation of human perceptions and of actions. Following this, we outline the methodology employed. Then, we examine a particular instance of an operator guidance system utilized in a road pavement project through a case study. Subsequently, we explore how these systems influence the perceptions and actions of operators. Various forms of action mediation are related to preconditions for the effective implementation and utilization of these systems. Lastly, we draw conclusions. The scientific importance of this study lies in bridging the functioning of the operator guidance systems in road pavement operations with the concept of technological mediation.

2. Technological mediation

In the context of technological mediation, technologies are first seen as tools that modify and transform human perceptions (Ihde, 2009). Additionally, the focus is placed on examining how technology influences actions of human beings (Rosenberger and Verbeek, 2015a, b). In the following, both perspectives will be discussed.

2.1 Mediation of perceptions

Regarding the mediation of perceptions, Ihde (2015) analyzes various context-dependent relationships between humans and technology. Each relationship positions humans in a distinct connection to technology, addressing specific ways in which technologies shape our perceptions of reality (Verbeek, 2015). Across all these relationships, human intentionality is channeled through technologies in various manners. Intentionality may be oriented toward the external world via a technology, akin to using glasses to enhance vision or through interpreting technological representations, like reading a thermometer for temperature. Alternatively, intentionality can be directed towards the technology itself, as seen with interactive ATMs or toward the world where technologies play a background role in shaping human experiences, like an air conditioning system that subtly influences how people perceive their environment (Aydin *et al.*, 2019). For the mediation of perception, the so-called hermeneutic and, based on this, the composite intentionality and digital materials relationships are most relevant.

In a hermeneutic relationship, humans concentrate their attention on a technology to interpret the representation it offers to the world (Ihde, 2012). Employing a particular technology facilitates the experience of a specific facet of reality, amplifying it while concurrently reducing the experience of other facets. Acting as a mediator, the technology presents a particular perspective on reality. Ihde (2009) illustrates this relationship as follows: human → (technology-world). The arrow signifies that a hermeneutic relationship entails a technology-generated representation of a specific facet of the world, which is then interpreted by a human (Verbeek, 2008). This representation may arise from a specific “directedness” of a technology toward the world.

Technological directedness is rooted in a technology’s “sensing apparatus” and its inherent “selectivities” that are configured to perceive and process inputs in specific ways (Ihde, 2015; Wiltse, 2014). These are predetermined by developers to direct a technology toward a particular aspect of reality (Ihde, 2015, p. xv). Incorporating this directedness into the hermeneutic relationship gives rise to “composite intentionality”, where not only humans but also technologies possess their own programmed directedness or intentionality (Verbeek, 2008). This duality of intentionality can be conceptualized as human → (technology → world), where the technological directedness is symbolized by the arrow connecting technology and world. Through this technological directedness, technologies produce representations of aspects of an object that would otherwise be imperceptible, necessitating interpretation by human intentionality (Verbeek, 2008).

In the realm of digital technologies, composite intentionality manifests as a form of responsive digital materials (Wiltse, 2014). This relationship can be illustrated as human → (digital material → world). Within responsive digital materials, the technology is delineated into “traces” and “substrates.” For instance, in the act of typing, the resulting trace is the text itself, which can be interpreted by humans (Wiltse, 2014). The substrate encompasses the physical devices like the keyboard and computer that enable the production of the trace. The keyboard, as a part of the substrate, acts as the interface between the typing action and the computer, which records the activity. Mediation occurs when the substrate reacts to an activity in a manner that generates a trace of that activity (Wiltse, 2014).

Mediation hinges on a substrate designed to respond in accordance with its programming. While a digital system automatically reacts to actions, its response is dictated by its design. In digital realms, the trace and the substrate are distinct and content is generated or measured by one device and displayed by another (Wiltse, 2014). This division between measurement and display in digital systems results in a representation of composite intentionality as human → ([trace | substrate] → world), where the vertical separator signifies this separation.

The hermeneutic, composite intentionality and digital materials human–technology relationships are presented in Table 1.

2.2 Mediation of actions

Technologies not only act as mediators of human perceptions but also have the potential to impact human actions (Verbeek, 2015). The mediation of actions parallels the structure of hermeneutic mediation of perceptions, where perceptions undergo transformation through amplification and reduction, while actions are transformed through invitation and inhibition.

The analysis of action mediation draws inspiration from Latour’s actor-network theory (2007), which considers both humans and “nonhumans” (e.g. technologies or physical objects), as “actants.” Actant technologies can shape user behavior by embodying a “script” that guides their actions. Technologies possess the capacity to direct our actions through invitation and inhibition. When individuals employ a specific technology for a particular task, its design either encourages or discourages certain actions, guiding users toward particular behaviors while deterring alternative ones. This interplay of invitation and inhibition by technology forms the core of action mediation. This concept can be linked to Latour’s notion of delegation (2007), wherein action is delegated from humans to technology, influencing users and guiding them in the specific directions.

In order to provide more detailed insights how the operator guidance systems impact or reshape users’ actions and behavior, the framework of Dorrestijn (2012, 2017) is used. Dorrestijn elucidates the broad concept of mediation of action through delineating specific interactions between humans and technologies. These interactions are classified based on the aspect of the human body that technologies “grasp”: physical, cognitive or contextual (see Table 2). This framework is used to conceptualize how the operator guidance systems mediate actions in road pavement practice.

The first type of mediation focuses on the influence of technologies on human physical behavior. The most direct form of such influence is coercion, as exemplified by Latour’s (2007)

Type of relationship	Schematic representation
Hermeneutic relationship	human → (technology-world)
Composite relationship	human → (technology → world)
Digital materials relationship	human → ([trace | substrate] → world)

Source(s): Table by authors

Table 1. Human–technology–world relationships

famous example of a speed bump compelling car drivers to reduce speed. Technologies can exert pressure and steer individuals in specific directions. Another aspect of physical influence is embodied technologies (Ihde, 2012). Individuals have to learn and employ technologies in their professional activities (Magalhães *et al.*, 2023). Here, the technology influences users when acquiring skills and learning routines. During these exercising processes technologies become embodied (Dorrestijn, 2012). The subliminal effect, another physical influence, occurs when individuals are attracted or repelled by subconscious sensations. For instance, supermarkets may introduce the smell of fresh bread to influence the buying mood of customers.

The second type of mediation examines the cognitive impact of technology on human decision-making processes (Dorrestijn, 2012). Guiding individuals toward specific actions is a significant form of cognitive influence through technology. Technologies can provide cues such as arrows, texts prompts and visual cues, all of which contribute to shaping the decision-making process. Moreover, technologies have the capacity to persuade individuals to alter their behavior, exemplified by websites that encourage users to click on certain links (Dorrestijn, 2012).

The third type of mediation explores the contextual impact of technology. Here, technology does not directly impact individuals through physical contact or decision-making processes, but rather through the surrounding environment (Dorrestijn, 2012). The effectiveness of a technology hinges on background conditions, including the necessary infrastructure for its operations. Technologies can also have unintended consequences or side effects. While a technology may offer advantages on one level, it may also bring about disadvantages on another level. For example, cars facilitate travel but can contribute to traffic congestion when their numbers exceed a certain threshold. Additionally, technical determinism reflects on how advancements in technology can reshape human values and necessities. The potential threat of surveillance through technology, for instance, may lead to behavioral changes (Davies and Harty, 2012).

This study uses these three types of mediation of action to analyze how the operator guidance systems mediate actions between their users and road construction practice.

3. Methodology

Studies on technological mediation have several characteristics in common (Rosenberger and Verbeek, 2015a, b). First, technological mediation studies take the role actual technologies play in practice as their starting point. Because of this, these studies focus on case studies of concrete technologies. Second, Ihde’s (2009) analysis of human–technology relations is a typical heuristic in these case studies (Adams and Thompson, 2011). These characteristics of technological mediation studies are also the basis for the research method followed here.

First, a specific application of an operator guidance system in a road pavement project is analyzed. Detailed information is provided about the process of converting input in the form of

Table 2.
Subcategories of mediation

Physical	coercion embodiment subliminal effect
Cognitive	guidance persuasion
Contextual	background conditions side effects technical determinism

Source(s): Table by authors

data from cameras and sensors into useful output in a road pavement operation using the system developed. To evaluate this system, a case study was conducted at Dutch training school for construction equipment. During this case study, using an actual paver and roller in a road compaction operation, three different scenarios were simulated: no guidance (operators use their expertise and no operator support systems), descriptive operator support (operators use provided temperature and compaction data) and prescriptive operator guidance (operators use compaction priority maps). Prior to the experiment, the paver and roller operators were briefed on the experiment, including details about the system's functionalities, the information it offers in various scenarios and the required compaction procedures.

Second, the technological "selectivities" (Ihde, 2015) of the system developed are discussed. These "selectivities" are important elements of composite and digital materials human–technology relationships. They concern data collection and analysis through the "sensing apparatus" of such a system. Using this system, technological mediation enables operators to access specific characteristics of the roads that need to be paved. An operator turns to this system in order to interpret the guidance it provides. Using the framework developed by Dorrestijn (2017), it is discussed in more detail how the operator guidance systems influence users' actions and behavior in three different ways (physical, cognitive or contextual) and how this is related to preconditions for successful implementation and use of these systems.

4. Case study findings

4.1 The case of an operator guidance system

The main limitation of most existing operator guidance systems is that they are designed as standalone systems, focusing on a single piece of equipment. Each system is tailored to a specific compactor, providing data solely from the sensors linked to that particular machine. However, in large projects, it is essential for compaction guidance systems to consider the status of the entire fleet. This can be achieved through the implementation of a network of sensors and machine-to-machine communication. A network of sensors gathers data from all the pavers and rollers involved in a project. These data are then transmitted to a central processing unit where it is integrated and analyzed (Makarov *et al.*, 2021). Subsequently, the processed data is customized for the requirements of the different operators and relayed back to them on the different pavers enrollers.

The abundance of data provided by the existing compaction operator systems poses challenges for operators in correlating pertinent information to their tasks. For instance, while operators prioritize knowing the next compaction location and determining compaction duration, current systems provide compaction count and temperature data. This leads to a cognitive burden for the operators and a diminished focus on operator support systems. This may result in sub-optimal intuitive decision-making.

Figure 1 presents the analyzed operator guidance system in the case study. The depicted process outlines the collection and analysis of data obtained from the construction site. Within this framework, essential data for the operator guidance system is acquired utilizing Internet of Things (IoTs). Four types of nodes are involved in the compaction process. Asphalt, Roller and Paver nodes are furnished with sensing and data transmission hardware, enabling them to collect, transmit and receive data to and from the Processing node. The gathered data are structured within a database and subsequently processed at this Processing node to generate three outputs: the cooling curve, a temperature contour plot and a compaction contour plot.

4.2 Data collection and transmission

A centralized architecture is implemented where all the data are gathered and processed in a central Processing node. The architecture is selected due to the comprehensive data requirements of the compaction guidance system.

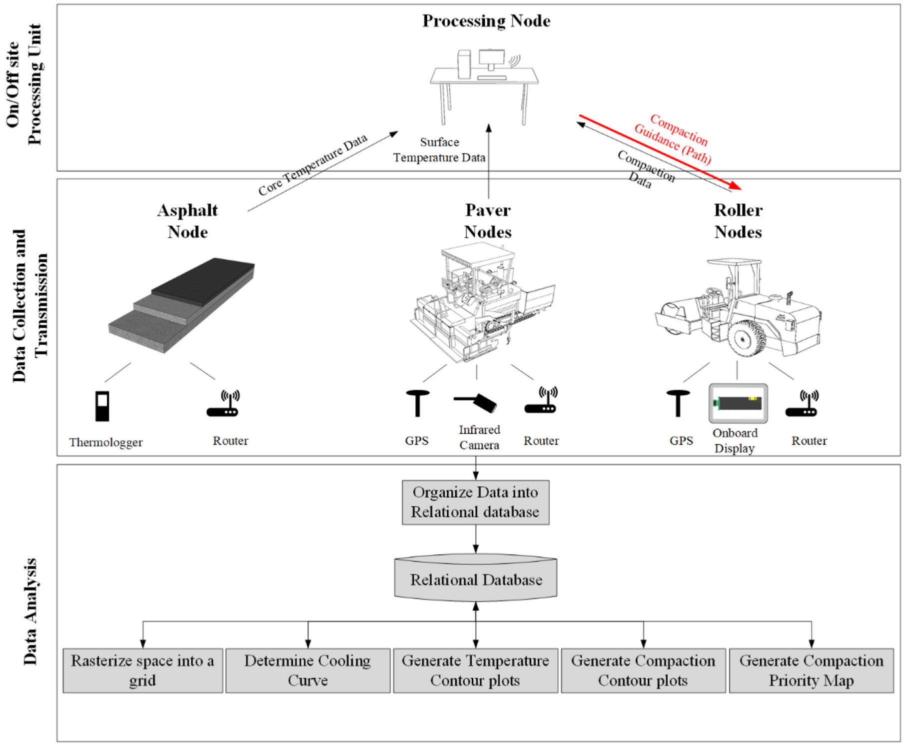

Figure 1.
Overview of the proposed framework

Source(s): Figure by authors

The Asphalt node is equipped with a series of thermocouples, electric devices utilized for temperature measurement, positioned within the asphalt layer at the construction site. These thermocouples are housed within a stand placed on the base layer before the paving process begins. Once paving commences, the core temperature is measured at various depths within the asphalt profile by the stand and its connected thermocouples. Subsequently, the temperature data are collected and transmitted to the Processing node through a router linked to the thermologger.

The Paver node is tasked with acquiring the surface temperature of the new asphalt. This is achieved through the installation of an infrared camera positioned at the rear of the paver. The data-capturing field and its width are determined by the lane width, which can be manually configured by the operator at the project's outset. Additionally, a GPS rover is affixed to the paver to georeference temperature data. Temperature data are recorded by the infrared camera in a grid pattern. The resolution of data collection is contingent upon factors such as the camera's resolution, field of view and installation height. The temperature data captured is registered using pixel coordinates in the camera images. Through the router mounted on the paver this data is transmitted to the Processing node.

The Roller nodes are purpose-built for monitoring roller activities and offering guidance to the operators. As such, they include routers for seamless data transmission between the Rollers and Processing node, GPS rovers installed on each roller and onboard displays that provide operator guidance. The GPS data are leveraged to assess the levels of compaction attained across various segments of the asphalt layer.

The Processing node, positioned either on-site or remotely, gathers data from the other nodes. It performs the essential analysis to produce guidance for the roller operators and subsequently, sends this guidance back to the Roller nodes for a visual presentation.

4.3 Data analysis

The data analysis encompasses several stages, which include data structuring and the creation of cooling curves, compaction and temperature contour plots and a priority map of compaction.

The database organizes data into three main groups: design, sensory and analytical data. Design data pertains to information derived from asphalt or process design, such as geometric specifications of the pavement layer, equipment details, project location, date, client, etc. Sensory data encompasses data collected and transmitted by various system nodes, including equipment location, heading, asphalt core temperature, etc. Analytical data represents the processed and integrated information derived from sensory and design data, which aids in generating relevant guidance. Examples of analytical data include rasterized temperature data and remaining time for compaction of various sections of the asphalt layer.

The granularity of data analysis are determined by the cell size used, influenced by factors such as the resolution of the infrared camera, computational capacity, roller dimensions and accuracy of GPS rovers used for equipment tracking. To organize the gathered data into a cell-based format, first, the initial step involves georeferencing surface temperature recorded by the infrared camera. This process involves establishing the translation vector between the physical positions of the camera and GPS rover on the paver as well as the transformation matrix based on the camera's installation configuration, its intrinsic matrix and the translation vector. The resulting projection matrix facilitates the mapping of temperature pixel data into world coordinates.

The asphalt cooling curve offers insights into the thermal dynamics of the asphalt layer during paving and compaction. This curve represents the core temperatures of the asphalt layer, calculated by averaging readings from the thermocouples. At regular intervals (e.g. every minute), the Processing node forecasts the asphalt cooling rate using the accumulated temperature data. The cooling rate equation considers various factors such as layer thickness, thermal transition coefficients and thermal conductivity to make accurate predictions.

Temperature contour plots (TCPs) are 2D visual representations from a top-down perspective, illustrating the temperature distribution across newly paved asphalt within a predefined area. They offer insights into the uniformity of the asphalt mixture applied by the paver. Generating TCPs necessitates data including surface temperatures of the asphalt mat and the paver's coordinates throughout the paving operation.

Compaction contour plots (CCPs) for a specific roller involve analyzing data related to the achieved compaction levels across different segments of the asphalt mat. A prepared cell grid for rasterization is utilized for this analysis. Each cell of the grid contains temperature information recorded during the initial and final roller passes at the first and last roller pass, indicating the commencement and completion of the compaction process on a specific area of the asphalt mat.

The compaction priority map (CPM) combines TCP and CCP data to provide guidance on prioritizing compaction of various segments of the asphalt. Two parameters are considered: the remaining time available for compacting a cell and the number of compactions completed for each cell. These parameters are transformed into a priority index. The CPM highlights sections of the asphalt mat that have been adequately compacted or are too cool for compaction, helping the roller operator identify parts with a greater need for compaction based on prevailing conditions.

4.4 Evaluation of the system

To evaluate the compaction process quality, the ECR$_{80\%,1}$ index is used. This index represents the ratio of cells that have received a specified percentage of their compaction passes (e.g. 80%). The value of 80% was based on the mix designer's recommendation. Additionally, the compaction results are categorized as under-compacted (i.e. <7 passes), over-compacted (i.e. >9 passes) or improperly compacted (i.e. <80% of 7–9 passes within the compaction window).

Table 3 displays the results comparing the three scenarios in terms of ECR80%,1, and the compaction results. Relative improvement refers to an enhancement in the effective compaction ratio and a reduction in the ineffective compaction ratio, the under-compaction ratio, and the over-compaction ratio. In the initial scenario (no guidance), only 13.3% of the cells were adequately compacted with 7–9 roller passes. In the second scenario (descriptive operator support with TCP and CCP), the effective compaction ratio increased to 22.3% of cells. In the final scenario (prescriptive operator guidance system with CPM), the effective compaction ratio further improved to 28.7%. In this case, the proportion of cells experiencing over-compaction decreased to 19.2%, whereas the incidence of under-compaction rose to 39.5%.

Descriptive operator support resulted in an improvement of ECR$_{80\%,1}$ from 13.3 to 22.3%. Transitioning to a prescriptive guidance system enhanced the efficiency of compaction further, increasing the ECR80$_{\%,1}$ from 13.3% to 28.7%. Moreover, there was a significant reduction in areas with ineffective compaction (from 27% to 12.6%) and over-compacted areas (from 33 to 19%). However, it should be noted that the prescriptive guidance led to a tendency of under-compacting the layer.

An operator was tasked with evaluating the various scenarios in terms of usability and practicality. The operator stressed that, being accountable for the pavement's final quality, he favored devising his own strategy over being directed on what to do. Despite recognizing that the operator guidance system was more user-friendly, he preferred having access to raw measurements to determine the pavement's condition and make his own strategic decisions for the remaining work.

5. Discussion

It is discussed first how technological selectivities make certain aspects of reality accessible to users of the system through data processing. Secondly, it is discussed how the operation guidance systems studied mediate actions physically, cognitively or contextually.

5.1 Technological selectivities

In digital environments like operator guidance systems, the separation of temperature measurement and display, i.e. substrate and trace, is performed by two different devices (Wiltse, 2014). When it comes to responsive digital materials, the mediation of technology

Table 3.
Comparison of the three scenarios

	Compaction quality indicators (in %)			
Scenario	Under-compacted	Effectively compacted (ECR$_{80\%,1}$)	Ineffectively compacted	Over-compacted
No guidance	26.7	13.3	27	33
Operator support	23.3	22.3	22.4	32
Operator guidance	39.5	28.7	12.6	19.2

Source(s): Table courtesy of Makarov *et al.* (2021)

using a guidance operator system can be conceptualized as users → ([TCPs/CCPs | images] → roads paved). In this case, the images based on pixels serve as the substrate. These images act as the intermediary interface between the project environment, characteristics of the roads paved and their traces in terms of the cooling curve, TCPs and CCPs. These traces are the outcome of translating the collected temperature and location data. In providing traces, the operator guidance systems respond to the input they receive according to their design and programming.

The production of these traces relies on the inherent technological selectivities embedded in the pixel data processing within the images (Ihde, 2015). Consequently, the directedness of the operator guidance systems does not solely aim to accurately depict the pavement project; instead, they construct a particular perception of this project (Verbeek, 2008). One technological selectivity concerns data collection through the "sensing apparatus" of the IR camera configured to capture temperature data and encode them as pixel coordinates in the camera's images. Another selectivity concerns data analysis. Collected data is structured into a cell-based structure using the translation vector between the physical positions of the camera and GPS rover on the paver as well as the transformation matrix for the camera images. Based on this cell-based structure, TCPs, CCPs and CPMs are generated.

These representations amplify an operator's perception of a specific facet of reality (the state of the asphalt layer in relation to its temperatures and levels of compaction) but reduce them to visualizations that can be rendered into a two-dimensional cell-based structure. This mediation relationship of double or composite intentionality can be depicted as user → (operator guidance system → road) (Verbeek, 2008). Technological directedness converts non-represented knowing into explicit knowing (Olaisen and Revang, 2018). Transparency is enhanced by making the performance of the operators more visible. The tacit dimensions of the skills and knowledge used by the operators in road pavement are made explicit.

5.2 Different types of mediation

While cooling curves, TCPs and CCPs show the temperatures and levels of compaction of the asphalt layer, the priority map attempts to combine both sets of data to offer guidance to roller operators on how to prioritize compaction in different areas of the asphalt mat. An operator guidance system as active technological environment (Aydin *et al.*, 2019) mediates actions in three different ways: physical, cognitive or contextual (see Table 2).

The physical mediation type indicates on how operator guidance systems influence physical behavior of their users (Dorrestijn, 2017). Once users acquire requisite skills and proficiency to interact with the system automatically and without reflection, an operator guidance system becomes embodied in road pavement practices (Riemer and Johnston, 2014). It transitions to being "ready-to-hand" when users no longer need to consciously deliberate on its usage. This embodiment requires training of operators and fostering trust in the system through increased exposure and experimentation. The use of operator guidance systems also subconsciously influences a firm's interactive learning processes, internally and externally, creating a subliminal effect. Operators learn from each other inside a firm by sharing tacit knowledge through visualizing the compaction process and addressing issues that arise during road pavement. Sharing tacit knowledge among the operators may improve team performance when it is subject to collective reflection. Externally, as seen in the case study, the construction firm participated in trials and pilot projects alongside other construction firms, their suppliers, a university and government agencies, gaining access to valuable knowledge that improved their paving skills.

The second type of mediation delves into the cognitive impact of technology on human decision-making (Dorrestijn, 2017). Operator guidance systems in road pavement are seen as “quasi-others” with their own agency: operators follow directions provided by priority maps. Decisions made by operators are influenced by visualized instructions during on-site pavement activities. Operators are not solely reliant on their own cognitive abilities as they receive context-aware instructions. The compaction priority map, as “quasi-other,” *guides* operators in a specific direction, inviting them to optimize pavement processes (Ihde, 2009). Insights into the actual quality of the pavement process may persuade operators to take corrective actions. Having precise information about the path a roller has taken, could suggest a different compaction strategy.

The third type of mediation examines how operator guidance systems in road pavement influence user behavior within their contextual surroundings (Dorrestijn, 2017). These systems shape the context in which operators operate. In terms of background conditions, operator guidance systems require an infrastructure that enables an effective interoperability among various technologies such as IR cameras, GPS rovers, thermocouples, Wi-Fi routers and other technologies to function properly. This interoperability makes real-time information on operator performance more visible, enhancing transparency and optimizing equipment utilization. However, this transparency can also reveal errors and potentially lead to less transparent behavior among the operators as side effect or even suspicious behavior, exemplifying technical determinism where technology induces behavioral changes.

5.3 Intervention strategies

Site managers and operators bear the primary responsibility for the quality of work, which often results in a reluctance to delegate decision-making to semi-automated systems. For these systems to be adopted, establishing trust is crucial. Different intervention strategies related to the three types of mediating actions can be employed to build trust and change mindsets.

A coercive intervention related to the physical influence of embodiment is followed when operators are compelled to learn to use operator guidance systems in road pavement practice. Individuals have to behave in accordance to the guidelines provided (Olugboyega *et al.*, 2023). Such intervention can disrupt routine behaviors in road pavement practice and may be perceived as infringing upon the individual freedom of the operators (Tromp *et al.*, 2011). Therefore, coercive interventions can only succeed if there is widespread agreement among the operators.

Persuasive interventions, focusing on cognitive influences when using operator guidance systems in road pavement, can also be employed. These interventions are most effective when collective and individual interests align, such as providing incentives for operators to improve their pavement processes. Operators are more likely to accept influences that increase efficiency and effectiveness through using operator guidance systems. In this scenario, the optimal outcome is achieved through the voluntary adoption of these systems.

The contextual influence is tied to the “decisive” designs of technologies, which dictate potential interactions between humans and technology when using them. Examples of such decisive designs include the system interoperability of the operator guidance systems and the choices made during their development, which significantly shape interactions between users and technology.

6. Conclusions

This study investigated how the operator guidance systems mediate the perceptions and actions of operators in road pavement practice.

Different technological built-in selectivities of the operator guidance systems mediate perceptions by making certain aspects of road pavement operations accessible to their users. By displaying cooling curves, TCPs and CCPs, an operator guidance system amplifies specific aspects of reality while reducing others. In the realm of responsive digital materials, the images serve as the substrate connecting the physical objects in the world, such as the roads paved, with their corresponding traces, such as the cooling curves, TCPs and CCPs, to be interpreted by the operators. Understanding this mediating role of operator guidance systems can lead to more realistic expectations regarding their capabilities. Neglecting this mediating role may result in incorrect usage and misguided expectations.

This study also revealed that the operator guidance systems in road pavement mediate actions physically, cognitively and contextually. The operator guidance systems can become embodied in daily routines, perceived as independent entities with their own agency and influencing the environment in which operators operate. These various forms of mediating actions are closely linked to the prerequisites for successful implementation and use of these digital technologies.

Implementation strategies involve coercive and persuasive interventions as well as decisive designs. A coercive intervention related to the physical influence of embodiment of systems compels operators to use the operator guidance systems. This intervention can only succeed if there is widespread agreement among the operators. Cognitive influences are related to interventions, where operators are guided and persuaded by the operator guidance systems as quasi-others. Persuasive interventions are most effective when collective and individual interests align, such as offering incentives for operators to improve pavement processes through system usage. Contextual influence relates to the decisive designs of technologies, which dictate the interactions between humans and technology during their utilization. This influence can lead to less transparency as a side effect or even suspicious behavior, exemplifying technical determinism.

While this analysis offers a novel perspective on the interaction between users and digital technologies in road construction, it does come with some limitations. The findings and analysis rely solely on a single case study, necessitating further cases to establish external validity. Additionally, more detailed information is required regarding the scope, usage and evolution of operator guidance systems in road pavement practice to gain deeper insights into user-technology interactions over time. The incorporation of artificial intelligence into various building objects and project environments requires further investigation into the structure and dynamics of human–technology relationships in the construction industry.

References

Adams, C.A. and Thompson, T.L. (2011), “Interviewing objects: including educational technologies as qualitative research participants”, *International Journal of Qualitative Studies in Education*, Vol. 24 No. 6, pp. 733-750, doi: 10.1080/09518398.2010.529849.

Aydin, C., González Woge, M. and Verbeek, P.-P. (2019), “Technological environmentality: conceptualizing technology as a mediating milieu”, *Philosophy and Technology*, Vol. 32 No. 2, pp. 321-338, doi: 10.1007/s13347-018-0309-3.

Bijleveld, F. (2015), *Professionalising the Asphalt Construction Process: Aligning Information Technologies, Operators’ Knowledge and Laboratory Practices*, University of Twente, Enschede, doi: 10.3990/1.9789036537650.

Davies, R. and Harty, C. (2012), “Control, surveillance and the ‘dark side’of BIM”, in Smith, S.D. (Ed.), *Proceedings of the 28th Annual ARCOM Conference*, Edinburgh/London.

Dorrestijn, S. (2012), “Theories and figures of technical mediation”, in Donovan, J. and Gunn, W. (Eds), *Design and Anthropology*, Routledge, London, pp. 219-230, doi: 10.4324/9781315576572.

Dorrestijn, S. (2017), "The product impact tool: the case of the Dutch public transport chip card", in Niedderer, K., Clune, S. and Ludden, G. (Eds), *Design for Behaviour Change: Theories and Practices of Designing for Change*, Routledge, London, pp. 26-39.

Ihde, D. (2009), *Postphenomenology and Technoscience: the Peking University Lectures*, SUNY Press, Albany.

Ihde, D. (2012), "Postphenomenological re-embodiment", *Foundations of Science*, Vol. 17 No. 4, pp. 373-377, doi: 10.1007/s10699-011-9244-9.

Ihde, D. (2015), "Positioning postphenomenology", *Postphenomenological Investigations: Essays on Human-Technology Relations: Postphenomenology and the Philosophy of Technology* (pp. vii-xvi), Lexington Books.

Latour, B. (2007), *Reassembling the Social: an Introduction to Actor-Network-Theory*, Oxford, University Press, Oxford.

Magalhães, R.M., Mello, L.C.B.d.B. and Hippert, M.A.S. (2023), "Organizational readiness for building information modeling", *Frontiers in Engineering and Built Environment*, Vol. 3 No. 2, pp. 137-152, doi: 10.1108/FEBE-07-2022-0028.

Makarov, D., Vahdatikhaki, F., Miller, S., Jamshidi, A. and Dorée, A. (2021), "A framework for real-time compaction guidance system based on compaction priority mapping", *Automation in Construction*, Vol. 129, 103818, doi: 10.1016/j.autcon.2021.103818.

Olaisen, J. and Revang, O. (2018), "Exploring the performance of tacit knowledge: how to make ordinary people deliver extraordinary results in teams", *International Journal of Information Management*, Vol. 43, pp. 295-304, doi: 10.1016/j.ijinfomgt.2018.08.016.

Olugboyega, O., Windapo, A., Aigbavboa, C. and Oseghale, G.E. (2023), "BIM implementation: an empirical validation for a four-wheel model", *Frontiers in Engineering and Built Environment*, Vol. 3 No. 1, pp. 1-15, doi: 10.1108/FEBE-04-2022-0016.

Ranasinghe, R., Sounthararajah, A. and Kodikara, J. (2023), "An intelligent compaction analyzer: a versatile platform for real-time recording, monitoring, and analyzing of road material compaction", *Sensors*, Vol. 23 No. 17, 7507, doi: 10.3390/s23177507.

Riemer, K. and Johnston, R.B. (2014), "Rethinking the place of the artefact in IS using Heidegger's analysis of equipment", *European Journal of Information Systems*, Vol. 23 No. 3, pp. 273-288, doi: 10.1057/ejis.2013.5.

Rosenberger, R. and Verbeek, P.-P. (2015a), *Postphenomenological Investigations: Essays on Human–Technology Relations*, Lexington Books, New York/London, pp. vii-xvi.

Rosenberger, R. and Verbeek, P.-P. (2015b), "A field guide to postphenomenology", in Rosenberger, R. and Verbeek, P.-P. (Eds), *Postphenomenological Investigations: Essays on Human-Technology Relations*, Lexington Books, London/New York, pp. 9-42.

Sivagnanasuntharam, S., Sounthararajah, A., Ghorbani, J., Bodin, D. and Kodikara, J. (2023), "A state-of-the-art review of compaction control test methods and intelligent compaction technology for asphalt pavements", *Road Materials and Pavement Design*, Vol. 24 No. 1, pp. 1-30, doi: 10.1080/14680629.2021.2015423.

Tromp, N., Hekkert, P. and Verbeek, P.-P. (2011), "Design for socially responsible behavior: a classification of influence based on intended user experience", *Design Issues*, Vol. 27 No. 3, pp. 3-19, doi: 10.1162/DESI_a_00087.

Verbeek, P.-P. (2008), "Cyborg intentionality: rethinking the phenomenology of human–technology relations", *Phenomenology and the Cognitive Sciences*, Vol. 7 No. 3, pp. 387-395, doi: 10.1007/s11097-008-9099-x.

Verbeek, P.-P. (2015), "COVER STORY beyond interaction: a short introduction to mediation theory", *Interactions*, Vol. 22 No. 3, pp. 26-31, doi: 10.1145/2751314.

Voordijk, H. (2019), "Building information modeling and its impact on users in the lifeworld: a mediation perspective", *Frontiers of Engineering Management*, Vol. 6 No. 2, pp. 193-206, doi: 10.1007/s42524-019-0013-8.

Wiltse, H. (2014), “Unpacking digital material mediation”, *Techné: Research in Philosophy and Technology*, Vol. 18 No. 3, pp. 154-182, doi: 10.5840/techne201411322.

Zhang, Q., Liu, T., Zhang, Z., Huangfu, Z., Li, Q. and An, Z. (2019), “Unmanned rolling compaction system for rockfill materials”, *Automation in Construction*, Vol. 100, pp. 103-117, doi: 10.1016/j.autcon.2019.01.004.

Corresponding author
Hans Voordijk can be contacted at: j.t.voordijk@utwente.nl