Paving and Compaction Support Systems

The status of implementation worldwide

Thalia Johanna Pilataxi Araujo

S2074613

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ASPARi Paving the way forward UNIVERSITY OF TWENTE. bam

Preface

The present thesis report focuses on the status of implementation of Paving and Compaction Support Systems. The report is part of the Civil Engineering Bachelor Program at the University of Twente (UT).

First, I would like to thank God for allowing me to study in this beautiful country. I would also like to thank my family, especially my parents Jorge and Fanny and my sisters Yessenia and Maritza, for the emotional and economic support throughout my bachelor's study. Moreover, I would like to thank the ASPARi network and BAM company, especially Ir. Denis Makarov, Dr.ir. Seirgei Miller, Ir. Marjolein Galesloot and Ir. Marco Oosterveld for all their guidance and support throughout the realisation of my thesis. In addition, I am very grateful to my friends who have been part of these three years of academic learning. Furthermore, I would like to thank the Ecuadorian institution named Secretaría de Educación Superior, Ciencia, Tecnología e Innovación (SENESCYT) for the financial support provided to fulfil the bachelor program of Civil Engineering. Last but not least, I would like to thank all the expert interviewees for providing the necessary information to realise the study.

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Author information:

Author: Thalia Johanna Pilataxi Araujo
Study: Bachelor Civil Engineering
Institution: University of Twente

Internal supervisors:

Institution: University of Twente
Department: Asphalt Paving Research and innovation (ASPARi)
1^{st} supervisor: Dr.ir. S.R. Miller (Seirgei)
2^{th} supervisor: Ir. D. Makarov (Denis), PDEng

External supervisors:

Company: BAM
Division: BAM Infra Asfalt
1^{st} supervisor: Ir. M. Galesloot (Marjolein)
2^{th} supervisor: Ir. M. Oosterveld (Marco)

Glossary of Terms

Term	Definition
BWM	Best-Worst Method
CBR	California Bear Ratio
CCC	Continuous Compaction Control
CCV	Compaction Control Value
CIR	Cold In-place Recycling
CMV	Compaction Meter Values
DCP	Dynamic Cone Penetrometer
DOTs	Departments of Transportation
FHWA	Federal Highway Administration
FWD	Falling Weight Deflectometer
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HMA	Hot Mix Asphalt
IC	Intelligent Compaction
IMCV	Intelligent Compaction Measurement Value
LWD	Light-Weight Deflectometer
MCDM	Multi-Criteria Decision-Making Method
MDP	Machine Drive Power
MVs	Measurement Values
PLT	Plate Load Test
Point-MV	Point Measurement Value
QA	Quality Assurance
QC	Quality Control
RCC	Roller Compacted Concrete
WMA	Warm Mix Asphalt

Summary

Every year, the private and public sectors invest vast amounts of money on asphalt construction because it plays a crucial role in the global transportation infrastructure. Therefore, asphalt construction is a process that should be closely monitored. In this sense, many paving and compaction support systems have been developed to assist the operators during their work operations.

The present study aims *to report the state of the art of paving and compaction support systems worldwide.* This aim can be achieved by answering the question: *How can the implementation and adoption of paving and compaction support systems for asphalt construction be fast-tracked given current approaches in development, contractual forms and regulations?* By employing different research methods (i.e. literature review, interviews, qualitative analysis, Best-Worst Method), the necessary information to answer this question can be retrieved.

The literature review was crucial for this study since it enabled the collection of information about paving and compaction support systems and the available solutions in the market. Additionally, the study focused on the differences between compaction support systems for soil and asphalt. Since their use has lagged, especially when it comes to asphalt compaction, it was possible to identify existing solutions from a research and development perspective. Likewise, the existing specifications and guideline documents for implementing paving and compaction support systems in road construction projects from different world regions were analysed. The gathered information served to identify the trends and views of the road construction industry from the clients perspective. Hence, this information served as a base for developing interviews conducted in this research with road construction industry specialists.

Interviews with specialists from the asphalt construction sector (e.g. contractors and machine manufacturers) were performed. The obtained information was then analysed, and the enablers and barriers to implementing high-tech solutions were determined. In order to classify the enablers and barriers of these technologies according to their importance, a multi-criteria decision-making (MCDM) method called Best-Worst Method (BWM) was applied. Two workshops were organized to retrieve the necessary information for using the BWM. Consequently, the technique allowed to obtain the weights of the enablers and barriers to categorize them in order of importance. This report concludes that the most important enabler for the use of paving and compaction support systems is *Long-term pavement performance.* Therefore, it is important to widespread this enabler within the road infrastructure sector. In this way, the use of such technologies could be increased. At the same time, the most important barrier is *Closed systems for integration.* Hence, it is important to overcome this barrier by enabling data transfer and communication between machines. Likewise, it is important to focus on overcoming other barriers such as: *Additional training*, *Increased systems costs*, *Paving and Compaction treated separately* and *Operator's mindset*.

Samenvatting
Elk jaar investeren de private en publieke sector enorme bedragen in de asfaltbouw omdat het een cruciale rol speelt in de wereldwijde transportinfrastructuur. Daarom is asfaltbouw een proces dat nauwlettend in de gaten moet worden gehouden. In die zin zijn veel bestratings- en verdichtingsondersteunende systemen ontwikkeld om de operators te helpen tijdens hun werkzaamheden.

De huidige studie heeft tot doel de stand van de techniek van bestratings- en verdichtingsondersteunende systemen wereldwijd te rapporteren. Dit doel kan worden bereikt door antwoord te geven op de vraag: Hoe kan de implementatie en adoptie van bestratings- en verdichtingsondersteunende systemen voor asfaltbouw worden versneld gezien de huidige benaderingen in ontwikkeling, contractuele vormen en voorschriften? Door gebruik te maken van verschillende onderzoeksmethoden (d.w.z. literatuuronderzoek, interviews, kwalitatieve analyse) kan de benodigde informatie worden verzameld om deze vraag te beantwoorden.

Het literatuuronderzoek was cruciaal voor deze studie omdat het verzamelen van informatie over bestratings- en verdichtingsondersteunende systemen en de beschikbare oplossingen in de markt mogelijk maakte. Daarnaast richtte het onderzoek zich op de verschillen tussen verdichtingsondersteunende systemen voor bodem en asfalt. Omdat het gebruik ervan achterloopt, vooral als het gaat om asfaltverdichting, was het mogelijk om bestaande oplossingen te identificeren vanuit een onderzoeks- en ontwikkelingsperspectief. Ook werden de bestaande specificaties en richtsnoeren voor de implementatie van bestratings- en verdichtingsondersteunende systemen in wegenbouwprojecten uit verschillende regio’s in de wereld geanalyseerd. De verzamelde informatie diende om de trends en opvattingen van de wegenbouw vanuit het perspectief van de klant te identificeren. Daarom diende deze informatie als basis voor het ontwikkelen van interviews die in dit onderzoek werden afgenomen met specialisten in de wegenbouwsector.

Er werden interviews afgenomen met specialisten uit de asfaltbouwsector (bijv. aannemers en machinefabrikanten). Vervolgens werd de verkregen informatie geanalyseerd en werden de instaat stellers en barrières voor de implementatie van hightechoplossingen vastgesteld. Om de enablers en barrières van deze technologieën te classificeren op basis van hun belang, werd een multi-criteria decision-making (MCDM) methode genaamd Best-Worst Method (BWM) toegepast. Er werden twee workshops georganiseerd om de nodige informatie op te halen voor het gebruik van de BWM. Derhalve maakte de techniek het mogelijk om de gewichten van de enablers en barrières te verkrijgen om ze in volgorde van belangrijkheid te categoriseren. Dit rapport concludeert dat de belangrijkste enabler voor het gebruik van bestratings- en verdichtingsondersteunende systemen langdurige bestratingsprestaties zijn. Daarom is het belangrijk om deze enabler wijdverbreid te maken binnen de sector van de wegeninfrastructuur. Op die manier kan het gebruik van dergelijke technologieën worden verhoogd. Tegelijkertijd is de belangrijkste barrière Gesloten systemen voor integratie. Daarom is het belangrijk om deze barrière te overwinnen door gegevensoverdracht en communicatie tussen machines mogelijk te maken. Evenzo is het belangrijk om te focussen op het overwinnen van andere barrières, zoals: Aanvullende training, Verhoogde systeemkosten, Bestrating en Verdichting afzonderlijk behandeld en De mindset van de operator.

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1. Introduction

Asphalt plays an essential role in the lives of people around the world. Asphalt is a mixture of aggregates, binder and filler, and it is one of the most versatile construction materials used to construct and maintain different infrastructures (e.g. roads, bicycle paths) (EAPA, 2021). A large variety of asphalt mixtures provide the best performance to different applications, especially for road construction. Since there are different requirements (e.g. amount of traffic, amount of heavy vehicles), the mixture should have adequate stiffness and resistance to deformation to cope with the pressure applied by the vehicle wheels and flexural strength to resist cracking due to the varying pressure exerted on the mixture. Generally, the quality of the asphalt is assessed by analysing the density of the mixture, the layer thickness, mechanical properties and pavement roughness (Makarov et al., 2019). Generally, the methods used to control and analyse the density or moduli of the asphalt are carried out manually and at limited spots (Zhu et al., 2018). However, there are some difficulties linked to these conventional practices, which include non-uniformity caused by the variability in the materials, unsuitable control of moisture content in the underlying layers, temperatures of the asphalt mixtures are low or non-uniform, longitudinal joints improperly compacted, and lack of feedback to the operator in order to achieve a continuous roller pattern (Federal Highway Administration, 2013). Over the years, it has been evident the willingness of the paving sector towards the implementation of advanced technologies to improve the paving operations. Hence, the efforts by academia and industry led to the development of high-tech solutions for asphalt construction. These solutions are used in paving and compaction processes and have been researched in many projects worldwide that have shown promising results regarding achieved asphalt quality.

The following study will enable the Dutch asphalt construction industry to familiarize themselves with existing paving and compaction support systems and their state of implementation within the guidelines and specifications of some countries worldwide. This information will be used to determine the enablers and barriers for implementing paving and compaction support systems. This will help understand the reasons for the slow implementation of high-tech solutions in asphalt construction.

1.1. Aim

The main objective of this study is to report on the state of the art paving and compaction support systems used for asphalt construction worldwide. This is accomplished by studying the application and integration in specifications and guideline documents, through an extensive literature review and structured interviews with experts on the topic (i.e. manufacturers and construction companies).

1.2. Project Scope

High-tech solutions for asphalt construction started its development in Europe around the 70s and they have proven to be effective in various projects within European countries (Federal Highway Administration, 2013; National Academies of Sciences, Engineering, and Medicine, 2010). Likewise, such technologies have received attention from North American countries in the last decades (Snook, 2019). A different situation can be found in various countries from South America, for which (in the majority of cases) these technologies are conceived as relatively new technologies (Román, 2015). Consequently, research about the adoption of such technologies in regulations from European, North American, and South American countries will provide views from different perspectives. Since, there are numerous countries from which valuable information for the sake of this study can be retrieved, the scope of this research will be narrowed to nine countries from Western and Southern Europe, three countries from North America and nine countries from South America.

1.3. Research Questions

The main question of this research project, which will fulfil the research objective, is formulated as follows:

How can the implementation and adoption of paving and compaction support systems for asphalt construction be fast-tracked given current approaches in development, contractual forms and regulations?

The main question will be divided into sub-questions, which will help clarify concepts and solve intermediate issues. The central question will be answered by answering the formulated sub-questions:

1. How have paving and compaction support systems evolved over the years?
    - What are the conventional equipment and practices for paving and compaction of roads?
        - What are the problems associated with conventional equipment and practices for paving and compaction of roads?
    - How were paving and compaction support systems developed?
    - What are the existing paving and compaction support systems for the construction of roads?
    - What is the integration status of paving and compaction support systems with other systems (e.g. pavement management systems)?
        - Can the collected data by paving and compaction support systems be exported to follow-up systems?
    - What is the prospected and desired end product through the use of paving and compaction support systems?
2. What are the differences among the implementation of support systems for soil and asphalt compaction of roads?
    - How have support systems been implemented for soil and asphalt compaction of roads?
    - Why has the implementation of support systems for asphalt compaction lagged?
3. How have paving and compaction support systems been integrated into specifications and guideline documents for road construction in Europe, North America and South America?
    - Which countries from Europe, North America and South America have implemented such technologies?
        - Which countries have integrated specifications and guidelines for paving and compaction support systems implementation?
    - For these countries, what are the reasons for not implementing such technologies?
4. What are the enablers and barriers to paving and compaction support systems becoming standard practice for road construction?

- Why are contractors and clients not prescribing the use of paving and compaction support systems?
- How can support systems available on the market be improved to be more profitable and better accepted among contractors and clients?

1.4. Research Methods

In order to achieve the aim, four methods are proposed: literature review, interviews, qualitative analysis and Best-Worst Method. These methods will be explained in detail in the following sections. The proposed research questions are answered with the aid of the research methods. In Figure 1, an overview of the research methods used per sub-question can be seen.

1.4.1. Literature review

The evolution of paving and compaction support systems has been evidenced throughout the last decades (Mazari et al., 2021). Consequently, academia and industry have drawn their attention to evaluating such technologies' effectiveness and their applicability for road construction. The growing interest to adopt these technologies has been boosted in some countries. Hence, it is essential to research the state of such technologies and how they have been implemented in each country. The findings from the literature review will form a solid foundation for the knowledge necessary to conduct the project, and it will serve to answer the sub-questions from phase one (Figure 1). Hence, it will be possible to understand the evolution of paving and compaction support systems and the differences between compaction support systems for soil and asphalt. Likewise, it will be possible to identify the current specifications and guideline documents to use these technologies for road construction purposes.

1.4.2. Interviews

Structured interviews (the same questions will be provided to all the interviewees) will be conducted with contractors and systems' manufacturers to obtain insights from two different perspectives. Afterwards, a qualitative analysis will be conducted with the compiled information. The first group of interviews will be conducted with experts from asphalt construction companies, which will provide insights regarding the current adoption of paving and compaction support systems from a client's perspective. The second group of interviews will be conducted with manufacturers experts, providing a better insight into the current needs for improvement and the main advantages of such technologies from a vendor's perspective. The interviewees will be provided with a list of enablers and barriers. They will be asked to give a score to each enabler and barrier on a scale from 1 (low relevance) to 9 (high relevance), which will allow categorising each enabler and barrier according to their importance. The retrieved information is an essential contribution for answering sub-question 4.

1.4.3. Qualitative analysis

In order to answer sub-question 4, the compiled information from the interviews will be analysed. Each interview will be reviewed to assess the respondents' explanations. The analysis will be performed by transcribing the interviews to examine the data and find patterns. With the initial ideas, it will be essential to establish codes (highlight sections of the text and develop shorthand labels to describe their content) to categorise the data. Afterwards, each participant's transcript will be examined, and the codes will be tagged depending on the found information. Finally, it will be possible to describe the enablers and barriers considering the contributions from all the participants. However, it will be essential to validate these preliminary results.

1.4.4. Best-Worst Method

The validation of the interviews' results will be accomplished using the Best-Worst Method (BWM). This method is a robust technique for pairwise comparison used to solve multi-criteria decision-making (MCDM) problems. In order to obtain more reliable results, workshops will be organised to retrieve the necessary information for applying the BWM. This will enable corrections to be made if necessary. Hence, it will be possible to determine enablers and barriers for the technology to become a standard practice for asphalt construction and their degree of importance.

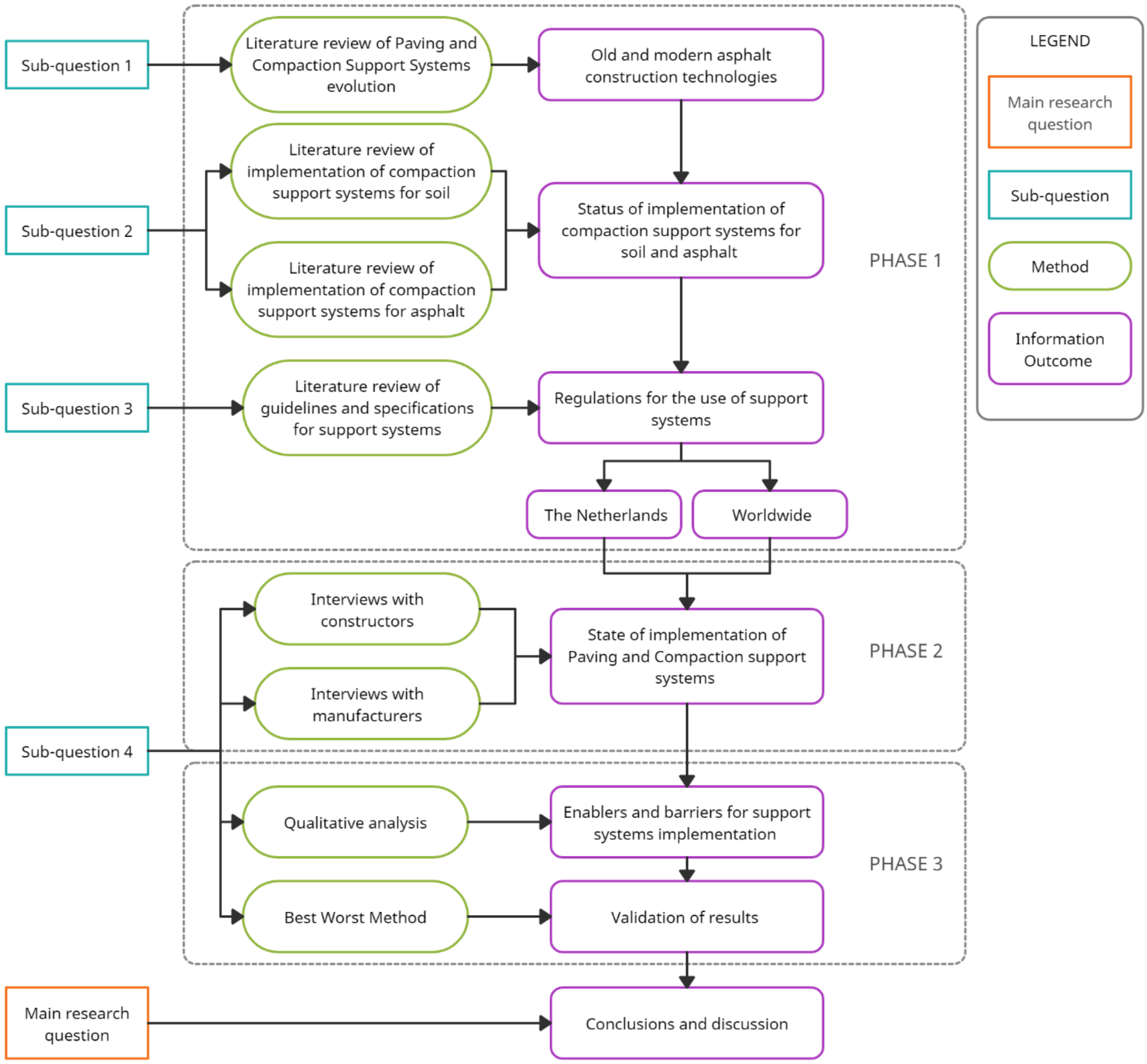

Figure 1: Overview of the proposed research methods

1.5. Reading Guide

Chapter 2 from this study discuss the evolution of paving and compaction support systems. In Chapter 3, the guidelines and specifications for road construction from different countries are described. With the information retrieved from Chapters 2 and 3, the enablers and barriers for implementing paving and compaction support systems are elaborated in Chapter 4. The conclusions and recommendations are elaborated in Chapter 5, in which the answer to the main question is stated. Finally, the discussion points of the study are described in Chapter 6.

2. Evolution of paving and compaction support systems

In order to report the state of the art of paving and compaction support systems, it is necessary to understand how they have evolved over the years. The first-sub question will be answered by reviewing the conventional practices for road construction. Afterwards, the development and research related to paving and compaction support systems will be described. Then, the available market solutions will be studied together with the current trend among existing support systems for paving and compaction.

2.1. Conventional practices for road construction

Numerous asphalt mixes are designed to provide the best performance for different applications (e.g. highway construction, railway tracks construction) (EAPA, 2021). Regarding road construction, different phases in the asphalt supply chain are relevant with respect to its final quality. For instance, the production and transportation of asphalt mixes are essential phases, which will be analysed in the following section. According to Makarov (2017), production and transportation of asphalt mixes could influence asphalt placement and compaction of asphalt mixes, which are the two main phases during road construction. However, both phases are traditionally carried out, meaning that the equipment used to perform such processes has not changed significantly over the last decades. This is also the case with conventional, random (spot) testing methods that will also be evaluated within this study. This research will enable information to be retrieved about problems with traditional practices for road construction. Especially with regards to paving and compaction of asphalt mixes and the use of random testing methods used for Quality Control and Quality Assurance. Therefore, it will be possible to understand the reasons that lead to the development of innovative paving and compaction support systems.

2.1.1. Asphalt mixes

According to the European Asphalt Pavement Association (EAPA & NAPA, 2011), there are numerous asphalt mixtures for the multiple types of pavement materials, which are designed to meet the requirements of the owner of the pavement. Such mixtures can be produced at different temperatures, and one of the commonly used for road construction in different countries is Hot Mixed Asphalt (HMA) (EAPA, 2021; Makarov et al., 2019). HMA mixtures are produced and mixed at temperatures between 120 and 190° C (EAPA, n.d.). Another innovative technology has been introduced known as Warm Mix Asphalt (WMA) mixtures, which are produced and mixed at temperatures between 100 and 140°C (EAPA, n.d.; Takamura & James, 2015). WMA mixtures are equivalent to conventional HMA mixtures with respect to properties and performance (EAPA, n.d.). However, less energy is required for the production of WMA mixtures because the lower temperature production compared to HMA mixtures. Since they are produced at lower temperatures, it results in lower temperatures at the site. This brings major benefits: (1) reduces green house gases and CO_2/ Carbon footprint due to reduced fuel and energy used; (2) reduces occupational exposure to contaminants during asphalt paving; and (3) enhances the crew's working conditions since they inhale less smoke and dust (EAPA, 2009; EAPA, n.d.; Federal Highway Administration, 2016; Olsen et al., 2021)

2.1.2. Production and transport of asphalt mixes

According to the European Asphalt Pavement Association and the National Asphalt Pavement Association (EAPA & NAPA, 2011), the asphalt mixes are produced in asphalt mixing plants and there are two types: batch plants and drum plants, as Figure 2 shows. In the former, the aggregates are stored in hot bins before being mixed with bitumen in separate batches; then, these are stored or loaded into trucks. In the latter, the aggregates and bitumen are mixed in a drum, and the mixture is stored in silos before being loaded into trucks for delivery. Within both types of plants, the mineral aggregates are dried and heated using a rotating drum.

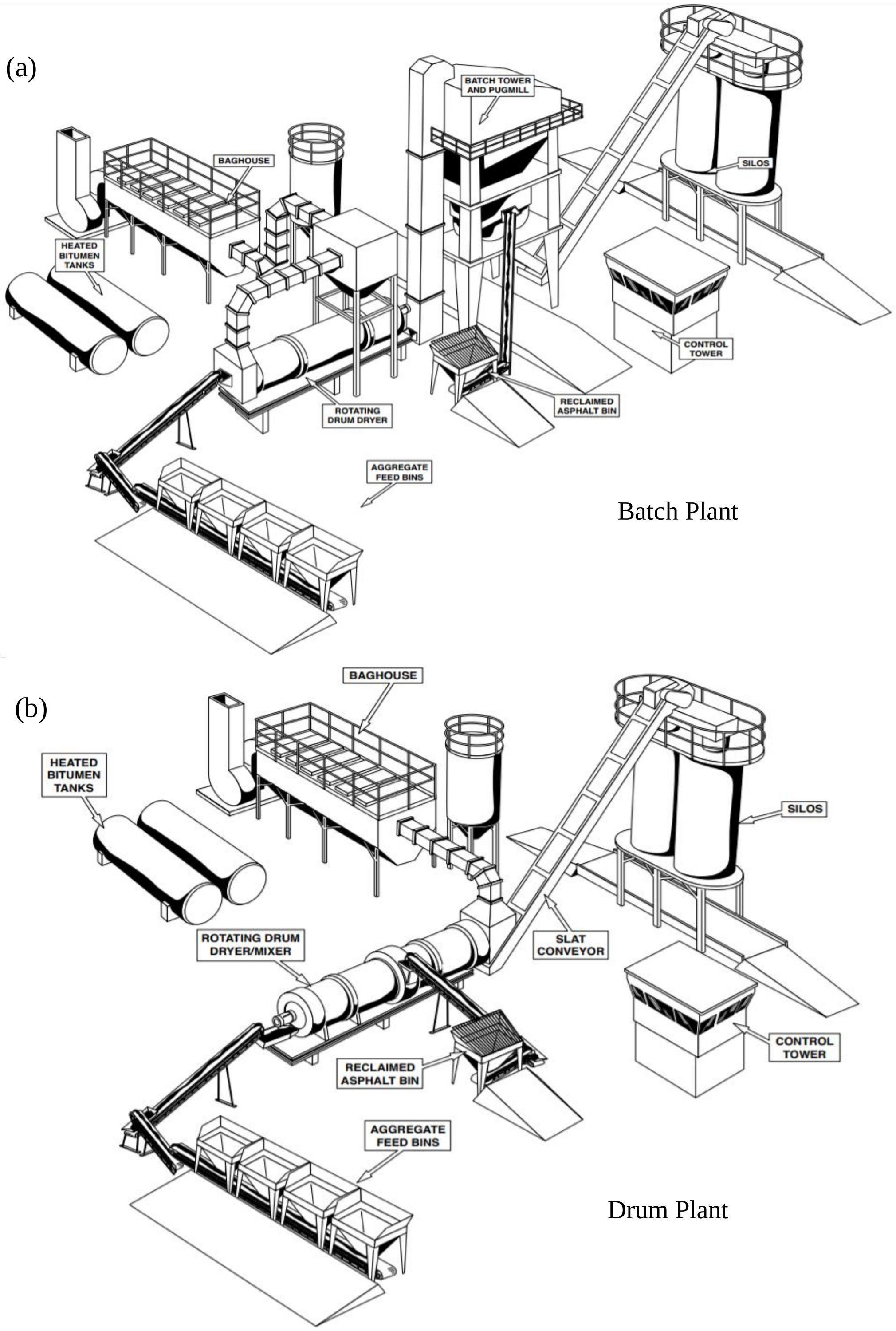

Figure 2: (a) Batch Plant and (b) Drum Plant. Adapted from (EAPA & NAPA, 2011).

Afterwards, the asphalt pavement will be discharged into trucks for being transported to the project site. Both HMA and WMA are loaded at a fairly uniform temperature (Pavement Interactive, n.d.). However, some of the heat can be lost during truck transport, especially around the surface of the truck wall, which produces that the surface area from the truck is hardened (crusty) (Muhammad et al., 2019; Pavement Interactive, n.d.). Transport distances are constrained since the asphalt mixes must be delivered when it is still warm enough for placing and compacting (e.g. the temperature for HMA when arrives at the jobsite should be around 135℃ (275°F) and 150℃ (300°F)) (EAPA & NAPA, 2011; Frost, 2020). Hence, the transport distances of asphalt mixes are generally within a range of 30-80km (18-50 min) (EAPA & NAPA, 2011).

2.1.3. Asphalt placement and roller compaction

The European Asphalt Pavement Association (EAPA, n.d.) reports that hot asphalt mixtures were spread manually with the aid of a shovel; this took place approximately at the beginning of the 20th century, as Figure 3(a) shows. Afterwards, asphalt paving machines were developed. In the 1930s, these machines were incorporated with floating screeds, which allowed a better levelling and pre-compaction of the asphalt layer, as presented in Figure 3(b). Nowadays, paving machines are more advanced, as Figure 3(c) shows.

(a)

(b)

(c)

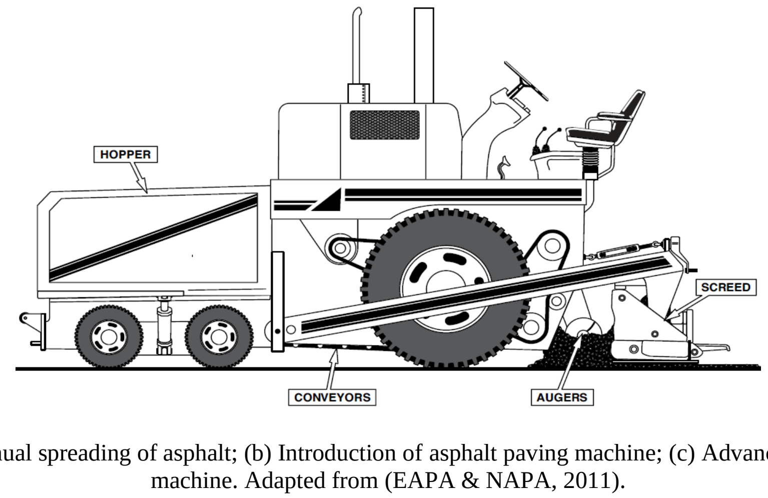

Figure 3: (a) Manual spreading of asphalt; (b) Introduction of asphalt paving machine; (c) Advanced asphalt paving machine. Adapted from (EAPA & NAPA, 2011).

The asphalt mix is discharged from the trucks into a hopper on the paver (EAPA, n.d.). The mixture is conveyed from the hopper and through the paving machine until it is spread across its width by augers located at the end. As the asphalt paving machine moves forward, the screed maintains the asphalt mat levelled and smoothed. Consequently, the mix in front of the screed is loose, while the material behind the screed is reasonable pre-compacted (Huerne, 2004). Non-homogeneities of the mixture (due to mixture composition and temperature), variations in paving speed, variations in layer thickness and screed adjustments may produce variations in the pre-compaction level achieved by the screed. This partly affects the final level of compaction of the layer since the final compaction level is principally determined by the roller. However, an acceptable pre-compaction level is essential for the final smoothness of the upper surface because the compaction process is carried out on a more stable layer. In other words, a variety in the pre-compaction level achieved by the paving machine usually results in varieties in the final compaction level achieved by the roller.

Compaction is the reduction of the volume of air in a mixture through the application of external forces (Huerne, 2004). Therefore, the mix occupies less volume and increases the density of the mass. There are different roller types available for the compaction of asphalt mixes, and the most commonly used are static-steel-wheel rollers, vibratory-steel-wheel rollers and pneumatic-tire rollers. According to Briaud and Seo (2003), compaction is typically accomplished with the help of static or vibratory rollers that cover parallel strips of an area with a certain number of passes. From which vibratory rollers are mainly used, their vibration frequency and amplitude are constant, while the operator decides the rollers' speed. Due to variation in material properties, water content, and stiffness of the underlying layer, a homogeneous compaction result may not be achieved. The operator can not control such factors; therefore, certain areas will be over or under-compacted despite a constant number of passes and roller parameters (i.e. frequency, amplitude and speed). Due to over or under-compaction, premature distresses may appear on the pavement, which causes bad long-term pavement performance and higher life cycle costs (Xu & Chang, 2013). At the same time, previous studies have revealed that two controllable parameters can influence the quality of the asphalt: dynamics of compaction (i.e. number of roller passes) and asphalt temperature. However, traditional compaction determines such parameters based on previous experience and rules of thumb, which has proven to be suboptimal (Makarov et al., 2019).

2.1.4. Random (Spot) Testing Methods

After compacting the asphalt layer, in-situ spot tests are carried out for quality control (QC) and quality assurance (QA) (Cai et al., 2017; Xu & Chang, 2013; Yoon et al., 2018). The former refers to control the quality of construction and the quality of the product being constructed. The latter refers to actions required to accept the construction quality and certify that the evaluated quality complies with the owner's specifications (Yoon et al., 2018). Nevertheless, there are several drawbacks related to conventional in-situ spot testing: (1) the compaction quality of the entire road cannot be represented since the tests are performed at limited locations and often randomly, which makes the quality assessment questionable; (2) some tests can be destructive to the compacted layer, which can affect the pavement performance by causing cracks and potholes; and (3) real-time collection of compaction data is not possible; therefore in-situ rectifications are not possible (Cai et al., 2017; Yoon et al., 2018; Zhu et al., 2018). These intrinsic shortcomings of conventional compaction spot tests may result in non-uniform and insufficient compaction, which leads to failure of long-term pavement performances and increase in maintenance costs (Zhu et al., 2018).

2.2.The historical track of the developments in asphalt construction

In the previous section the embedded problems of conventional practices (i.e. paving, compaction and spot testing methods) for road construction were discussed. These problems relate principally to the performance of the pavement at long-term and the costs for maintenance. Consequently, the academia and industry have developed high-tech solutions to deal with such problems, as Figure 4 shows.

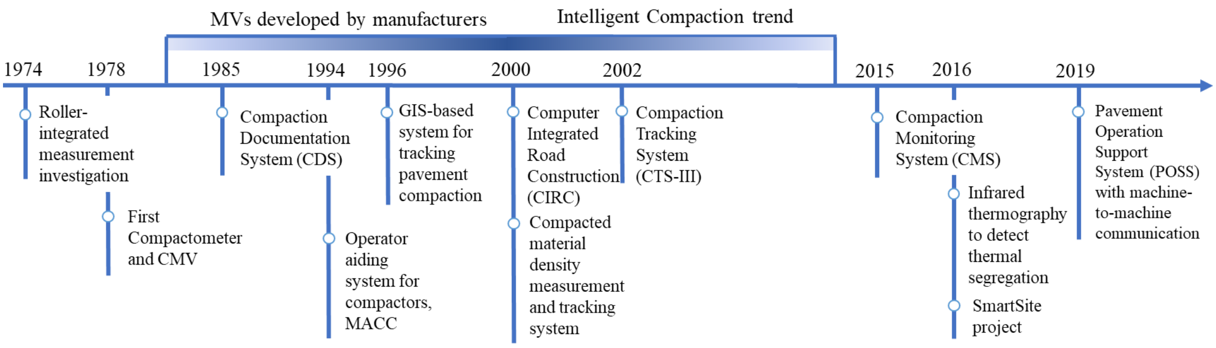

Figure 4: Development of paving and compaction support systems. Adapted from (Makarov, 2017).

One of the initial investigations related to high-tech solutions was on roller-integrated measurement, which took place in 1974 (National Academies of Sciences, Engineering, and Medicine, 2010). At that time, Dr Heinz Thurner from the Swedish Road Administration researched the relation of drum harmonics with soil properties. In the following year, Dr Heinz and Åke Sandström founded Geodynamik to develop further the roller-mounted compaction meter. This concept is based on the hypothesis that pavement properties under compaction correlate with changes in stiffness (Yoon et al., 2018). In the compaction process, air voids decrease, making pavement denser and leading to a high density and stiffness in asphalt pavements. In 1978, Geodynamik and Dr Lars Forssblad from Dynapac introduced the first commercial Compactometer and the compaction Meter Value (CMV). This value was an index related to the stiffness of the compacted layer. After 1980, manufacturers developed several indices individually to obtain more detailed information about the compacted layers. Bomag presented the Omega value and measurement value E_{vib}, which indicates the soil dynamic modulus value. Caterpillar, Dynapac, and HAMM used CMVs, which are accelerometer-based stiffness values. Caterpillar also uses Machine Drive Power (MDP) which measures roller resistance and is energy-based stiffness. Likewise, Ammann/Case introduced roller-integrated stiffness (K_b). Finally, Sakai presented the Compaction Control Value (CCV), which follows the principles of CMV by using the harmonic content from the vibration measured from the drum to estimate the compacted state (National Academies of Sciences, Engineering, and Medicine, 2010; Yoon et al., 2018).

Many breakthroughs can be identified within the area of system development for asphalt paving and compaction (Makarov, 2017). In 1985, the 'Compaction Documentation System' (CDS) developed by GEODYN in Sweden was the initial step towards automating compaction procedures, which principally focused to the monitoring of compaction works. The operator had to enter the compaction data (e.g. number of passes) manually, which could be stored and analysed by employing algorithms. Hence, CDS formed the basis for future developments of systems since the operator's actions became more traceable. However, there were no sensors available to identify the orientation and position of the compactor; therefore, the operator must follow the earlier decided path (Oloufa, 2002).

Throughout the next decade, the focus of developers was on devices and sensors which could be implemented in construction machines for providing the position and work performed by pavers and compactors (Makarov, 2017). In 1994, a prototype named MACC was developed by the 'Road Test Center' and the 'Public Works Research institute' in France (Froumentin & Peyret, 1996). In the following year, it was tested in cooperation with the French road builder Cochery Bourdin Chaussé. The system was composed of an onboard computer, an interface for operators, and a positioning system called CAPSY. This prototype of the automotive system was used on the compactor and provided the number of rollers passes on each point of the asphalt layer. The information was presented to the operator in real-time through a two-dimensional coloured map of the area to be compacted, together with the position of the machine. Furthermore, quality control of the asphalt pavement could be performed with the system's collected data. However, the prototype had some drawbacks related to its components. For instance, the size of the screen was not suitable for the small cab of the machine. This problem was combined with the poor legibility of the screen caused by the surrounding illumination. Also, the map of the compaction process drawn with three colours was not very efficient. Additionally, the CAPSY positioning system was composed of a laser which was not feasible for the construction site and sensible to rain and vibration (Froumentin & Peyret, 1996). In 1996, a similar approach for tracking pavement compaction was presented (Li et al., 1996). This GIS-based system was developed in the USA by researchers from Penn State University and aimed to automate data collection for quality control in real-time. At that time, GPS positioning was not accurate enough, although it was inexpensive. Therefore, the researchers used Differential GPS (DGPS) together with software corrections to enhance its accuracy. In the presented system, the positioning device transmitted the information to a remote computer. The software used the retrieved data to depict graphically the number of passes executed over a road using different colours. Therefore, the focus of research was on displaying the number of roller passes by improving algorithms. Furthermore, they pointed out that future improvements would relate to the installation of sensors for temperature, moisture content and other variables (Li et al., 1996). Likewise, the 'Computer Integrated Road Construction' (CIRC) was presented by Peyret et al. (2000). In this project, two products were developed: CIRCOM for compactors and CIRCPAV for pavers. The focus of CIRCOM was on assisting the operator with the number of passes at an appropriate speed and recording the work performed by the compactor. On the other hand, CIRCPAV helped the paver's operator by suggesting a suitable trajectory at a proper speed. Also, it could control the position and cross-slope of the paver screed, together with the record of the performed work (Peyret et al., 2000). According to Makarov (2017), it was the first system that considered radio modems and Wave LANs with Peer-to-Peer architecture for enabling communication between machines. Hence, each machine was equally capable of gathering information about other machines.

Even though, Intelligent Compaction (IC) technology started its development around the 1970s, the IC trend marked a new era of development beginning in 2000, as discussed by Makarov (2017). From this year onwards, researchers changed their attention to the information retrieved from the roller by incorporating sensors and prediction algorithms for mixture density and roller passes. For instance, a Compaction Tracking System (CTS-III) was proposed and developed by Oloufa (2002). This system was able to track various compactors simultaneously and principally analysed the number of roller passes and surface temperature of the asphalt pavement. At the same time, much attention was drawn towards evaluating the effectiveness of IC for asphalt compaction and its application for QC and QA purposes. Numerous studies have tried to found correlations between roller MVs and spot-test measurements (e.g. Plate Load Test (PLT) modulus, Light Weight Deflectometer (LWD) modulus) (National Academies of Sciences, Engineering, and Medicine, 2010). Such studies will be described in more detail in section 2.3.

The research carried out within the last decade focused on the obtention of temperature of the asphalt layer, density of the asphalt layer and communication among machines. For instance, Kassem et al. (2015) developed the compaction monitoring system (CMS) for monitoring and documenting the compaction process of asphalt pavement. This system consisted of a GPS unit to localise the rollers. Furthermore, temperature sensors were included to record the surface temperature of the asphalt pavement, which was combined with accelerometer sensors to determine the mode of operation (i.e. static or vibratory). This system produced colour-coded maps indicating the number of roller passes, the compaction index (number of roller passes times effectiveness factor), and the temperature of the asphalt layer during the first pass of the roller. Additionally, a method for predicting the asphalt density by using the compaction curves of from static and vibratory rollers was developed (Kassem et al., 2015). Five subtest sections were constructed with vibratory and static compaction methods, and for each subtest section the compaction curves were retrieved for both the static and vibratory methods (Kassem et al., 2012). Figure 5 shows an example of the prediction of the density of subtest section 5.

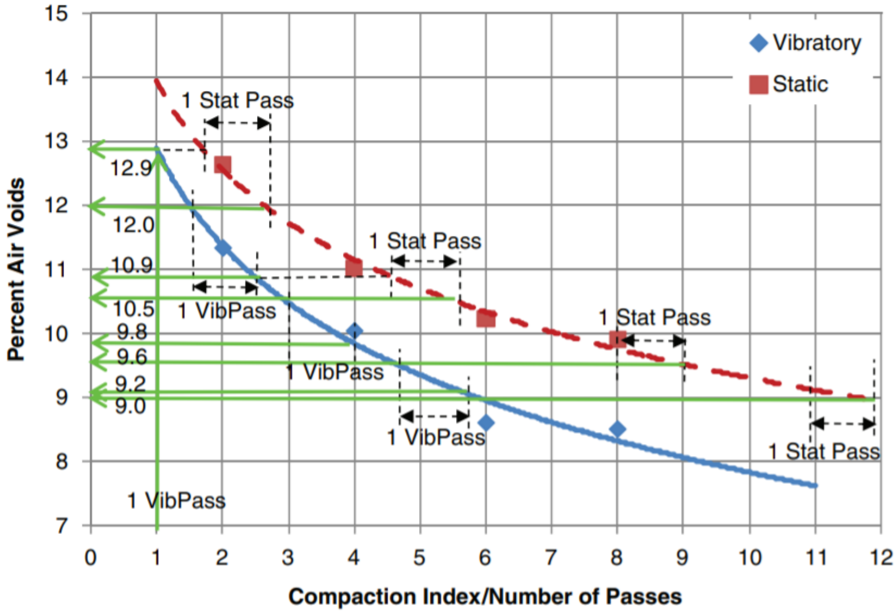

Figure 5: Density level prediction with compaction curves. Adapted from (Kassem et al., 2012).

The process is summarised as follows: (1) the air void percentage after the first pass of the vibratory roller was 12.9%; (2) considering the air void percentage of 12.9% on the compaction curve of the static roller and after applying one pass of the static roller (moving one pass towards the right in the static compaction curve), an air void percentage of 12% can be obtained; (3) taking into account the air void percentage of 12% on the vibratory roller compaction curve and applying one pass of the vibratory roller (moving one pass towards the right in the vibratory compaction curve), an air void percentage of 10.9% can be obtained; (4) The aforementioned steps are repeated up to the final toller pass (Kassem et al., 2012). Dhakal and Elseifi (2016) used infrared thermography to detect thermal segregation in the asphalt mat. This research showed that temperature losses might occur when the asphalt mat is paved above longitudinal and transverse joints. Another related study was the SmartSite project presented by Keunzel et al. (2016). In this project, software agents were developed for representing asphalt compactors. Each agent had a group of rolling patterns from which it was able to choose. Furthermore, it transformed input from sensors to driving instructions by considering previous knowledge of rolling patterns and physical causes and effects. Therefore, this system enabled the operators to control the equipment and to react to disturbances or changes. Also, this system estimated the core temperature of the asphalt layer by measuring the surface temperature and using the layer thickness. However, due to the variance in temperature of the asphalt mat, the estimation may be inaccurate (Kuenzel, 2016). Recently, Makarov et al. (2019) proposed a support system for paving and compaction, which uses machine-to-machine communication (M2M) and sensor network (GPS, temperature linescanner, thermologger). This system assisted operators to achieve a higher process/product quality by providing a comprehensive view of the construction operations. Due to the integration and analysis of data collected from rollers, pavers and asphalt in real-time. Furthermore, an innovative method was presented in the system to obtain the asphalt layer temperature based on asphalt mat surface and core temperatures.

Overall, the asphalt construction industry has experienced technological advances throughout the decades. The first investigations for retrieving information about the stiffness/modulus of the compacted layers was the start of a vital development era. With the pass of time, academia focused on more specific matters. For instance, at the beginning of the systems development, the operator had to manually enter the compaction data, which could later be analysed using algorithms. After some years, the implementation of devices and sensors increased, which facilitated the job for the operator by providing the location and performed work (e.g. number of roller passes) from pavers and compactors. Following this development era, the IC trend made an essential contribution by retrieving information about work of an asphalt roller with the implementation and improvement of algorithms and sensors. Nowadays, enhanced technologies (i.e. devices and sensors) are being developed; thus, roller operators can be provided with essential data in real-time (Makarov, 2017). At the same time, the contributions by the industry towards the development of asphalt support systems have also been evidenced over the years.

2.3. Studies regarding the implementation of compaction support systems

The crucial moments within the development of high-tech solutions for asphalt construction were described previously. Even though such technologies have made important improvements, they have not been widely implemented. One of the concerns relates to the ability of such technologies to take over conventional machinery and practices. Conventional machinery have showed drawbacks related to failure in long-term pavement performance and increased maintenance costs. Hence, the academia has researched the quality of the asphalt pavements based on high-tech solutions. Especially the technologies used for compaction purposes have been analysed, since compaction is considered as the most important factor which affects the performance of asphalt pavement (Transportation Research Board, 1989). Therefore, researchers have principally focused on IC technology. Over the last three decades the studies principally have been dedicated to evaluate the relation of compaction MVs from soil and asphalt to spot-test measurements (e.g. density, LWD modulus). Specially, because asphalt and soil have different properties. The performed studies aim to substantiate the feasibility of compaction support systems for QC and QA purposes.

2.3.1. Continuous Compaction Control (CCC) and Intelligent Compaction (IC)

The conventional quality control is mainly based on spot acceptance tests executed after compaction (Gomes et al., 2020). In the 70s, an innovative technology was presented to deal with the shortcomings of conventional practices of compaction. This technology used the responses measured on the rollers within the compaction process for continuous compaction control. Over the years, this technology has evolved to represent modern compaction quality control methods, recognised as the "third revolution of road construction technology" (Gomes et al., 2020). The use of compaction support systems has increased worldwide, especially in Europe, Asia, and the United States (Federal Highway Administration, 2013). The name of these technologies varies among continents. In Europe, these technologies are called Continuous Compaction Control (CCC). On the other hand, the term Intelligent Compaction (IC) is employed in the US. Both terms are interchangeable (Gomes et al., 2020).

CCC and IC are vibratory-based technologies that enable the measurement of the level of compaction during construction works. Commonly, the use of these technologies by engineers and practitioners has been improving towards Quality Control (QC) in highway construction. However, after approximately 40 years of creation, there is a lack of knowledge about CCC/IC technologies by the industry (Gomes et al., 2020). Hence, many studies have been devoted to documenting the correlations between the measurements obtained by compaction support systems and conventional in situ measurements in the last decades. These studies have been carried out because it is intended that the measurement values from compaction support systems can be used widely for QC and QA purposes. In previous studies, the measurement values recorded by compaction support systems and soil point measurement values (Point-MV) have shown good correlations. On the other hand, few studies have shown good correlations between measurement values from CCC/IC and asphalt Point MVs (Hu et al., 2019).

2.3.2. Compaction control index or Intelligent Compaction Measurement Value (ICMV)

Compaction control index or Intelligent Compaction Measurement Value (ICMV) is one of the main components of the CCC/IC technology (Gomes et al., 2020). A standard measure for reporting the compaction results from CCC/IC was not established over the years; thus, manufacturers have developed various measurement values (which is also incorporated into their proprietary software for the processing and displaying data) (Federal Highway Administration, 2014). However, the calculation of all types of measurement values is done through a common mechanism which measures the vertical acceleration at the centre of the vibrating drum, then ICMV/Compaction control index is computed using various models and methods (Federal Highway Administration, 2017). Hence, by measuring the properties of the compacted materials during compaction a real-time compaction control and monitoring can be achieved. As Figure 6 shows, a compaction force is exerted by the roller drum on the compacted materials, such materials react the force back to the roller drum. Hard compacted materials produced a large reactive force, and soft compacted materials produced a small reactive force. The reactive force is captured in terms of acceleration by the accelerometer mounted on the roller drum. Afterwards, the control system will compute ICMV by processing the acceleration signals (Federal Highway Administration, 2017).

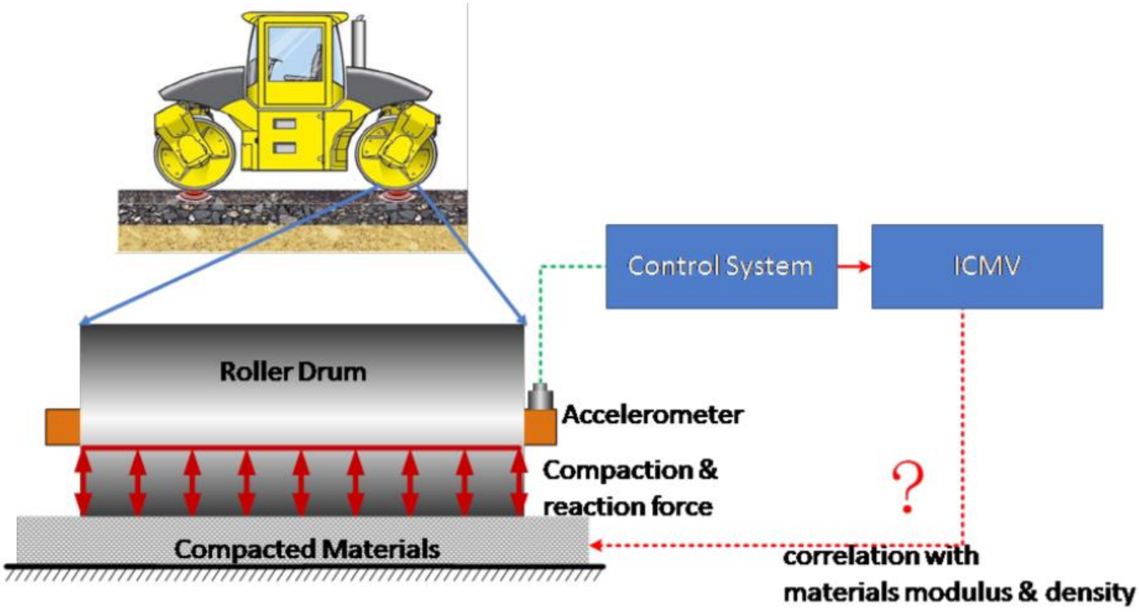

Figure 6: Common mechanism for calculating ICMV/Compaction control index. Adapted from (Federal Highway Administration, 2017)

The first measurement value from this type of system is obtained by calculating the ratio between two different harmonics in the response signal of the vibratory roller, commonly known as "harmonic ratio" and "Compaction Meter Value". At the start, the correlation between CMV and conventional spot tests (e.g. plate load tests) was poor, which restrained CCC/IC from being broadly used. Later, a new method was presented for calculating the vibration modulus of the materials being compacted with the dynamic response from the vibratory roller. Nevertheless, some of these solutions were part of vendor-specific rollers, which hindered the popularity of such systems (Gomes et al., 2020).

The current measurement values vary in their measurement principle and theoretical background; however, the more recognised are described in Table 1. More detailed information about these measurement values can be found in Appendix A.

Table 1: CCC values/ ICMVs

CCC value/ ICMV	Description	Manufacturer/ Supplier/ Used or Implemented by
Compaction Meter Value (CMV)	CMV was introduced in 1978 as the first established compaction control index. CMV is an indicator of the asphalt or soil layer's stiffness/modulus and is dimensionless. (Federal Highway Administration, 2014)	Dynapac, Caterpillar and Trimble report CMV.
Compaction Control Value (CCV)	This value is a measure of the compacted layer's stiffness. Like CMV, the use of CCV is available for both soil and asphalt and is dimensionless (Federal Highway Administration, 2014).	CCV is Produced by the rollers from Sakai.
Vibratory Modulus (E_{VIB})	$\mathrm{E_{VIB}}$ value represents a measure of the compacted layer's stiffness. The units of this value are in mega pascals (MPa). The use of this value is available for soil and asphalt (Federal Highway Administration, 2014).	This value is produced by rollers from Bomag.
Roller Integrated stiffness (kB)	It is the measure of the stiffness of the compacted layer and its units are in mega Newtons per meter (MN/m) (Federal Highway Administration, 2014).	The rollers from Ammann and Case use this value.
Machine drive power (MDP)	This value measures the necessary energy to overcome the resistance from the roller. The use of MDP is available for soil compaction and can be used in granular and cohesive soils (Federal Highway Administration, 2014).	Caterpillar developed MDP.

2.3.3. Studies of CCC/IC values and soil Point-MVs

Linear solid correlations have been identified among CCC/IC measurement values throughout many studies and various types of soil Point-MVs (Hu et al., 2017). For instance, between 2008 and 2010, the Federal Highway of Administration (FHWA) conducted demonstration projects using compaction support systems, in which 13 states from the US participated (Federal Highway Administration, 2014). The study was named 'Accelerated Implementation of Intelligent Compaction Technology for Embankment Subgrade Soils, Aggregate Base, and Asphalt Pavement Materials'. The study aimed to demonstrate and evaluate this type of technology in field projects. Six of the involved states participated in soil/subbase case studies, which were successful and it was determined that ICMVs increased with in-situ measurements. The correlations of the values from lightweight deflectometer (LWD) and falling weight deflectometer (FWD) with soil and subbase ICMVs were decent. Nevertheless, Plate Load Test (PLT) values, California Bear Ratio (CBR), and non-nuclear density had generally poor correlations with soil and subbase IMCVs. There was no evidence demonstrating that machine settings (e.g. frequency, amplitude and speed) will affect the quality of the correlation from these six projects. Furthermore, within these six projects, separated trends for the correlations were observed for different materials. In general, the correlations between soil and subbase

ICMVs and deflection-based moduli (FWD and LWD) had the most acceptable results (Federal Highway Administration, 2014).

Another research conducted in 2017 was elaborated to establish a basis for incorporating compaction support systems in QC/QA specifications for soil (Cai et al., 2017). In previous studies, the correlations between measurement values from support systems and conventional in situ measurements from soils were good. However, some aspects from the earlier studies were contemplated within this research. First, the data is often retrieved from a test strip in a controlled environment. Therefore, high soil correlations may not be attained in real projects. Another evident problem is that the locations of in situ measurements are not precisely matched with the areas of compaction support systems measurements. In order to deal with this problem, the interpolation of IC values measured at the in situ test locations has been carried out. However, the assumptions or requirements for interpolation may not always be valid. Finally, it is crucial to realise a broad cross-comparison among CCC/IC measurement values and in situ measurements to provide valuable insights for using CCC/IC technologies for soil compaction. Within this research two compaction control indices were collected from soil: compaction meter value (CMV) and the machine drive power (MDP). Furthermore, in situ measurements were conducted to evaluate soil compaction, exclusively Dynamic Cone Penetrometer (DCP), falling weight deflectometer (FWD), and lightweight deflectometer (LWD) (Cai et al., 2017). The obtained correlations are shown in Table 2.

Table 2: Correlations between ICMVs and In Situ Measures. Adapted from (Cai et al., 2017).

Variable	MDP	CMV	DCP	LWD	FWD
MDP	1.000				
CMV	0.752	1.000			
DCP	-0.647	-0.264	1.000		
LWD	-0.649	-0.343	0.709	1.000	
FWD	-0.842	-0.611	0.732	0.853	1.000

High values of CMV and MDP imply a high soil stiffness (Cai et al., 2017). On the other hand, LWD and FWD measure deflection as a response to the falling weight; hence high LWD and FWD values indicate low stiffness. The DCP enables the measurement of the rate of penetration of the cone of DCP per blow. A high DCP penetration index indicated low soil stiffness. Consequently, the DCP index should positively correlate with FWD and LWD and negatively correlate with CMV and MDP. On the one hand, the FWD showed the highest correlation with the other measurements, expected from a statistical position when FWD measures the soil stiffness with the slightest error margin. On the other hand, CMV showed poor correlations with the other measurements, attributed to mechanical issues from the machine that performed the measurements. On the contrary, there is a high correlation between CMV and MDP.

Regarding soil compaction with CCC/IC, the major factor that affects the correlations among ICMVs and soil Point-MVs is heterogeneity in support conditions of layers underlaying the compacted soil layer (Hu et al., 2019). Nevertheless, the obtained good correlations (especially with deflection-based moduli tests) confirm the possibility of using the results from high-tech solutions to be used for acceptance tests of soils. Thus the requirements for performing in situ tests can be minimised. Furthermore, the results from different studies suggest that these technologies can be used to identify weak areas rather than for determining acceptance of soils.

Currently, this is the most practical application of the compaction support systems for QC/QA with soils (Cai et al., 2017).

2.3.4. Studies of CCC/IC values and asphalt Point-MVs

On the other hand, good correlations are rare among CCC values/ICMVs and asphalt Point-MVs (Hu et al., 2017). Within a study conducted by the FHWA, 10 of the 13 participant states worked in HMA demonstration projects (Federal Highway Administration, 2014). The use of IC technology demonstrated to be a success in the ten states. One consistent finding is that IC base mapping does help to detect soft and stiff areas before HMA placement. Another significant result from these case studies was that the correlation between ICMV and HMA density (from nuclear and non-nuclear gauges) range from poor to good. The majority of cases showed an increment in ICMV with an increment in density; however, the data were highly scattered. Furthermore, the correlations among ICMV and HMA density (from drilled cores) were contradictory because the results showed that density could increase or decrease with an increment in density. Finally, the correlations among IMCVs and values from the LWD base layer modulus were commonly fair. However, the sensitivity was low, and the scatter was significant among the ICMV, increasing the layer modulus data. In conclusion, there were correlations between ICMVs and in-situ measurements; however, there was considerable variability (Federal Highway Administration, 2014).

According to Hu et al. (2019), the inconsistency in correlations is caused by several factors: (1) the measuring depth of CCC/IC measurement values is greater than the asphalt layer thickness. Therefore, the measured values on the top layer are affected by the stiffness of the underlying layers. This makes it necessary to explain the effect of the underlying support when using CCC/IC; (2) CCC/IC measurement values depend on the asphalt temperature. Due to the cooling of asphalt during the compaction process, the stiffness will continuously change. While values obtained in conventional tests (e.g. drilled cores) are not influenced by temperature. Since asphalt is a viscoelastic material, its dynamic modulus depends on volumetric and rheological properties such as temperature. That makes the behaviour of this material more complex than in the case of soils, and (3) ICMV is influenced by roller operating parameters such as amplitude or frequency. Such critical factors of IC for asphalt paving were researched by Hu et al. (2019). In the research, IC technology was investigated in two asphalt base layer projects, as Figure 7 shows:

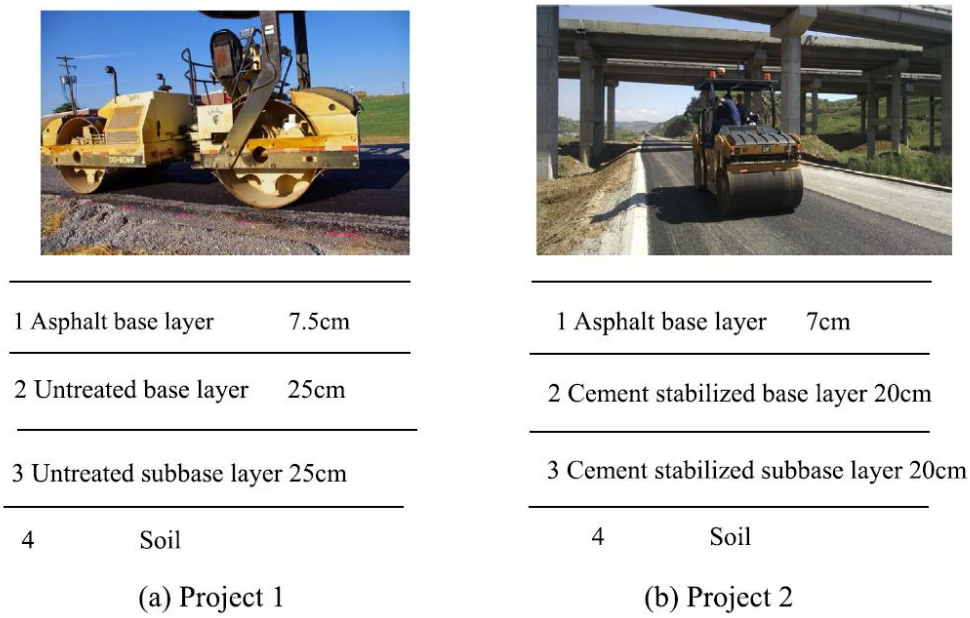

Figure 7: Projects with treated and untreated underlying layers. Adapted from (Hu et al., 2019).

CMV values were documented in the study for two projects involving an asphalt base layer over-treated or untreated base and subbase (Hu et al., 2019). By comparing the results from both projects, CMV primarily reflects the stiffness of the underlying layers based on their layer thickness and stiffness contrast between layers. Additionally, roller operator parameters may also influence CMV. In order to analyse this, three different amplitudes were applied to project 2. The results from the research suggest that improper roller settings may affect CMV; therefore, the potential use of CMV for asphalt modulus evaluation could be compromised. Likewise, the temperature will influence the dynamic modulus of asphalt, which can affect the CMV value. In theory, a low asphalt temperature connects with a high dynamic modulus of asphalt and CMV and vice versa. Nevertheless, other factors (i.e. air void content, loading frequency, and gradation) will affect the dynamic modulus of the asphalt. Considering layer thickness, stiffness contrast among layers and amplitude of vibration will influence the CMV value. This makes the relationship between temperature and CMV hard to identify. The temperature change was analysed for both projects. For project 2, the areas with low temperatures were commonly accompanied by high CMVs and the areas with high temperatures registered low CMVs. The correlation analysis indicates that with strong underlying support and proper roller settings, roller operating parameters can be minimised. Hence, CMV can reveal changes in the asphalt modulus more efficiently.

Overall, the poor correlations found among CCC values/ICMVs and asphalt Point-MVs have constrained the use of such systems widely. Since, they are caused by three important factors affecting CCC/IC values. Such values have a greater influence depth than the asphalt layer thickness, they continuously change with changes in temperature and they are influenced by roller operating parameters. Hence, it is important to set an appropriate amplitude setting and strong underlying support make CCC values/ICMVs more sensitive to the change in asphalt modulus. It is also essential to focus on the temperature from the asphalt since it is one of the parameters which can be easily obtained from the parameters which control the asphalt modulus.

2.4. Market available solutions

Previously the research by the academia regarding high-tech solutions was discussed. Such research results and the increasing demand from the road construction sector pushed the industry towards developing high-tech solutions that can offer support for the asphalt crews by documenting asphalt construction parameters (e.g. number of roller passes). The most recognised paving and compaction support systems will be described in the following sections.

2.4.1. Paving support systems

Build Analytics: Q Asphalt

Q Asphalt is an asphalt management system which links and controls the construction process. This system enables the planning of construction sites in a short period of time. The influence from each modification within a construction project to other parameters is processed by the system. Hence, the efficiency of the construction process starting from the mixing plant to the construction site is improved (Build Analytics, n.d.).

Leica: Leica iCON pave asphalt

Leica Geosystems offer 3D machine control solutions for asphalt pavers. Without the dependency on string lines, the consistency and quality of the surface can be enhanced. It is possible to combine sensors depending on the required paving task, which is available for any paver brand. Moreover, it enables tracking, visualising, and synchronising data via Leica ConX, a cloud-based collaboration tool (Leica Geosystems, n.d.).

MOBA: PAVE-IR

PAVE-IR system generates a comprehensive thermal profile of the road in real-time. This system consists of a thermal profile sensor and an onboard computer. The sensor enables measurement of the material's surface temperature to detect thermal segregation and analyse and record temperature values. The retrieved data can be uploaded to the MOBA cloud, or there is the possibility to use other external solutions. Moreover, the operators can visualise the thermal profiles and thermal material properties in real-time. Additionally, it is possible to analyse the data and make reports from this analysis. In the same way, the onboard computer optimises the management of data from the machine (i.e.paver) and improves its usability (MOBA, n.d.).

Trimble: Paving Control for Asphalt Pavers

There are two options for paving control offered by Trimble: 3D Paving Control and 2D Paving Control. On the one hand, 3D Paving Control enables to control the screed, which paves with variable slope and depth based on a 3D design. On the other hand, 2D Paving Control uses a 2D reference, which enables to pave with a predetermined thickness (Trimble, n.d.).

VOGELE: RoadScan and WITOS Paving

RoadScan is a temperature-measurement system with no contact with the pavement surface being laid, which continuously monitors the temperature of the supplied mix. The system's core is the high-precision infrared camera that scans the asphalt pavement behind the screed, combined with an accurate GPS receiver. This facilitates recording the position of the temperature data together with external parameters influencing the paving process. Additionally, before paving, a pyrometer is mounted in front of the undercarriage to measure the base temperature. The retrieved data can be assessed using WITOS Paving, which can generate graphs and charts from the paving process. In this way, the job site can be analysed using temperature data, and measurements can be filtered according to current specifications (Wirtgen Group, n.d.). There are two systems available WITOS Paving Docu and WITOS

Paving Plus. The former can be used for the documentation of small and medium-size projects. The latter is used when there is an increment in the requirements from the customer or big projects (Wirtgen Group, n.d.).

2.4.2. Compaction support systems

Ammann: GPS-based compaction (ACE^{pro+} and ACE^{force+})

In 1998, Ammann launched the first generation of Ammann Compaction Expert (ACE), an automated compaction measurement and control system, which contributed to the development of Intelligent Compaction. Nowadays, this technology is available for soil and asphalt compaction, and there are three available options: ACE^{pro},ACE^{force}, and ACE^{econ}. ACE^{pro} and ACE^{force} are employed with rollers, and the main difference between both technologies is that the former provides automatic control while the latter does not include this feature. On the other hand, ACE^{econ} is utilised specifically with plates. In order to provide an efficient analysis and documentation system for Continuous Compaction Control (CCC), ACE technology is combined with a navigation system (i.e. GPS). This technology is called ACE^{plus} and can be found in $ACE^{pro+}$and ACE^{force+}. Hence, it accurately allocates the measured compaction values to the position coordinates and the time (Ammann, n.d.).

Bomag: Bomag Compaction Management (BCM)

BCM allows to manage and record compaction in a construction site. This system is presented in three versions: BCM *start*, BCM *05*, and BCM *net*. BCM *start* is an application for indicating the number of roller passes that have been made by using colour. When it is used for asphalt compaction, the colour also shows the surface temperature. BCM *05* is a tablet PC that processes the E_{VIB} values and communicates with the roller. It can also generate an accurate map of compaction values and the number of passes and temperature recorded by BCM *start*. Furthermore, BCM *05* has a software tool called BCM office to create and manage projects appropriately. It is a unique system that can work without a GPS receiver, which is useful when working inside structures or tunnels. BCM *net* connects all the compaction rollers; therefore, communication between rollers is possible. Moreover, the paver can be integrated with the roller, meaning that the roller operators can visualise the mat track laid by the paver together with its temperature (Bomag, n.d.).

Build Analytics: Q Compaction

Q Compaction is an assistance system which enables to monitor the compaction of earthworks and asphalt. It records stiffness and temperature values automatically without the action from the roller operator. Furthermore, geodata is retrieved with the use of a GNSS receiver. Such system also assists the paving team by interconnecting multiple compactors (Build Analytics, n.d.).

Dynapac: Continuous Compaction Control (CCC) - Compaction meter (Dyn@lyzer)

The experience of Dynapac in Intelligent Compaction started approximately in the late 70s. Subsequently, Dynapac developed a compaction control and documentation system called Dyn@lyzer, which is build up in two levels: (1) Compaction Meter, which documents E_{VIB} readings for both soil and asphalt; and (2) Dynapac Compaction Meter and Dyn@lyzer with GNSS (Global Navigation Satellite System). Dyn@lyzer system for asphalt and soil rollers has nearly the same characteristics because it records and maps the stiffness and stiffness progress of the compacted layer in real-time together with the number of roller passes. Additionally, a

GNSS is used for positioning. This system can record the temperature when used on asphalt rollers (Dynapac, n.d.).

Caterpillar: Compaction Control Technologies

The Compaction Control Technologies provide data for the compactor operator. Furthermore, they include measurement, positioning and analysis systems. According to Caterpillar (n.d.), they rely on each other and are the foundational components of an Intelligent Compaction system. The measuring system enables monitoring site conditions in real-time, which can affect job quality and efficiency. At the same time, a GNSS system is used for positioning. Finally, the collected data can be analysed and used for documentation or to discover deficiencies. Caterpillar employs Compaction Meter Value (CMV) and Machine Drive Power (MDP), indicating soil stiffness. CMVs are accelerometer-based measurements suitable for granular soils, while MDPs are energy-based measurements suitable for granular and cohesive soils.

On the other hand, CMV, infrared temperature sensors, and Auto Adjustable Compaction (ACC) are available for asphalt compaction. The available positioning technologies are GNSS and machine-to-machine communication. The former occupies global navigational satellite constellations for positioning of the measurements made. The latter enables the operators to visualise the individual and collective progress of machines working on a specific area (Caterpillar, n.d.).

HAMM: HAMM Compaction Quality (HCQ)

HCQ is a modular system encompassing various products designed to measure, monitor, record and control compaction related processes. One of the available products is the HAMM Compaction Meter which can determine the stiffness values for both soil and asphalt compacted layers. Another product is the HAMM Temperature Meter which can measure the temperature of the asphalt. Furthermore, an HCQ Navigator uses a GNSS receiver to determine the position of the roller and combine it with the collected values. Throughout a panel PC, the data is displayed in a real-time compaction map; also, parameters such as amplitude, frequency, and speed from the roller are displayed. Finally, HCQ Navigator software allows displaying, analysing, and exporting the gathered data (Wirtgen Group, n.d.).

Sakai: Compaction Information System 2 (CIS2)

Sakai developed the Compaction Information System 2 (CIS2) technology to support soil compactors and asphalt rollers in achieving uniform density for the compacted layer. The system comprises an accelerometer located in the roller/compactor’s drum, which enables the measurement of the stiffness of the compacted material in real-time. A detailed map of the compacted area is generated using a high-precision positioning system (provided by Topcon). This map indicates poorly compacted portions that the operator can use to focus on subsequent passes or spot-checking. The system can register the temperature of the asphalt mat when it comes to asphalt compaction. The technology from Sakai can record the number of roller passes, vibration frequency and speed, roller speed, and compaction measurement value (i.e. Compaction Control Value CCV) (Power Motive Corporation, n.d.).

Topcon: C-53 intelligent compaction, Sitelink3D

In addition to registering the number of passes, the C-53 system also connects to the global Sitelink3D service. This service provides a constant record showing the roller position in real-time. Furthermore, it allows making contact between office and machine, and among machines, which makes it possible to access a machine, provide assistance, send files to machines, and create reports. The C-53 system is integrated with temperature sensors which allow constant feedback into the system. Moreover, GNSS technology provides information related to passing counts, geographic locations for each run, together with geo-referenced completion and assignment of tasks. Finally, the accelerometer delivers the surface stiffness values (Topcon, n.d.).

Trimble: Trimble Compaction Control System (CCS900)
This system is available for both soil and asphalt compactors. One of its features is that wireless data share allows an individual compactor to visualise the work performed by other compactors. Furthermore, the data can be transferred to the office for analysis. Among its configurations, single GNSS, double GNSS, and total station-based can be found. When it comes to monitoring and analysing soil compaction, this system ensures uniform lift and reliable pass counts, which can also be encountered on the system for asphalt compaction (Trimble, n.d.). However, for asphalt compaction, the system can also monitor temperature maps, pass counts, and compaction meter values (Trimble, n.d.).

Volvo: Compact Assist for Asphalt with Density Direct
Compact Assist is Volvo's Intelligent Compaction system developed for soil and asphalt compaction. When it comes to soil compaction, this system offers compaction and pass mapping. For asphalt compaction, pass and temperature mapping are provided together with density calculation mapping. Therefore, IC offers real-time insight into the work being done and enables access to clear and detailed data. The density values are measured and monitored with the Density Direct feature developed by Volvo. This tool is available for asphalt compactors and allows to calibrate to cores or an asphalt density gauge. This process enables us to estimate the density values with a tolerance of +/-1.5%. Compact Assist allows extracting and accessing retrieved data on-site or anywhere with cloud-data download (Volvo, n.d.).

Völkel: Völkel Navigator
Völkel developed the Völkel Navigator, an assistance system for comprehensive compaction control for earth and asphalt construction. This system has various applications: (1) CCC-Navigator is used for soil compaction; (2) Logistics-Navigator is utilised in the asphalt supply chain; (3) Pave-Navigator is employed in the asphalt paver; and (4) CCC-A-Navigator is used for asphalt compaction. The interaction between Völkel Navigators is achieved through the Völkel-Cloud. Therefore, the asphalt mixing plant, truck, paver, and rollers are networked together. Völkel Navigator (CCC, PAVE, CCC-A) has many components: (1) navigator set which consists of a navigator display and a GNSS receiver with the modem; (2) pre-equipment, which are fixed parts that can be mounted on any manufacturer and machine-independent (e.g. asphalt temperature sensor or GNSS tacker for asphalt trucks); and (3) PC software CompactDoc which allows accessing remote data via Völkel-Cloud servers through PC in real-time. This software is utilised to prepare the compaction work, analyse and evaluate the project (Völkel, n.d.).

2.4.3. The current trend of market available solutions
Since conventional equipment and practices showed a lack of certainty about the quality of the asphalt being paved, the industry and academia researched and developed various support systems for enhancing the paving and compaction process. Nowadays, the use of these support systems has led to a emerging technological revolution within the road-building industry (EAPA, n.d.; Kaufmann, n.d.). In this revolution, gathering, storing, documenting, and analysing jobsite data in real-time has grown remarkably (Kaufmann, n.d.; Wirtgen Group, n.d.). Therefore, current solutions in the market enable operators to make jobsite adjustments, resulting in better machine utilisation, quality improvements of the asphalt pavement, and

reduced fuel consumption (Kaufmann, n.d.). The associated cost savings are considerable; therefore, those who embrace the changes will benefit from this revolution and outpace those who do not. Such revolution is the result of advances in telematics and machine control, which are encountered commonly in soil and asphalt compactors. However, in recent years, pavers, graders, dozers, excavators, haul trucks are also using these technologies (Raczon, 2019; Kaufmann, n.d.). On the one hand, telematics is defined as collecting data, organising it for site management and machine monitoring, and optimising the machines (Kaufmann, n.d.). On the other hand, machine control refers to the monitoring and controlling of equipment on-site. Communication between equipment is essential for machine control, since an individual system can adjust its work depending on the performance of other systems. This communication is carried out in real-time, which enables to make adjustments immediately (Kaufmann, n.d.).

Nowadays, technologies offer numerous benefits and are more flexible to fit the customer needs. For instance, current interfaces present only relevant information or the information which has been demanded by the operator. On the contrary, previous technologies presented too much information which was overwhelming to the operator (Kaufmann, n.d.; Makarov et al., 2021). Hence, the available support systems are more user-friendly with the users. Likewise, the support systems introduced by the industry have adopted high-precision technologies (e.g. infrared cameras, positioning systems) to obtain more accurate results. These technologies capture data (e.g. temperature values, stiffness values, number of passes) in real-time and present it to the operators. In this way, they offer assistance to the operators. Furthermore, since operators obtain data in real-time they can perform their job in a more efficient way. Hence the productivity within paving and compaction processes is optimised which increases the amount of roadway material that can be constructed in a day of production. At the same time, the information presented to the operators enable to take corrective actions in case of poor paving and compaction processes. Thus, the occurrence of spot failures is minimised and the efficiency of compaction and paving operations leads to a reduction in maintenance cost of roads for contractors, authorities in charge and the traveling public. For instance, in a study carried out by Mazari et al. (2021), it is discused that the average life cycle of the pavement constructed with conventional compaction is 10 years, and the cost for annual maintenance per mile (approximately 1.6 kilometers) would be $25.000 (approximately €21.205). On the other hand, with the use of high-tech solutions such as IC technolgy the lifetime of the pavement is extended to 15 years; hence the annual maintenance cost per mile (approximately 1.6. kilometers) would be $9.600 (approximately €8.150). At the same time, the information presented to operators is also available for supervisors and quality managers through software tools, which enable in-depth evaluation and quality analysis of results. These software tools allow to display, analyse and export of the collected data. Currently, some companies enable to transfer data using USB or wirelessly from machine to office. Another important aspect considered by manufacturers is the communication between machines. From which some manufacturers have focused on the data share between compactors. While others have tried to network more equipment from the asphalt supply chain. For instance, Bomag presented the BCM net, enabling the rollers' communication and the paver to be integrated. In this way, roller operators can visualise the overall picture of passes made and temperature, together with the mat track laid by the paver and its temperature (Bomag, n.d.). Another example is the Logistics-Navigator from Völkel allows to network of multiple assets from the asphalt supply chain through the Völkel-Cloud (Völkel, n.d.)

2.4.4. Future developments of market available solutions

In the future, machines will improve the gathering of data, which process improvements will accompany (Kaufmann, n.d.). Hence, the data on how machines previously performed in specific applications and conditions will be available from the start of the project. Hence, the communication among machines from different manufacturers and different phases of the road construction life-cycle will improve to take advantage of the data being gathered. Consequently, the machines without interoperability will be phased out from construction works. The standardization of tools for collecting such information will be necessary for machines to communicate with each other. Hence, the devices from machines of different manufacturers will be a bit different; however, all of them will collect the same data and communicate with each other in real-time. In other words, the hardware will be standardised and integrated into machines.

Another expected development for the future decades is autonomous machines, fundamentally those that do not require an operator (Kaufmann, n.d.). Many exciting developments have already taken place by some of the most recognised manufacturers (e.g. Ammann, Sakai) (Ammann, n.d.; Sakai Heavy Industries, 2019). However, concerns related to safety will have to be addressed before implementing such machines.

3. Guidelines and specifications for road construction

Over the years, some countries have implemented specifications and guidelines for the adoption of paving and compaction support systems, while others have not adopted such technologies within regulations. In order to understand the reasons for this to happen the regulations from countries of Europe, North America and South America will be analysed.

3.1. Europe

There are 44 countries pertaining to Europe; hence, it was decided to only consider two specific regions which are Western Europe and Southern Europe (United Nations Statistics, n.d.). This division follows the EuroVoc classification, which is maintained by the Publications Office of the European Union. According to the EuroVoc classification, there are 12 western countries and 9 southern countries (EUR-Lex, n.d.). Hence, the 8 bigger countries were selected from the 21 considered countries. Since the study was carried out in the Netherlands, it was necessary to understand the situation within this country. Overall, 9 countries were considered as Table 13 from Appendix B shows.

Generally, countries from Europe are known because of the development and implementation of high-tech solutions for road construction. One clear example was the development of CCC/IC technology which occurred in Europe (National Academies of Sciences, Engineering, and Medicine, 2010). By studying the specifications of such countries, it would be possible to determine what the status is of high-tech solutions within regulations and the outcomes i.e., if such countries have not introduced such technologies within their regulations, what are the reasons for this to happen.

3.1.1. France

In the 1980s, much research was realised by the academia on CCC for earthworks within France. However, research about this technology has not continued. Nowadays, the French road network has suffered deterioration caused by traffic, bad weather and lack of maintenance (Routes De France, 2021). Cerema conducts innovation and research activities in France, which scientifically support the development, implementation and evaluation of public policies. One of the approaches developed by Cerema is called IQRN, which stands for "Image Qualité du Réseau National" (National Network Quality Index) (Gayte et al., n.d.). This index is currently being used for assessing the deterioration of the pavements every year (Routes De France, 2021). Through a lidar survey, tools for automatic detection of degradations and classifications algorithms, the IQRN can be determined, as shown in Figure 8.

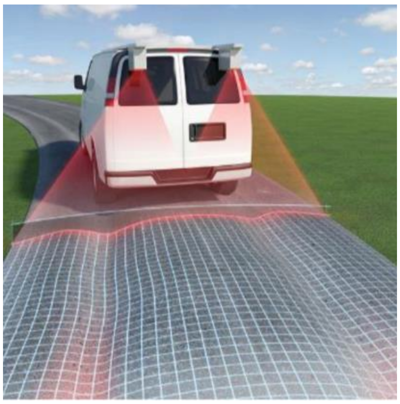

Figure 8: Laser sensors used for IQRN determination. Adapted from (Gayte et al., n.d.)

The government principally wants to focus on the maintenance of the roads in the coming years. Hence, it needs to know the state of the roads and their evolution to schedule their maintenance. Furthermore, it wants to prioritise service levels and optimise maintenance techniques in order to maintain an acceptable service level. Hence, research about the deterioration of the road network could represent an opportunity to implement new methods for construction and maintenance, sustainable equipment and smart infrastructure (Routes De France, 2021). Overall, the government is working on the maintenance of deteriorated roads; therefore, the adoption of other technologies such as IQRN has increased in the last years.

3.1.2. Spain

In the general technical specifications for road works with hot asphalt mixtures, metallic, static or vibratory, pneumatic or mixed rollers are advised (Ministerio de Fomento, 2019). It is required that the director of the works should approve at least one vibratory or mixed roller and one pneumatic roller of the works being done after obtaining the results from the test section at the jobsite. The static or dynamic contact pressures from the employed compactors will be required to achieve adequate density and homogeneity without causing cracks and winding of the mixture at the compaction temperature. High-tech solutions for asphalt construction are commercialised within Spain. For instance, manufacturers such as Bomag and MOBA offer their services in this country. However, there are no specifications regarding the use of these systems.

In the last two decades, the low investment compared to other European countries has been evidenced in the maintenance of roads and the construction of new roads in Spain (europapress, 2021). For instance, United Kingdom invest 108.141 euros per kilometre of road and Germany invest 49.229 euros per kilometre of road. Whereas, Spain invest 22.489 euros per kilometre of road. These are the effects of a financial crisis in Spain in 2008, which extends to the present day (CincoDías, 2020). Another concern is that existing roads in Spain will have a service life of 20 years by 2030. Thus, the experts insist on constructing, maintaining and checking the road infrastructures more efficiently and intelligently (Ministerio de Transportes, Movilidad y Agenda Urbana, n.d.).

3.1.3. Germany

According to the National Academies of Sciences, Engineering, and Medicine (2010), the German specifications for CCC of soils were officially introduced in 1994 and updated three years later. They are referred to as the ZTVE-StB and are applied to subgrade and embankment soils. There are no specifications for base and subbase layers since roller MVs measure much deeper than the 20 to 30 cm thickness of the base course layers used in Germany. CCC for subgrade and embankment soils is specified in Germany in two ways. The first approach relates to calibrating the roller Measurement Values (MVs) to Plate Load Test (PLT) modulus or density; then, the correlation can be used within QA. The second approach refers to identifying weak areas using CCC, which serves for spot testing with PLT, Lightweight (LWD) or density methods. Both approaches will be explained in detail in the following two sections.

Calibration approach

The calibration approach entails some steps: (1) the calibration is carried out for developing correlation(s) among roller MVs and soil density or PLT modulus; (2) identification of the MV target value (MV-TV), which is consistent with the required density or modulus values from soils; and (3) acceptance testing, which involves the comparison of MV with MV-TV. The calibration is performed on a minimum of three test strips of 20-m long, as Figure 9 shows (National Academies of Sciences, Engineering, and Medicine, 2010).

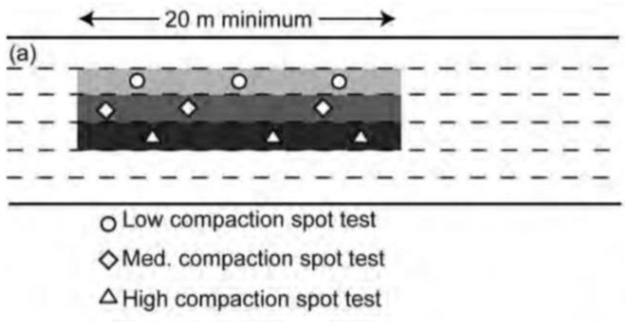

Figure 9: Calibration approach from German specifications. Adapted from (National Academies of Sciences, Engineering, and Medicine, 2010).

The roller MV data is collected on a low degree (e.g. after the first pass), medium degree (e.g. after three to five passes), and high degree (e.g. after multiple passes until no compaction is observed) of compaction test strips (National Academies of Sciences, Engineering, and Medicine, 2010). The number of static PLTs or density tests performed ranges from three to five on each test strip. After obtaining MVs and spot-test values, a regression analysis can be performed to obtain the MV-TV. Throughout acceptance testing, 90% of the obtained MV should be above the MV-TV. A variable amplitude and frequency control or jump-mode are not allowed within calibration or acceptance testing.

Furthermore, CCC-based QA is not suggested when the project site is not homogeneous in soil type and underlying layers (National Academies of Sciences, Engineering, and Medicine, 2010). Some updates were planned for the CCC specifications. For instance, the employment of LWD or dynamic PLT is suggested instead of static PLT, for which the target values for LWD were published. Also, the 10% of MVs that are below MV-TV should be distributed along the evaluation area. The specifications will enable to use of automatic feedback control by the rollers during compaction. However, their use is not allowed within calibration and acceptance testing.

CCC used to identify weak areas for spot testing

This approach is more commonly used within Germany, in which the use of CCC is meant for mapping the compacted soil area (National Academies of Sciences, Engineering, and Medicine, 2010). The generated maps are used for identifying the weak areas for spot testing (e.g. density methods or PLT). The minimum number of in situ tests are specified, for instance, four tests per 500 m^2. In order to be accepted, the density or modulus values must be greater or equal to the desired value. When the acceptance is not meet, the soil must be reworked until it achieves an acceptable criterion. It is inferred that the other areas of the map meet acceptance when roller and external parameters (i.e. soil, moisture, and subsurface) are held constant. Finally, the initial calibration is not required for this approach.

In Germany, there is a high level of knowledge and high demands regarding the construction of roads (This Magazine, 2013). Hence, it is necessary to research the feasibility of new technologies before introducing them within specifications and guidelines. German specifications for CCC were established for the application of soils. However, the use of these technologies in asphalt is being researched within this country. For instance, a research project was driven by the association known as FGSV, which is in charge of the technical regulations for the road and transport sector in Germany and the Federal Highway Research Institute (BASt) (Federal Highway Research Institute, 2018). The project analysed five sections from which one section (reference section) did not use large-scale compaction control. At the same time, the remaining sections used manufactured specific applications. From this study, it could be concluded that there are no significant differences in the degree of compaction among the reference section and the remaining sections. Another conclusion is that the degree of compaction is achieved with fewer passes using compaction control systems. Also, compaction control systems enable more regular compaction, which results in more homogeneous compaction. In general, compaction control systems positively affected the achieved compaction (Federal Highway Research Institute, 2018).

3.1.4. Italy

The technical document for road paving is provided by ANAS, which is the organisation in charge of managing the national road network (including national roads, motorways, junctions, and slip roads) in Italy (ANAS, 2017). In the document, a distinction is made among compactors, tandem rollers, combined rollers, rubber rollers and static three-wheeled rollers, as Figure 10 shows (ANAS, 2019).

Figure 10: (a) compactors; (b) tandem rollers; (c) rubbed rollers; (d) static three-wheeled rollers. Adapted from (ArchiExpo, n.d.; Wirtgen Group, n.d.)

The compactors are used commonly for soil compaction, which has a smooth or sheep foot drum with vibration, oscillation, or vibration/oscillation. The tandem rollers are equipped with two drums and are designed mainly for the compaction of the bituminous conglomerate. On the other hand, combined rollers are mainly employed for compacting asphalt layers, which have one axis on which rubber wheels are centrally mounted, and on the other axis, a smooth drum is mounted. Rollers with rubber wheels are used only for static compaction. Furthermore, they provide a good seal due to the mixing effect from the vertical and horizontal forces caused by the tires, which makes them suitable for defining the upper layer of the conglomerate layers. Finally, the static three-wheeled rollers have a drum placed at the front and two rear drums placed at the sides at the back. Hence, the traces from the drums overlap each other. They can be employed for conglomerate layers compaction and when dynamic compaction can not be used (ANAS, 2019).

In general, the quality of the Italian national infrastructure is in line with the European average, from which one of the mature sectors is the construction of motorways. There has been research from academia regarding the use of IC and CCC. However, it has not been widely implemented in Italy. Innovation and technology have always been part of the national road network of Italy. For instance, The Cesano Experimental Road Centre is in charge of, among other things, experimental and research projects in Italy (ANAS, n.d.). They also carry out advanced control activities concerning road pavements and bridges using high-performance systems. One of the widely used systems by this centre is the FWD, which enables determining the characteristics of the road surface. With nine sensors, the deflection can be measured around the point of application of a dynamic load. Afterwards, the collected information is processed by a processing software that provides information on the remaining life of the pavement and indications about adequate maintenance.

3.1.5. United Kingdom

The Specifications for Highway Works state that the weight of the static smooth wheeled rollers should be 8 tonnes, and pneumatic and vibratory rollers should achieve the standard compaction of an 8 tonnes static roller. Furthermore, the use of vibratory rollers is not recommended on bridge decks (Highways Agency, 2019). In the Notes for Guidance on the Specification for Highway Works, procedures for maximising the durability of the finished pavement are stated. It is indicated that there is no hard evidence that shows that the vibratory rollers enable to achieve superior compaction than with the use of conventional static rollers. It is advised that the vibratory rollers should be used to determine the required number of passes, frequency, amplitude and roller speed. Furthermore, the Contractor must present evidence regarding how the required compaction will be achieved (Highways Agency, 2018).

The existing UK Specifications for Highway Works makes no mention of the use of CCC in the construction of earthworks for roads and highways. Even though, research has demonstrated that CCC can be used in earthwork construction (Winter, 2017). Generally, the constructors can use these techniques; however, they can be more motivated if they are implemented into specifications. According to Winter (2020), there are no significant obstacles to CCC being introduced within road and highway earthworks of the UK. It is necessary to elaborate specifications clauses regarding CCC. These specifications can be developed and refined with major UK infrastructure projects, which can bring CCC to mainstream use.

3.1.6. Greece

The specifications for compacted concrete pavement state that the compaction equipment shall consist of a smooth heavy vibrating roller with a static load and a heavy roller with tires. There are no specifications regarding the use of compaction support systems. However, it is mentioned that the checks during the construction process are required to prove that the rollers have performed the required number of passes for achieving the required density in the time specified by spot tests. The use of continuous measuring instruments installed on the compaction machines is allowed for controlling the speed, vibration frequency, operating time, and the distance travelled by the roller (Ministry of Infrastructure and Transport, 2009).

In recent years the road network has improved remarkably in Greece because numerous projects were carried out to enhance the national, regional and local roads (Enterprise Greece, n.d.). After the COVID-19 pandemic, the government decided to principally focus on infrastructure projects as part of the recovery plan of Greece (Karamanlis, 2021). The projects aim to expand, improve and modernise the existing infrastructure to address the current road network issues (Region Solid Greece, 2020). In Greece, there is support for research and innovation in the infrastructure sector. Hence, there is a chance for implementing new technologies for road construction on a larger scale in the coming years.

3.1.7. Portugal

The normative provisions for the construction and rehabilitation of road pavements are provided by the Institute of Mobility and Transport from Portugal. Within these specifications, there are no particular requirements about the equipment used for construction and rehabilitation purposes. However, it is stated that the final mixture should have specific volumetric, mechanical, functional and performance characteristics depending on the targeted applications (Institute of Infrastructure, n.d.). Even though there are no specifications regarding the use of compaction support systems, there is research from academia from which demonstration projects using such systems occur in Portugal. For instance, the results of a demonstration project carried out in a test section of 160 meters showed that with IC technology, it is possible to achieve higher stiffness with a lower number of passes related to other conventional systems. IC for soil compaction showed homogeneity of the degree of compaction and stiffness at the end of compaction. Furthermore, it revealed that IC is effective for QC purposes. Because of its ability to assess the stiffness conditions of a large area in a short amount of time and in the determination of areas that have problems concerning the obtained results from the soil layers (Gomes & Parente, 2014).

According to Ferreira (2010), there is no need for new infrastructure within Portugal. However, there is a need for solving the safety problems and the conservation and rehabilitation of existing road infrastructure. The budgets assigned for dealing with the maintenance of safety and quality of road infrastructure are not sufficient. Hence, it is intended to optimise the ratio between investment and quality. With the appearance of new developments associated with safety, environment and quality of the road infrastructure, more research is required to implement them (Ferreira, 2010).

3.1.8. Austria

The research within this country has mainly focused on CCC for soil. The Austrian specifications were the first roller-integrated CCC specifications for soils to be introduced in 1990 and were revised in 1993 and 1999 (National Academies of Sciences, Engineering, and Medicine, 2010). The International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE) developed CCC specifications based on the Australian specifications. These specifications enable two approaches for roller-integrated CCC. The first approach relates to the correlations based on regression conducted during on-site calibration for acceptance testing. At the same time, the second approach is advised for small sites or where the calibration can not occur. This approach requires compaction with roller-integrated measurement up to the point that the average of MVs do not increase more than 5%. In this approach, the acceptance is based on the values obtained from static PLT or LWD (dynamic PLT) dynamic modulus performed at weak areas. The Austrian specifications state that the roller MVs should be dynamic, applied to subgrade, subbase, base materials, and recycled materials. The measurement occurs during the compaction process when the soil is compacted dynamically. In contrast, the measurement occurs after compaction if the soil is compacted statically.

Acceptance based on calibration

This method refers to developing a relationship among roller MVs and initial values from the PLT modulus (National Academies of Sciences, Engineering, and Medicine, 2010). As an alternative, density spot testing can be applied; however, it is not advised. It is required that the calibration takes place over the total width of the construction area with a minimum length of 100 m for each material being laid (subgrade, subbase, and base). The calibration process should be carried out with constant roller parameters (i.e. frequency, amplitude and forward velocity). The MVs are recorded during every pass; afterwards, PLT or LWD tests are performed at low, medium and high MVs, as Figure 11 shows.

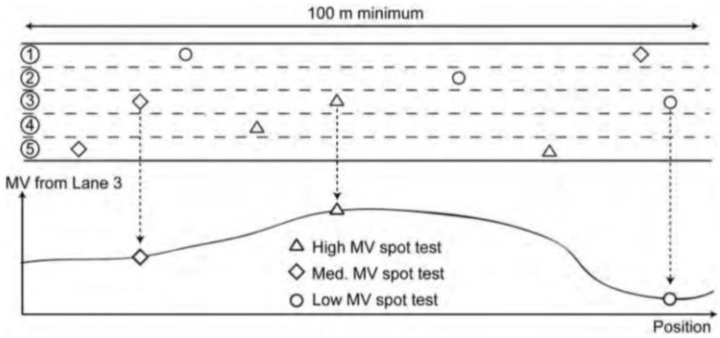

Figure 11: Calibration approach from Austrian/ISSMGE specifications. Adapted from (National Academies of Sciences, Engineering, and Medicine, 2010)

Then, linear regression is performed among MVs and modulus values (i.e. E_{V1} or E_{LWD}). The obtained regression coefficient R^2 need to be higher or equal than 0.5. Afterwards, the regression equation is used together with the specified modulus value shown in Table 3.

Level	E_{V1} (MN/m²)
1 m below subgrade[a]	15 (cohesive); 20 (cohesionless)
Top of subgrade	25 (cohesive); 35 (cohesionless)
Top of subbase	60 (rounded); 72 (angular)
Top of base	75 (rounded); 90 (angular)
Level	**E_{LWD} (MN/m²)**
1 m below subgrade[a]	18 (cohesive); 24 (cohesionless)
Top of subgrade	30 (cohesive); 38 (cohesionless)
Top of subbase	58 (rounded); 68 (angular)
Top of base	70 (rounded); 82 (angular)

[a]If fill section is to be constructed.

Table 3: E_{V1} and E_{LWD} values required in Austria. Adapted from (National Academies of Sciences, Engineering, and Medicine, 2010)

Which allows obtaining a modulus value E_i. This leads to the determination of the minimum roller MV (MIN) and mean roller MV (ME). These values correspond to 0.95 E_i and 1.05 E_i, respectively, as Figure 12 shows. Finally, the maximum roller MV (MAX) is defined as 1.5MIN.

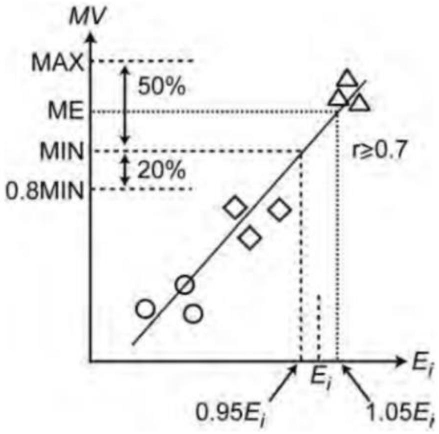

Figure 12: Roller MVs vs E_{V1}/E_{LWD} regression and key parameters from Austrian/ISSMGE specifications. Adapted from (National Academies of Sciences, Engineering, and Medicine, 2010)

There are three acceptance criteria: (1) The mean roller MV should be higher or equal than the ME value; (2) all roller MVs should be higher or equal than 0.8MIN; and (3) 90% of the roller MVs should be higher or equal than MIN.

Acceptance based on the change of MVs

This method is advised for small areas and sites in which calibration can not take place. The approach states that the compaction process should continue until the average of the MVs from the roller is less than 5% different from the mean MVs from the previous pass (National Academies of Sciences, Engineering, and Medicine, 2010). Then, PLT or LWD are conducted on the weakest areas by taking into account the retrieved MVs from the roller.

Within one investigation carried out by Hager (2015), the importance of the compaction of the ground placed under the asphalt was pointed out. Furthermore, it was discussed that CCC has improved remarkably to such an extent that it is already considered state of the art and has shown the disadvantages of the outdated spot compaction tests methods. Furthermore, it was recognised that the innovation and development of compaction technology in the last years regarding quality assurance in construction earthworks, particularly on CCC, paved the way for work with dynamic compaction control. The knowledge, experience and understanding of the effects of dynamic compaction are thanks to extensive research projects, which has increased and promoted the use and applicability of these systems.

Nevertheless, more research is needed regarding the influence of machine and soil parameter variations on the measured values (e.g. amplitude, frequency, stiffness). It would be suitable to have measured values that are not affected by roller settings or operating states of the roller. Thus, these values will only be influenced by the changes in rigidity of the substrate during compaction. Compaction control will continuously play a crucial role in the construction processes in the future and is essential for the quality assurance of structures. The emerging work-integrated dynamic compaction control will be of high importance. Hence, CCC's research and development must be continuously promoted to gain knowledge and have new approaches for solving pending issues (Hager, 2015).

3.1.9. Netherlands

The Standard RAW Provisions are used in the Netherlands, which is a practical and dynamic system of legal, administrative and technical conditions for contracts in the civil engineering sector (CROW, n.d.). From the specifications of 1995, the requirements for implementing asphalt require that one or more pavers should apply the asphalt. Furthermore, the surface behind the screed should have a uniform texture, and the compaction should also be uniform over the surface. The asphalt should be spread by hand in places where the machine cannot do it. The paver's supply of asphalt and speed must be without or as few interruptions as possible; the occurrence of interruptions entails quality risks. There should not be marks after the compaction process. The texture of the compacted surface should be uniform after compaction. The compaction should be carried out as soon as possible after being laid by the paver (CROW, 1995). Within these specifications, there is no mention of the use of specific equipment. However, there has been researching in the last decade related to paving and compaction support systems.

According to Dekkers and Koudstaal (2016), the checks for the degree of compaction are still carried out traditionally. The Standard RAW Provisions state the tests that should be carried out to calculate density and calculate the degree of compaction. After the realisation of the tests, they are tested against the requirements from the RAW specifications. However, with the adoption of new contract forms such as the Design, Building, Finance, and Maintain (DBFM) contract, other requirements are also emerging. In DBFM contracts, the contractor is responsible for designing and constructing the project and financing and maintenance. The difference between a DBFM contract and a traditional contract is that the client does not purchase a product but a service. In this way, the contractor has the same interest in the project's success as the client (Rijkswaterstaat, 2021). Hence, there are different specifications regarding the completed work in this type of contract than in the RAW specifications with their traditional assessment methods. One of the introduced requirements for testing the compliance of the construction with the design for large construction projects is the load-bearing capacity of the paved road.

Nevertheless, load-bearing capacity and the degree of compaction are different from each other, which questions the use of traditional compaction as a standard in the future. A more functional approach is being used called the falling weight deflectometer (FWD) for testing the bearing capacity of pavements. Likewise, it is essential to have a good insight into the bearing capacity during the compaction process. Hence, it is preferred to measure the stiffness of each construction layer and test them against the design principles.

According to the findings from an ASPARi network contractor, the roller passes are unevenly distributed over the road surface. Although the roller operators perform roller passes with a fixed moving pattern (Dekkers & Koudstaal, 2016), it is hardly possible for them to remember starting and ending points of paths along the paved area. Hence, it is necessary to use tools for real-time registration of roller passes. Dekkers and Koudstaal conducted a study in 2016 in which an intelligent roller system was employed on asphalt rollers. However, the test was not successful because of three reasons: (1) the MVs from the system mainly consisted of the bearing capacity of the underlying layers; (2) the stiffness value of the asphalt was continuously changing due to its dependence on the temperature of the asphalt; (3) the use of the vibratory mechanisms is not allowed for some skeleton mixtures in the Netherlands, hence no information from bearing capacity/stiffness was available from the roller. On the other hand, the use of the intelligent system on a roller used for compaction of foundations showed promising results in different projects for which it was able to monitor the bearing capacity of the layers and covered the entire surface. The high-quality road starts at the base, and this concerns the underlying layers of asphalt. According to Dekkers & Koudstaal (2016), the traditional compaction controls do not fit the new contracts' functional framework. Hence, the intelligent rollers for foundations might make it possible to compact the construction layers optimally and with sufficient bearing capacity.

The introduction of innovative techniques and machines from market parties is continuing given clients' demands (Vilsteren et al., 2018). Hence, it is necessary to validate them, meaning that it should be demonstrated that they are suitable for the application. One of the validation centres is – the Innovation Test Centre (ITC). According to Vilsteren et al. (2018), there were good results achieved by some innovative techniques. For instance, a two-layer machine was studied between 2002 and 2007, which is showed in Figure 13. This machine lays the two-layer ZOAB in a single pass; therefore, both layers cool down slowly, which benefits the asphalt quality.

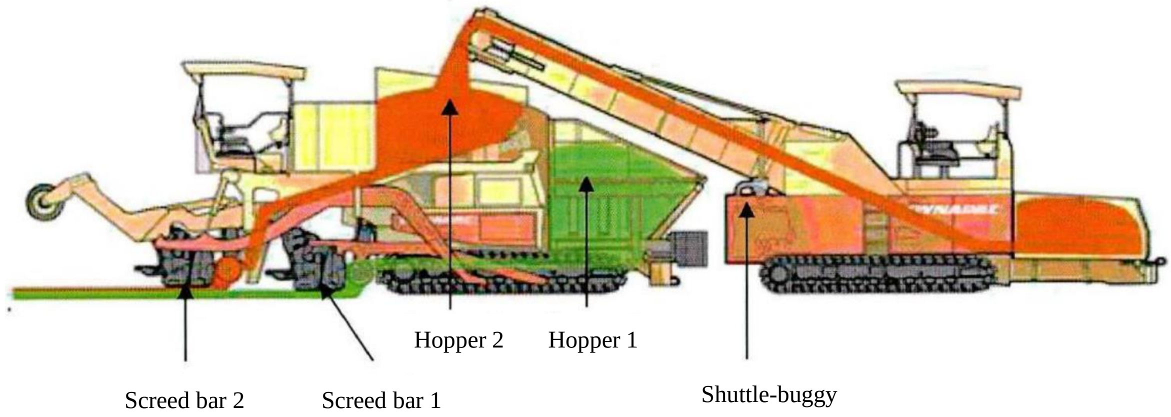

Figure 13: Two-layer machine. Adapted from (Vilsteren et al., 2018)

Compaction support system developed by ASPARi has been going through a validation process. The intelligent system is a part of the foundation for future roller which consists of various sensors mounted on a machine (e.g. GPS sensor). Going through a validation process, it is possible to determine whether the system can be used for guaranteeing the quality control of sand courses and foundation layers. Overall, various innovations have already been approved, and others are expected since this is encouraged in the Netherlands. These non-standard solutions will only be used once stated on the validation list from Rijkswaterstaat, the implementing organisation of the Ministry of Infrastructure and Water Management (Rijkswaterstaat, 2021). This validation process has been established for assessing alternative techniques in terms of performance and properties for approving them as standard products or implementation techniques. If the process is successful, the new technology may be used in Rijkswaterstaat works (Vilsteren et al., 2018).

3.2.The Common trend in European countries

The term CCC is commonly used within European countries, from which two trends have been distinguished. Some of the studied countries have adopted high-tech solutions for asphalt construction within their specifications. At the same time, others have focused more on the research regarding the use of such technologies or the adoption and research of other innovative technologies for road construction and maintenance. Table 4, shows an overview of the adoption of regulations in the studied countries.

Table 4: Summary of the current trends from European regulations

Country	Implemented high-tech solutions within regulations	Current Trend
France	No	The government is currently focused on the maintenance of the roads. Hence, technologies such as IRQN have been implemented, which assess the deterioration of asphalt pavements through a lidar survey.
Spain	No	High-tech solutions are commercialised within Spain. However, their use has not been standardised. Nowadays, there is a low investment from the government from Spain on road maintenance and road construction. Hence, there is a need for the implementation of more efficient and intelligent technologies within this country.
Germany	Yes	The introduced specifications are applied to subgrade and embankment soils. Such specifications are stated in two ways: (1) calibrating MVs and spot-tests and such correlation can be used within QA and (2) weak areas are identified with the use of CCC.
Italy	No	The academia has researched about the adoption of high-tech solutions. However, other technologies are being used within this country such as the FWD, such technology enables to retrieve information for pavement maintenance.
United Kingdom	No	Generally, contractors use high-tech solutions in the construction works; however, their use can be boosted with the implementation of specifications. The implementation of such regulations require the realisation of major infrastructure projects within the country.
Greece	No	The government is focused on improving the existing road infrastructure. Since, there is support for research and innovation regarding road infrastructure, the implementation of high-tech solutions could be boosted in the future.
Portugal	No	There is a need for road conservation and rehabilitation within Portugal. It is intended to deal with such issues with the implementation of new technologies; however, they require more research before being standardised.
Austria	Yes	The introduced specifications are applied to subgrade, subbase, base materials, and recycled materials. Such specifications enable two approaches: (1) correlations are carried out within MVs and spot-tests for acceptance testing and (2) the compaction works should be carried out up to when the average of MVs do not increase more than 5%.
Netherlands	No	The research about the adoption of high-tech solutions in ongoing within this country. The adoption of a new contract form (DBFM) has influenced such research, since the contractor has shared interests with the client. A validation process should be carried out for new technologies to be standardised within the country.

Even though the European Committee for Standardisation (CEN) introduced specifications for the use of CCC as a QC method for earthworks through the use of roller-integrated dynamic documentation and measuring systems in 2016 (European Committee for Standardization, 2016). France, Spain, Italy, UK, Greece, Portugal, and the Netherlands have not implemented CCC within their specifications and guideline documents. Germany and Austria are the only countries that have adopted CCC within their specifications. Austria was the first country to introduce these specifications, and there are two approaches allowed for rolled-integrated CCC. This situation has also been seen in Germany, for which there are two ways in which CCC can be specified. Austria recommended such specifications for subgrade, subbase, base and recycled materials. In comparison, Germany recommended these specifications only for subgrade and embankment soils. However, there are no specifications for the implementation of high-tech solutions for the compaction of asphalt layers.

Conventional practices are still used for road construction in the majority of the analysed countries; however, the quality of their roads is generally good (European Comission, n.d.). Nowadays, authorities are willing to construct, maintain and check the road infrastructures more efficiently and intelligently. Hence, more demands are being introduced in the construction of roads. Consequently there has been a lot of development of innovative technologies and machines on the market. Generally, construction companies can use these technologies. However, an additional incentive for them could be the implementation of such technologies into specifications and guideline documents. Hence, more research has been put on these high-tech solutions in the last years, because it is essential to determine the feasibility of a new technology before introducing it into the regulation from a country. From some of the studies, it has been evidenced that the use of CCC technologies had a positive effect on the achieved compaction of soils. Some of the benefits related to the use of these solutions are higher stiffness with a lower number of passes and the homogeneity of compaction and stiffness. On the other hand, the use of these systems for asphalt compaction have shown some limitations, for instance, the depth of influence of MVs is greater than the asphalt layer, and the measured stiffness values depend on the temperature of the asphalt layer. The research from these countries has not only been focused on these technologies. For instance, in France, another technology was developed for road maintenance, which asses the deterioration of pavements using laser sensors and GPS mounted in a vehicle. Similarly, the use of LWD in Italy has the purpose of testing the deflection of road pavements. Hence, authorities from some countries have focused more on the research regarding the implementation of other technologies different from paving and compaction support systems.

Since there are more demands for road construction, more attention has been put on using these high-tech solutions in recent years. It has been evident that they will continue to play a role soon, especially for QC. Hence, competent organisations and authorities must continuously promote the research to gain knowledge and find new approaches for solving existing issues. In the end, this will enable us to introduce them into specifications and guideline documents for bringing such technologies to conventional use.

3.3. North America

Europe started with the development of high-tech solutions and over the decades such technologies have spread to different parts of the world. For instance, they have also received the attention from North American countries. By analysing how they have been implemented in another continent it will be possible to analyse which factors play a role in the implementation of such technologies from a different perspective. It was decided to analyse the specifications from three countries from North America: Canada, USA and Mexico. Canada and USA have adopted different regulations in each province and state, respectively.

3.3.1. United States

The Intelligent Compaction (IC) implementation started around 2000's in the United States (Chang & Arasteh, 2018). Throughout the following decades the use of such technologies has been accelerated within this country. Consequently, the specifications for the use of IC have been developed. In the following sections the general IC specifications and state IC specifications will be reviewed. Furthermore, the considerations and recommendations for IC implementation will be analysed.

Intelligent Compaction

IC rollers are vibratory rollers that record real-time parameters with an integrated measurement system, onboard computer reporting system, a Global Positioning System (GPS) based mapping and optional feedback control (Federal Highway Administration, 2017; Transtec Group, 2021). IC is commonly applied to vibratory rollers; although, some manufacturers are studying ways to use the technology on static drum rollers (Horan, n.d.).

The US Federal Highway of Administration coined the term Intelligent Compaction Measurement Value (ICMV). This value represents the stiffness from the compacted layer and is calculated based on the measurements on the vibratory roller drums (Hu et al., 2019; Mazari et al., 2021). Nowadays, several ICMVs are used because diverse equipment manufacturers have developed their method for describing the state of the compacted layer (Hu, et al., 2019). For instance, Compaction Meter Value (CMV) was introduced by Geodynamik and the vibration modulus (E_{vib}) was presented by Bomag (Savan et al., 2014; Zhu et al., 2018).

IC Specifications

The Federal Highway of Administration (FHWA) is an agency within the U.S. Department of Transportation. This agency supports State and local governments in the design, construction, and maintenance of the Nation's highway systems and federally and tribal-owned land through financial and technical assistance (Federal Highway Administration, 2012). Several design standards and standard specifications adopted by FHWA through rulemaking are established by the American Association of State Highway and Transportation Officials (AASHTO). AASHTO is an association that represents 52 State highway and transportation agencies (including the District of Columbia and Puerto Rico). The organisation develops and issues standards, specifications, and related materials used by the states for highway projects (Federal Highway Administration, 2020).

The FHWA and AASHTO have developed national IC specifications, both are very similar to each other (Federal Highway Administration, 2017). Also, many state agencies have developed their own IC specifications. All the available IC specifications in the US are listed in Appendix C. In the following section the FHWA generic IC specifications for soil and asphalt will be discussed.

FHWA generic IC Specifications for Soil and Asphalt

The generic specifications are similar for both soil and asphalt. These specifications principally refer to the required equipment, Quality Control Plan (QCP), IC construction, measurement method, and payment basis (Federal Highway Administration, 2014).

The Contractor will supply the necessary equipment to fulfil the compaction requirements for specific materials. Furthermore, the Contractor will determine the number of IC rollers to be used depending on the project. In general, the compaction process is divided in three phases: initial, intermediate and finishing. On the one hand, the use of IC rollers for asphalt compaction is recommended in the initial phase (breakdown) in the compaction sequence. They can also be used in the intermediate phase as long as the temperature of the asphalt mat is sufficient for compaction. The use of IC rollers is not advised in the finishing phase (Federal Highway Administration, 2014). On the other hand, IC rollers for soil applications is advised during soil compaction and for the evaluation of soil compaction operations (Federal Highway Administration, 2014).

Equipment

The IC rollers shall meet specific requirements related to their components. For asphalt, there should be self-propelled double-drum vibratory rollers (Federal Highway Administration, 2014). On the other hand, self-propelled single-drum vibratory rollers are advised for soil compaction (Federal Highway Administration, 2014). Furthermore, the contractor shall provide High Precision Positioning Systems (HPPS) that meet specific requirements related to the accuracy and consistency of the measurements among all devices on the same project. Within the specifications, the standardised analysis software Veta (formerly known as Veda) is advised (The Transtec Group, n.d.). Veta principally enables the use of IMCV data to analyse coverage, uniformity and stiffness values documented throughout the construction process (Federal Highway Administration, 2014).

Quality Control Plan (QCP)

A written QCP for the project should be prepared and submitted by the contractor (Federal Highway Administration, 2014). This plan will be specifically dependent on the project and indicates how control activities will be carried out and the experts involved in these processes. This Plan is vital since asphalt pavement and embankment operations shall not commence until QCP is accepted. Furthermore, it should include the procedures for pavement sampling and testing also, how GPS check testing should be conducted before starting the production. Test section evaluations should be carried out to verify the volumetric mixture and determine the compaction curve concerning the number of roller passes and the mixture's stiffness. Pre-paving mapping (pre-mapping) of existing support materials (i.e. soil subgrade, aggregate bases, or similar) using an IC roller is recommended to identify weak areas.

IC construction

The IC roller representatives shall provide on-site technical assistance coordinated by the contractor during the initial seven days of production and when needed (Federal Highway Administration, 2014). Furthermore, on-site training should be provided for the personnel involved in the project. Such training should last approximately 4-8 hours in an enclosed facility in which different topics should be treated (e.g. background information from IC systems, set-up and checks for IC systems). The training of roller operators is important, since the roller operators have generally completed a training or earned a certification regarding the use of conventional machinery (Study.com, 2021). However, they are not aware of the use of IC systems.

There are IC Construction areas, which are subsections of the project worked by the Contractor for which the minimum coverage, the optimal number of roller passes and the target IC-MVs shall be achieved or exceeded. The areas which do not meet these criteria should be reworked and re-evaluated before continuing operations.

Method of measurement

IC will not be measured since it will be paid as a lump sum for the compaction of asphalt mixtures and soils (Federal Highway Administration, 2014).

Basis of Payment

The incorporation of Intelligent Compaction will be paid at the contract lump sum price, which will account for the costs for IC provision including fuel, roller operator, GPS system and any other equipment required for compaction works (Federal Highway Administration, 2014).

State IC Specifications

Generally, the state asphalt IC specifications are focused on: construction operations (e.g. roller pattern, temperature range) and finished properties (e.g. density or voids). On the other hand, the approaches followed by the state soil IC specifications relate to ordinary compaction, stiffness control and density control (The Transtec Group, 2021). Until 2017, 23 states implemented IC specifications for asphalt, soils or both (Federal Highway Administration, 2017). The asphalt IC specifications from seven states were analysed to determine differences or similar patterns among them, which comprehended three states situated in the Northern part of the country (i.e. Massachusetts, North Dakota and Vermont), three states located in the Southern part of the country (i.e. Alabama, Arizona and New Mexico) and Alaska. In Appendix D, the most significant differences are shown. In general, there is much variance in the content of the state IC specifications (Federal Highway Administration, 2017). Hence, it was not easy to find similar specifications between states situated in the Northern and Southern parts of the country and Alaska. However, it was evident that all the analysed state specifications were based on specifications provided by the AASHTO and FHWA, from which in the state specifications more information was added, or some of the existing specifications were changed.

Considerations for the implementation of IC specifications

According to the Federal Highway of Administration (2017), there are some considerations regarding the implementation of IC specification within the US:

- There is a need for a qualification and certification process for IC rollers and operators. Nowadays, there are only specifications provided by the AASHTO regarding contractor personnel certification and a checklist for approving IC rollers in the appendices.
- Qualified onsite training is required in most state IC specifications. However, it is challenging to provide qualified trainers.

- The qualification of the onsite technical support has not been specified, which may raise concerns regarding the quality of the support.
- Conducting a GPS validation every day requires careful steps to ensure consistency and accuracy.
- The pre-mapping process should be carefully realised.
- Even though test strips are optional, they are desirable in the majority of available IC specifications. Nevertheless, they are not practical due to constraints such as time and changes in support conditions.
- Some Departments of Transportation (DOTs) specify the requirements to determine the target number of roller passes and target ICMV from the test strip information. However, this process is complex due to the limitations of some types of ICMV, uniformity of support conditions and material gradation. When there would be an improved ICMV, the spot test locations may be determined by ICMV. The correlation between ICMV and conventional acceptance tests is expected to improve.
- The available systems allow manual and wireless data transmission of IC data. Data loss may occur with the manual method. On the other hand, wireless data transmission may be impeded due to the lack of cellular coverage. Nowadays, the contractors are still learning how to handle vendor's software to export the retrieved IC data in Veta compatible format. Furthermore, some DOTs require performing a Veta analysis, which should be submitted by the contractors together with the IC data. These requirements are often not met because there are delays or other issues caused by the lack of training.

Recommendations for the implementation of IC specifications

In order to facilitate the implementation of IC in the future, the Federal Highway of Administration (2017) have provided some recommendations:

- During the development and revision processes of IC specifications for states, communication among contractors and vendors is essential.
- It is recommended to provide national guidance for IC roller equipment and personnel certification.
- It is recommended that the GPS validation process should be automated and simplified.
- The data transmission can be speed up and simplified by directly importing IC Data from the cloud to Veta.
- It is expected that ICMV will improve to reflect the mechanical properties of materials from specific layers. Therefore, ICMV will potentially be an acceptance metric.

According to Chang and Arasteh (2018), the keys to the successful implementation of IC in the US are: (1) the commitment from agencies and companies; (2) well-thought plans are essential since it takes time for implementing IC; (3) the communication among agency, IC suppliers, earthwork/paving contractors and contractors is crucial; and (4) to minimise the risk, it is significant to start by solving minor problems (e.g. lack of training for operators).

3.3.2. Canada

There are 13 provinces in Canada and each of them has adopted different regulations for road construction. Table 5 shows an overview of the current regulations from 9 provinces.

Table 5: Road construction specifications from different provinces in Canada

Province	Description of Specifications
Alberta	The ‘Standard Specifications for Highway Construction’ from the province of Alberta were updated in 2019 (Profesional Services Section Alberta Transportation, 2013). In general, there are no specifications regarding the rollers or pavers to be used for the construction of highways. In the ‘Asphalt Concrete Pavement- End Product Specification’ it is stated that the asphalt mat shall be thoroughly compacted and the finished surface after compaction shall be free from segregation, hairlines, cracks and other defects.
British Columbia	The standard specifications for highway construction in British Columbia were completed and adopted in 2020 (Ministry of Transportation and Infrastructure, 2021). The are no specifications regarding equipment to be used. For instance, within the specifications for ‘Asphalt Pavement Construction’, it is only stated that the equipment should be in good mechanical conditions and perform the required work.
Manitoba	The ‘Construction Specification for Bituminous Pavement’ states that the equipment used for asphalt compaction should be clean and free from accumulations, and the finished surface from the mat shall be free from defects (Government of Manitoba, 2020). There are no specifications about the type of rollers or pavers to be used. Since, a Pre-Construction meeting should be held in advance before commencing operations in which topics such as the type and quantity of equipment to be used, sequence of work, and other pertinent topics should be discussed.
New Brunswick	Within the ‘asphalt concrete- End Results Specifications (ERS)’, the use of at least each type of the rollers is mentioned: vibratory roller, pneumatic-tired roller and steel drum tandem finish roller (Department of Transportation and Infrastructure, 2019). Furthermore, they should be equipped to prevent that the asphalt mix can adhere to the rubber tires.
New found land and Labrador	In the specifications book for the road contractors, it is stated that rollers designed specifically for compaction should be used, which should be operated by competent and experienced operators (Government of Newfoundland and Labrador, 2011). The use of steel drum rollers and self-propelled pneumatic tired rollers is advised. Furthermore, they should be equipped with devices to prevent the bituminous mixture from accumulating on the tires.
Nova Scotia	In the standard specification for highway Construction and Maintenance from Nova Scotia, it is stated that the compaction equipment shall comprise at least one of the following: vibratory roller, pneumatic roller and finish roller (Government of Nova Scotia, 2021). Along curbs and similar structures and not accessible locations to full-size rollers. The use of smaller compaction equipment is recommended. These specifications were initially published in 1997 and revised in 2021.
Ontario	The municipal oriented specifications for construction of Hot Mix Asphalt from Ontario state that the rollers are classified into three categories: • Class S: Self-propelled steel-drum, tandem, or three-wheel rollers • Class R: Self-propelled pneumatic-tired rollers • Class V: Self-propelled vibratory rollers designed for the specific compaction of HMA Among the general requirements for the rollers, it is required that they are able to reverse without backlash. These specifications were updated in 2016 (Ministry of Transportation, 2017).
Prince Edward Island	The General Provisions and Contract Specifications for Highway Construction from Prince Edward Island province were revised in 2021 (Government of Prince Edward Island, 2021). Within the specifications, it is stated that every roller used should be designed for asphalt compaction purposes. Furthermore, they should be in good condition and be able to reverse without backlash. The compaction equipment shall comprise at least one of the following: vibratory roller, pneumatic tire roller, and steel-drum tandem finish roller.
Saskatchewan	Within the end product specifications for asphalt concrete from the ‘Standards Specifications Manual’ of Saskatchewan, the are no specifications about using a particular type of rollers or pavers. However, it is required that after the final rolling, the surface shall be free of defects (e.g. waves, hairlines cracks) (Government of Saskatchewan, 2020).

After analysing the existing specifications from the provinces of Canada, it is clear that the studied provinces have not implemented paving and compaction support systems within their specifications. In the majority of provinces, the extraction of cores is suggested for QC purposes of the different layers. Another important characteristic from the specifications is that in the majority of provinces, there were 'End Product Specifications' or 'End Result Specifications' for asphalt pavement, in which the Department does not define methods for construction. Therefore, the Department is in charge of monitoring the Contractor's control of road construction process and will accept or reject the end product depending on the specified acceptance plan (Profesional Services Section Alberta Transportation, 2013). In other words, the Contractor is entirely responsible for the QC, whereas the Department is in charge of QA (Government of Newfoundland and Labrador, 2011).

In recent years, Canada is also looking to implement IC systems following the steps from the US, since more efficiency is wanted on future highway jobs (Snook, 2019). For instance, one project carried out in British Columbia by a private company in 2020 made use of IC systems provided by Bomag and HAMM. This project demonstrated how the IC technology works and the benefits can bring to the Ministry of Transportation from British Columbia. Furthermore, it could be concluded that the criteria stated by the authorities for road construction projects could be met more efficiently with the use of such systems (Asphalt Pro, 2020).

3.3.3. Mexico

The specifications for the construction of hot mix asphalt layers in Mexico were approved in October of 2020. Concerning the equipment to be used to construct roads, self-propelled pavers and rollers are required. The pavers must be able to spread and pre-compact the hot mix asphalt layer. They should be equipped with a screed, hopper and automatic level control sensors. At the same time, two types of rollers are mentioned for compaction works: metal roller compactors and pneumatic rollers. There are no other specifications about the use of other systems. Finally, it is stated the number of cores that should be extracted to judge the quality of the materials (Gobierno de México, 2020).

Within the guide of procedures and techniques for road maintenance in Mexico, it is explains that up to the end of the 90s, the evaluation of the pavement was realised with traditional techniques and applying previous normative techniques and references (Secretaría de Communicaciones y Transportes, 2014). From 2000 onwards, new equipment was implemented that had better technology and provided more efficiency, combined with updated regulations. Nevertheless, a significant percentage of the existing roads in Mexico were constructed during the 1970s and 1990s and their quality was determined by obsolete specifications, which is reflected in the poor state of the roads (World Economic Forum, n.d.). This results in significant economic investments required to reconstruct or restore the existing roads by using better materials and new techniques. However, at this moment, there is a slow recovery from the construction sector, which can be explained by a low public and private investment (Construlista, 2020).

3.4. The Common Trend in North American countries

The United States is the only country which has implemented specifications regarding the use of high-tech solutions. A summary of the reviewed specifications from each country can be found in Table 6.

Table 6: Summary of the current trends from North American regulations

Country	Implemented high-tech solutions within regulations	Current Trend
United States	Yes	General and state IC specifications have been established for the use of Intelligent Compaction. The general specifications detail that IC rollers should be used. At the same time a Quality Control Plan (QCP) should be elaborated. Furthermore, how the construction process will take place. Finally, how the payment will take place within the contract. The state specifications have been adapted from general specifications. The adoption of such general and state IC specifications has implied other issues related to their adoption such as the lack of training and the need for qualified equipment and operators.
Canada	No	The provinces from Canada have adopted their own specifications. However, any of them refers to the use of high-tech solutions. This could be influenced, because there are 'End Product Specifications'. Hence, the Department does define methods for construction. In recent years, this country has focused more on the use of IC for road construction.
Mexico	No	There is a low public and private investment within the construction sector. Such investment is necessary to reconstruct or restore the existing road network due to the poor state of the roads. Hence, the use of new materials and techniques is required.

IC specifications for soil and asphalt have been implemented in the US. Initially, IC was a new technology introduced in the US around 2000 (Chang & Arasteh, 2018). Through the years, the lack of experience, the lack of knowledge and the shortage of available IC equipment were evident. At the same time, this technology has been through a refinement process, especially when used for asphalt compaction purposes. Hence, it was difficult to implement such technologies by Departments of Transportation and construction companies. The FHWA boosted the implementation IC for embankment subgrade soils, aggregate base, and asphalt pavement materials by implementing demonstration projects. Additionally, the FHWA introduced generic specifications for IC. The collaboration of FHWA, DOTs, contractors, vendors, consultants and academia, throughout workshops and projects enabled to update such specifications over the years. Hence, some of the issues regarding the implementation of IC have been solved over the years. For instance, the vendors have increased the supply of IC equipment and provided support and training at a local and national level, which was a representative issue within the US. In the past, there was a lack of attention to these technologies by high authorities and a lack of resources and personnel. Nowadays, information about the advantages of such technologies is provided to authorities which are assigning personnel and resources to the implementation of IC. Furthermore, validations processes have been implemented for the GNSS/GPS. Finally, there was a lack of certification of the personnel is in charge of checking the QC of the projects. Currently, this certification process has started in some states (Chang & Arasteh, 2018).

Canada has shown more interest in adopting such technologies in the last few years since its neighbour country has advanced with the implementation of IC systems. Nevertheless, none of the analysed provinces have done significant research related to the use of IC. At the same time, the research about IC systems has not been evidenced in Mexico, which is related to the low investments in maintenance and construction of road infrastructure. In general, the quality of roads from the examined countries is acceptable (World Economic Forum, n.d.).

3.5. South America

A different situation can be perceived in the South American countries from which high-tech solutions have been discussed in some countries, while it is an unknown concept for others. Hence, the study of guidelines and regulations from these countries will enable an understanding of the barriers encountered in the implementation process of such technologies. The study will focus on nine South American countries, which are listed on Appendix E.

3.5.1. Brazil

According to their paving manual, the compaction equipment is divided into two categories: (1) static rollers which comprise static rollers with steel drums, tyres or sheep foot rollers. (2) vibratory rollers (Instituto de Pesquisas Rodoviárias, 2006). There are no specifications regarding the use of compaction support systems. However, the use of IC has been a topic of discussion in the last decade in Brazil. This relates to the fact that big manufacturers, such as Bomag, have opened their factories within Brazil. Hence, the inauguration of production headquarters has solved problems such as technical assistance and supply of parts. Furthermore, the network with the resellers has also been consolidated. In the end, builders and rental companies are more confident of acquiring IC systems (brasilengenharia, n.d.). In Brazil, brands such as Atlas Copco, Hamm, XCMG and Bomag, are the most recognized (temsustentavel, n.d.).

IC technology has been widely used in Europe and the United States (brasilengenharia, n.d.). However, standards about the use of such technology in Brazil have not been implemented yet. According to Santos et al. (n.d.), when using IC systems, more attention should be put on the working conditions of the compactor and how to use it within changing environmental conditions. Even though, IC technologies offer apparent advantages (e.g. providing compaction information to the roller operator), they are still in an introduction period in Brazil because the customer must first understand how the technology works and its benefits (vibromak, 2021).

3.5.2. Argentina

Specifications

The general technical specifications for hot and warm asphalt concrete of the dense type state requirements for the compaction equipment. For instance, the number and characteristics of the compaction equipment should be according to the surface, type of asphalt mixture, type of asphalt mix, the thickness of the layer to be compacted and level of production (work rate) (Ministerio de Transporte, 1998). The pneumatic rollers must have smooth wheels and configurations for allowing the overlapping of the front and rear tracks. Also, the use of metallic rollers is discussed; within this category, static, vibratory or oscillatory rollers are included. The vibratory and oscillatory compactors should have automatic devices for stopping vibration/oscillation when desired. Likewise, the metallic rollers should not present irregularities on the cylindrical surfaces. Pneumatic and metallic rollers should be able to reverse through a smooth action and obtain a homogeneous surface without marks or flaking in the asphalt mix (Ministerio de Transporte, 1998).

Guidelines

The Guide for Good Practice Guide for Quality Control Asphalt Mixes and Bituminous Applications was published by the Government of Argentina (Ministerio de Obras Públicas, 2019). It was elaborated for supporting inspectors, supervisors, and any professional interested in verifying the quality of execution of road works in all its stages: design of work formulas, production process and laying process. According to this guide, IC is defined as the compaction assisted from the vibratory roller through accessories that localise the number of passes and the material's resistance to be compacted. The speed values and number of passes, and the precise location of the roller are placed on a map using GPS or a similar system. The effectiveness of compaction is determined by an accelerometer mounted in the equipment, which monitors the applied compaction stress, sequence and response from the compacted layer. Each manufacturer has its methodology to calculate the response from the material. In general, a compaction index is established or module values that can be related to the density. Furthermore, these rollers are also able to measure the temperature of the surface of the asphalt mat. Construction companies can adopt this type of technical assistance for compaction works in Argentina. However, the density values considered for approval will always come from the drilled cores from the finished section (Ministerio de Obras Públicas, 2019).

3.5.3. Peru

Within the General Technical Specifications For Construction with Hot Asphalt Mixtures, the use of self-propelled rollers is advised with metallic drums, static or vibratory, tandem, and pneumatic (Ministerio de Transportes y Comunicaciones, 2015). These rollers should be free from grooves and irregularities. The supervisor will approve the compaction equipment after obtaining the results from the test section. The vibratory compactors should possess devices to stop vibration when reversing; it is recommended that they should be automatic. Furthermore, it should have independent controllers for the frequency and vibration (Ministerio de Transportes y Comunicaciones, 2015). There are no specifications regarding the use of support systems.

IC is an emerging technology being implemented in developed countries (Román, 2015). This topic has been discussed among construction companies in the last decade in Peru; however, this technology is not widely recognised. The adoption of innovative technologies originated in other countries represents an organisational and technological challenge since they need to be adapted to the conditions of Peru. In a research carried out by Román (2019), the analysis of a project in which IC technology was used to rehabilitate and maintain a national road was made. In this way, the aspects that should be investigated for the implementation of IC were identified: (1) correlations among ICMVs and in situ spot tests; and (2) estimation of the most suitable parameters (i.e. amplitude, frequency and speed) for the compaction process. From the obtained results, it was recommended to change the traditional construction process by implementing IC systems. This makes it necessary to apply IC technology to other construction projects with asphalt pavement. After realising the required investigations, the technology can serve for quality control, which can also be included in the specifications for road construction.

3.5.4. Colombia

The specifications for the construction of Hot Asphalt Mixtures state that at least one vibratory roller and one pneumatic roller should be provided for the compaction works. For general works, the use of self-propelled metallic, static, vibratory and pneumatic rollers is advised. The equipment to be used will depend on the type and thickness of the asphalt layer, which should have approbation from the supervisor following the results obtained in the experimentation phase (Instituto Nacional de Vias, 2014). Despite there are no specifications regarding the use of support systems. The investigation of IC by academia, especially universities, has been evident in the last decade.

IC technology was an unknown concept for companies working on road construction ten years ago (Esquivel, 2011). Thus, it is challenging to implement new technologies which have not been standardized or regulated by authorities. State entities should motivate the implementation of innovative technologies since they can decide about this topic and are involved in the planning process of the projects. This highlights the fact that this is an economical, intergenerational, social and political problem. One critical concern about the acquisition of such systems is the cost. Additional costs regarding import taxes, nationalisation and transport to Colombia should be considered. Another concern regarding these technologies is the additional training provided to operators and engineers because they are unfamiliar with the systems. From a survey carried out with fifteen engineers and nine roller operators, it was concluded that the participants did not recognise the concept of IC. However, after receiving information about this technology, they were enthusiastic about using them for road construction projects. Therefore, it is suggested to perform test strips in which conventional equipment and IC equipment are employed to show the benefits of using this technology. Furthermore, the authorities who are in charge of executing and administering projects involving the construction of roads must be more aware of these innovative technologies (Esquivel, 2011).

3.5.5. Bolivia

The specifications for the construction with Hot Asphalt Mixtures state that a pneumatic roller should be used together with a vibratory tandem roller. The pneumatic rollers should be integrated with devices that allow the automatic change in the pressure of the wheels between 0.25 to 0.84 MPa. Furthermore, the equipment to be used in road construction should be approved by the supervisor (Grupo APIA XXI, 2011). Over the country, there has been no significant research or projects related to paving and compaction support systems. Despite there has been a considerable investment in the road infrastructure from Bolivia within the last few years, especially for road maintenance and research studies (El Deber, 2018). This could represent an opportunity of implementing new technologies within the road construction processes. Nevertheless, the majority of projects in Bolivia within the last decades have suffered severe problems because any project was finalized within the available time and budget. Furthermore, the breach of contracts and hiring processes have not been done arbitrarily. These projects are poorly executed, which leads to some projects presenting severe and dangerous deterioration after only one year of completion (SDSN Bolivia, n.d.).

3.5.6. Venezuela

The specifications for road construction with asphalt pavements state that there should be at least one tandem roller, a self-propelled pneumatic roller and a vibratory roller for each paver within a construction work (COVENIN, 1987). In the 80s, Venezuela occupied an important place within the available physical infrastructure in Latin America; this situation was close to the western countries and Asia (Corrales, n.d.). After some decades, a different situation can be perceived because Venezuela has lost its competitive advantage compared to other Latin American countries. In this country, the investment in roads and transportation has received low attention historically. The basis of this problem has multiple elements: (1) In the 90s, a decentralisation process began in which the central government transferred the competencies of interurban road networks to state governorates. However, these organisations were not administrative and technically prepared. (2) At a national level, there is no planning and regulation regarding road infrastructure works. (3) Some estates have improved the quality and maintenance of the road network; however, this has not been widely evidenced. (4) There is a deficit and instability in the investment for road infrastructure (Corrales, n.d.).

3.5.7. Chile

The general technical construction specifications with Hot Asphalt Mixtures establish that the amount, weight and type of roller employed should be adequate to reach the required compaction within the time in which the mixture can be compacted. There are no specifications regarding the type of rollers used for the compaction works (Dirección de Vialidad, 2020). On the other hand, within the code of standards and technical specifications for compaction, metal, static or vibrating, pneumatic or mixed roller compactors are advised. Furthermore, at least one vibratory and pneumatic roller should d be used (Ministerio de Vivienda y Turismo, 2018).

More attention has been put on soil compaction in Chile since mining is one of the main pillars of its economy. The Chilean Chamber of Construction made a publication about compaction systems for soil. It is recognised that there are more demands regarding security and productivity related to the compaction processes. Hence, multiple solutions developed by the manufacturers for soil compaction are used. Manufacturers such as Caterpillar, JCB, Hamm, Atlas Copco and Bomag commercialise their products within Chile. However, there is no specific mention of a project using paving or compaction support systems to construct roads (Avaria, 2016). On the other hand, much attention has been put to other technologies such as lightweight penetrometer PANDA (Pénétromètre Autonome Numérique Dynamique Assisté) for soil compaction control of the road infrastructure and backfill projects in Chile (Herrera, Espinace, & Palma, 2015).

3.5.8. Paraguay

The specifications for the construction with Hot Asphalt Mixtures states that self-propelled rollers should be used with metallic drum, static or vibratory, tandem and pneumatic. The inspector should approve the equipment to be used after obtaining the results from the experimentation phase. The vibratory compactors should possess devices to stop vibration when reversing; it is advised that they should be automatic. Furthermore, they should have independent controllers for frequency and vibration (Ministerio de Obras Públicas y Comunicaciones, 2011). Paraguay has invested considerably in road construction; however, the connectivity has been prioritised rather than the quality of roads (La Nación, 2020). Some recognised manufacturers are working within this country, such as Volvo and JCB. However, there are no documented projects with the use of paving and compaction support systems. In 2021, the first road technology centre in the country was inaugurated, which aims to develop good quality road infrastructure, enabling the research of innovative technologies and training of Paraguayan road engineers and technicians.

3.5.9. Ecuador

Within the specifications for the construction with Hot Asphalt Mixtures, self-propelled rollers with metallic drums, static or vibratory, tandem, and pneumatic are advised. The inspector will approve the compaction equipment by considering the obtained results from the experimentation phase. The vibratory compactors should possess devices to stop vibration when reversing; it is advised that they should be automatic. Additionally, they should have independent controllers for frequency and vibration (Ministerio de Transporte y Obras Públicas, 2013). In the last years, the universities have done some research to know more about Intelligent Compaction, since this is an unknown technology within this country.

The lack of an adequate infrastructure network for transportation represented a vital barrier to Ecuador's economic and social growth. However, from 2007 to 2017, the government made considerable investments in the road infrastructure system, which positioned Ecuador in second place in Latin America regarding the global transport infrastructure quality. The current regime did not continue with the investment projects carried out by the last government. Hence, the situation has changed within this country, which currently experiences low investments and poor quality of road infrastructure (Confirmado.net, 2020).

3.6. The common trend in South American countries

Some countries in South America acknowledge that IC technologies have been adopted in some developed countries such as the United States. However, adopting a new technology represents a technological and organisational challenge since the technology needs to be adapted to the country's conditions in which it is being introduced. A summary from the analysed countries can be found in Table 7.

The IC term is used in South America. IC systems have not been implemented in the specifications and guideline documents from South American countries. Two situations can be evidenced among these countries. Countries such as Argentina, Brazil, Colombia, and Peru have not implemented these technologies within their specifications. However, various studies and projects related to IC technology have been carried out. Hence they are recognised within these countries. This shows that these countries are willing to acquire more knowledge about the use of such systems. On the other hand, in Bolivia, Venezuela, Chile, Paraguay and Ecuador, the IC concept is unfamiliar. Some have made significant investments in road infrastructure, and others have not invested in this type of infrastructure.

The countries which have advanced more regarding the research of these technologies have determined various impediments for their adoption. One of them is that even though construction companies can use these technologies. It is not recommended for approval of the constructed work. Hence conventional spot tests should still be carried out. This is caused by the lack of research related to the correlations from ICMVs and in situ spot tests. Another impediment regarding implementing these technologies is that they have not been standardised and regulated by competent authorities. These authorities can influence the adoption of such systems since they can decide about the existing regulations and are involved in planning projects at a national level. Another concern related to the use of these systems is the increased costs of the IC systems compared to conventional compaction systems, which entail additional costs regarding the import taxes, nationalisation and transport of machinery. Furthermore, additional training should be provided to the engineers and operators because they are unfamiliar with these technologies.

Table 7: Summary of the current trends from South American regulations

Country	Implemented high-tech solutions within regulations	Current Trend
Brazil	No	Different manufacturers from high-tech solutions commercialise their products within Brazil. However, their use has not been standardised. Since, such technologies are in an introduction period because it is first necessary to understand the functioning and advantages from the technology.
Argentina	No	The adoption of high-tech solutions is not stated in the specifications for road construction within Argentina. Nevertheless, the use of such technologies is advised for QC, whereas QA will come from spot-testing.
Peru	No	The adoption of high-tech solutions in Peru represents a technological and organisational challenge. Nevertheless, the research carried out by this country suggest the possibility of replacing traditional construction processes. But, also it highlights the importance of researching how these solutions can serve for QC purposes.
Colombia	No	High-tech solutions have not been standardised within Colombia. Some of the concerns are related to the machinery cost regarding the acquisition of such technologies. Furthermore, this technology is unknown for the road construction personnel. Hence, there is a need for projects to be carried out with the use of such technologies. But, also the need for support from the authorities.
Bolivia	No	There has been a high investment related to road maintenance and research studies within Bolivia. However, the executed projects suffer problems because they are poorly executed. Which lead to poor quality of roads despite the investment.
Venezuela	No	The roads have received low attention from the government in the last decades, which has different causes: decentralisation from the competences from the government to state governorates, there is no planning and regulations, there is disparity in road quality among states and there is a deficit in road infrastructure investment.
Chile	No	Compaction within mining works is highly important for these country. Hence, more attention has been put on the research of soil compaction. For instance, lightweight penetrometer PANDA enables a better research and compaction control of backfill projects and road projects.
Paraguay	No	There has been a considerable investment in road construction. Nevertheless, the government is focused on the amount of roads being constructed rather than their quality. Recently, a technology centre was inaugurated which will enable to research new technologies and train engineers.
Ecuador	No	Some research has been done regarding high-tech solutions in recent years; however, there is little knowledge about them in general. The government from this country invested significantly in road infrastructure, which resulted in better roads' quality. Currently, there is low investment in roads; hence, the road quality has worsened.

At the same time, the countries which have not studied such technologies have obtained different outcomes regarding the quality of the roads. Some countries, such as Bolivia and Paraguay, have invested in road maintenance and research studies. However, the completed projects have shown severe and dangerous deterioration after some time of being completed because the quantity of roads being constructed has been prioritised rather than their quality. On the other hand, countries such as Chile and Ecuador, which have not invested in these technologies, have obtained a good quality of road infrastructure (World Economic Forum, n.d.) since they have designated considerable amounts of money for the construction and maintenance of roads. At the same time, countries such as Venezuela, have received low attention to road and transportation investment over the last decades. Hence, the quality of roads has worsened over the years. This highlights the critical role of authorities in the quality of road infrastructure of South American countries and how the investment destined for road infrastructure can make an enormous difference in road quality.

4. Enablers and Barriers

The enablers and barriers for implementing paving and compaction support systems were identified based on the information from the literature review. Afterwards, these enablers and barriers were used in nine interviews with field experts, for which it was intended to rank the enablers and barriers in order of importance. From such interviews initial results could be obtained. However, they should be validated and in order to do that a multi-criteria decision-making method (MCDM) called Best-Worst Method (BWM) was used since it has proven to be a robust technique for pairwise comparison (Rezaei, 2015). The input for such method was retrieved from two workshops performed on different days online, which helped to obtain the final raking of enablers and barriers according to their importance.

4.1. Enablers of high-tech solutions in asphalt construction

The enablers for the implementation of high-tech solutions were retrieved taking into account the information from section 2.4. (especially section 2.4.3.). This section discussed the market available solutions which are commercialised and widely used by contractors. After analysing such information four principal enablers could be recognised:

- Increased productivity: Paving and compaction processes are more efficient when the work is achieved in less time, minimising fuel consumption and machinery wear and tear.
- Reduction in maintenance costs of roads: These systems document inconsistencies throughout the compaction and paving process. This information can be used to reduce quality-related faults. Thus, they help reduce the expenditures in rectifying defects and prevent claims and complaints, together with an extended pavement lifetime.
- Assistance to the operators: The systems document and analyse each stage of the work instantaneously and continuously. In this way, operators can improve their working strategies when it comes to paving and compaction. Therefore, the quality of the asphalt layer can be improved. In other words, such technologies provide the operator with real-time feedback.
- User-friendly systems: These systems are easy to set up and offer simple and intuitive interfaces. Furthermore, they present only relevant information to the operators.

4.2. Barriers of high-tech solutions in asphalt construction

The barriers for the implementation of high-tech solutions were identified taking into account the information from the solutions available in the market discussed in section 2.4. and the regulations for road construction discussed in section 3.

- Additional training: The roller's operator and construction supervisor should learn how to handle these new technologies. Since, they are used to work based on their experience and rules of thumb.
- Increased systems cost: There is a significant concern related to acquiring these new systems due to their increased cost compared to conventional paving and compaction systems.
- Paving and Compaction are treated as separated processes: The solutions presented by manufacturers and academia treat both processes as separated, leading to inaccurate assumptions about the actual temperature of the asphalt mat.

- Closed systems for integration: Several solutions have to be used by the customer to control the obtained data from construction operations. In other words, support systems provided by machine manufacturers and developers do not integrate with others.

4.3. Organisation of the interviews

The interviews had four different sections. First, the opinion of the interviewees about the implementation of high-tech solutions was discussed. Afterwards, they were asked about the role that regulations play in the implementation of such technologies. Then, the interviewees were presented with the enablers and barriers identified from literature and were asked to give a qualitative score to the enablers and barriers on a scale from 1 to 9. This scale measures the extent to which each interviewee considers the importance of each enabler and barrier. A score of 1 denotes low relevance, and a 9 indicates high relevance. Furthermore, the interviewees could judge the stated enablers and barriers if some are missing or misleading. Finally, the interviewees were asked about their expectative regarding the future developments of such technologies. The questions for the interviews can be found in Appendix F.

4.4. Analysis of results

The analysis was performed by considering the given scores to each enabler and barrier for implementing paving and support systems. It is worth mentioning, that even though the interviewees were asked to give an integer score. Some of the interviewees did not decide between two numbers, in such cases an average of the two numbers was taken. For instance, one interviewee claimed that an enabler should receive a score of 7 or 8; hence the value of 7.5 was used for the analysis of the results. Seven out of the nine interviewees work within road construction companies, while the rest work within manufacturing companies. Furthermore, a crucial aspect considered before performing the analysis is that some of the interviewees from the constructions companies have adopted paving and compaction support systems, and others are planning to implement these systems. An overview of the status of implementation of the support systems by each construction and manufacturing company can be found in Table 8. Furthermore, in order to obtain analyse the information from the interviews. They were transcribed and then such information was analysed.

Table 8: Performed interviews

Interviewee number	Representative of	Status of support system usage/ advisor of a particular solution
1	Contractor	Working with three different support systems
2	Contractor	Working with a compaction support system
3	Contractor	Working with a paving support system
4	Contractor	Developing a support system
5	Contractor	Working with a paving and compaction support system
6	Contractor	Looking for the implementation of support systems
7	Contractor	Looking for the implementation of support systems
8	Manufacturer	Developed a paving support system (i.e. WITOS Paving) and a compaction support system (i.e. HAMM Compaction Quality)
9	Manufacturer	Developed a paving support system (i.e. Q Pave) and compaction support system (i.e. Q Compaction)

4.4.1. Analysis of the Enablers

The average of the scores of each enabler was calculated. The enabler which received the highest score is the reduction in reparation costs. At the same time, increased productivity is the enabler that received the lowest score. The results from the conducted interviews will be discussed in the following sections.

Table 9: Enablers scores

	Interviews									
Enablers	First	Second	Third	Fourth	Fifth	Sixth	Seventh	Eigth	Ninth	Avg.
Increased productivity	2.5	4	7.5	5	8	9	8	6	3	5.89
Reduction in maintenance costs	8	9	9	9	7	3	9	7	7.5	7.61
Assistance to the operators	7	6	5	7	5	5	7	9	9	6.67
User-friendly systems	7	5	7	2.5	6	9	9	8	7	6.72

Increased productivity

The interviewees that rated this enabler with a low score (i.e. lower than 5) claimed that productivity is independent of support systems. Since the paving crews already work with conventional methods and obtain results with acceptable quality. Furthermore, it was discussed that the paving efficiency is more dependent on the number of available trucks. Therefore, these support systems do not significantly reduce fuel consumption and machinery wear and tear. Although it was claimed that the support systems could be used to enhance the quality of the asphalt, this is seen as an enabler of relatively low importance.

On the other hand, the interviewees who assigned a high score (i.e. higher than 5) to the enabler considered that by providing feedback to the operators, they could compare and learn from the differences in the retrieved data. Thus, it is possible to improve the quality of the asphalt pavement and avoid discussions. However, it was considered that not every pavement project can be optimised because it also depends on the project's size.

Reduction in maintenance costs of roads

According to some interviewees, this is the main reason they implemented or planned to implement paving and compaction support systems. These systems bring benefits for both the contractor and the client. On the one hand, they allow the contractors to reduce inconsistencies by giving them reasonable estimates of the areas which require reparation. Thus, they enable the construction of pavements with a longer life which is beneficial for the client. Nevertheless, it was claimed that there is no direct relation between paving and compaction support systems and reduced reparation costs. In other words, the reduction in reparation costs has not been calculated. The interviewee who rated this enabler with a low score considered that high-quality materials are enough to produce satisfactory results regardless of the system used. In general, the scores for this enabler were high, which means that interviewees considered it noteworthy.

Assistance to the operators

For the interviewees working within construction companies, the score ranged from 5 to 7. According to their judgement, this enabler should face the fact that operators have worked with conventional systems and practices for an extended period. Additionally, sometimes operators might encounter data logged by the support system against their usual practices with paving works. Therefore, they are not willing to work with paving and compaction support systems.

Currently, the experience of the operators plays a fundamental role to obtain good-quality results, which the use of these systems cannot replace. Even though the available systems provide decent documentation, operators usually do not know how to improve their working strategies. In the future, available systems should be further automated; in this way, there would not be much reliance on operators. On the contrary, the interviewees from manufacturer companies considered this the most relevant enabler because they consider that operators can be assisted with the feedback from the machines, enabling them to achieve high-quality results.

User-friendly systems

The respondents who gave this enabler the highest score (i.e. 9) have not implemented these systems within their companies yet; they believe these systems can be used easily and that there have been improvements in the last years. The other respondents claimed that this is a significant enabler because if a system is not user-friendly, the operators will not use the support systems. Therefore, the systems that are being developed should be focused on the paver and roller operators. On the other hand, it was claimed that the current systems are not very user-friendly because sometimes the wrong data is presented to the operators. Two of the respondents indicated that this is one of the reasons why these systems have not been widely implemented.

Additional enablers

In general, the majority of interviewees agreed with the selected enablers. One of the reviewed enablers is the long-term pavement performance which can be achieved by monitoring and analysing the retrieved data from the support systems since it is possible to enhance the pavement quality, which will result in a longer lifetime.

4.4.2. Analysis of the Barriers

The averages from the scores of each barrier allow ascertaining that the most critical barrier is closed systems for integration, and the least essential barrier is paving and compaction treated as separated processes. The results from the performed interviews will be discussed in the following sections.

Table 10: Barriers scores

	Interviews									
Barriers	First	Second	Third	Fourth	Fifth	Sixth	Seventh	Eigth	Ninth	Avg.
Additional training	7.5	3	5	2	9	9	4	9	4	5.83
Increased systems costs	3	8	2.5	1	6	7	8	4	9	5.39
Separated processes	2	8	6	1.5	9	3	7	7	2	5.06
Closed systems for integration	9	6	4	9	9	9	8	6	1	6.78

Additional training

Four respondents gave this barrier high scores (i.e. higher than 5) because they think operators need to be constantly trained about using these systems until they get used to them. In some companies, the operators have to use different machines in different circumstances. Therefore, all operators must be aware of the proper use of the systems, which will be time-consuming. Furthermore, they claimed that if this barrier is overcome, the support systems will be used better. On the other hand, the remaining respondents expressed that the training is not complex, especially if time is available. Because additional training is always necessary when implementing new technology within a company. One way to familiarize the paving crew with these systems is by implementing them in a pilot project.

Increased systems costs

The respondents who gave this barrier a high score (i.e. higher than 5) claimed that the increased costs of support systems represent a more significant barrier for small companies. Furthermore, they consider that the expenditure is relatively high and do not earn money directly. Therefore, this could be regarded as a long-term investment, in which the benefits (e.g. fewer claims, higher quality of roads) are obtained over the years. While the interviewees who gave this enabler a low score considered their own experience within the companies in which they work. Since in large companies often they have to work in big projects (e.g. highways) and often the client demands to know their status of development. Therefore the required information can be retrieved from the obtained data from the support systems. Hence, they recognize that even though the cost is considerable, the obtained benefits (e.g. reduction in penalties, quality improvement, improved productivity) from using these technologies are higher.

Paving and Compaction are treated as separate processes

Two interviewees assigned a score of 2 to this barrier because they work with paving and compaction support systems that try to connect both processes. Hence, the operator can visualise the temperature of asphalt behind the paver and the temperature from the asphalt within the compaction process. The interviewees who assigned a score of 1.5 and 3 claimed that both processes could be separated as long as they are optimized. Nevertheless, also that they should be interoperable, meaning that they are connected and can exchange data. The remaining respondents expressed that this barrier is common among these systems. It was claimed that paving and compaction processes are related to each other; therefore, they cannot be separated. Because if something occurs to the paver, it will also affect the roller.

Closed systems for integration

The majority of respondents expressed that this is an essential barrier because some of the support systems available in the market cannot be integrated with systems from different manufacturers. One of the respondents indicated that this represents a problem within the company he is working on since they are working with three different suppliers. It was considered that the information could be shown in one dashboard or software application interface. Another respondent expressed that they do not work with closed systems since they do not enable an optimized analysis of the retrieved information. Furthermore, the importance of interoperable systems which can be connected with each other to exchange data was pointed out. On the other hand, the respondents that considered this as a low importance barrier claimed that some of the available systems in the market are more accessible since they enable retrieving the recorded data from the machines of different companies.

Additional barriers

In order to determine additional barriers, two questions were elaborated. First, the interviewees were asked to express their views about why these technologies have not been widely adopted. Second, they were asked if they consider more barriers that were not included in the interview. The barriers were settled by considering the number of people who mentioned the barrier. From this information, it was possible to deduct that the paver and roller operators' mindset plays an essential role in implementing the paving and support systems because they work based on their experience. Therefore, sometimes they seem unnecessary to work with these systems since they obtain good-quality results using conventional practices.

Furthermore, they can be concerned that their superiors can see the results, and in case of poor performance within their jobs, they can be penalised for it. Another concern relates to the amount of information presented to the operators, which can overwhelm them. Thus, they would set aside these technologies and work according to conventional practices. Overall, if the paving crew is willing to work with these support systems, the results will enhance. Another barrier mentioned among the interviewees is that the systems are expensive, which was already considered in the barriers retrieved from the literature review.

4.5. Enablers and Barriers

With the aid of the literature review and experts opinions, the most relevant enablers and barriers for the implementation of support systems were retrieved:

Table 11: Enablers and Barriers for the implementation of paving and compaction support systems

Enablers	Barriers
Increased productivity	Additional training
Reduction in reparation costs	Increased systems costs
Assistance to the operators	Paving and compaction treated separately
User-friendly systems	Closed systems for integration
Long-term pavement performance	Operator’s mindset

4.6. Ranking of the Enablers and Barriers

The ranking of enablers and barriers according to their importance were realised with the employment of the Best-Worst Method.

4.6.1. Best-worst method

After determining the enablers and barriers to implementing paving and compaction support systems, the Best-Worst Method (BWM) was applied in order to obtain more reliable results. This is a multi-criteria decision-making method (MCDM) used to rank the enablers and barriers. This method was selected because it is a strong MCDM for pairwise comparison (Rezaei, n.d.). According to Rezaei (2015), this method has a good performance in terms of consistency proportion and other assessment criteria such as like-least infringement, complete deviation, and congruity. Furthermore, this method provides relevant features compared to other MCDM methods since it requires less comparison of data and leads to more consistent comparisons, producing more reliable results.

Steps

Five steps should be carried out in order to obtain the ranking of the enablers and barriers using the BWM:

1. The enablers and barriers for implementing paving and support systems were determined with the collected information from literature and interviews.
2. The best (*B*) (e.g. most desirable, most important) and worst (*W*) (e.g. least desirable, least important) enablers and barriers were identified.

3. The preference of " the best criterion over all other criteria" is expressed by using a scale from 1 (*B* is equally important to *j*) to 9 (*B* is absolutely more important than *j*). As a result, the vector Best-to-Others (BO) vector is as follows:
   $A_B = (a_{B1}, a_{B2}, \dots, a_{Bn})$
   In which the vector a_{Bj} suggests the scores from the preference of the best criterion B over criterion j, which can be visualised in Figure 14. It is worth mentioning that this step was carried out for the enablers and barriers.
4. The preference of "all other criteria over the worst criterion" is expressed by using a scale from 1 (*B* is equally important to *j*) to 9 (*B* is absolutely more important than *j*). As a result, the vector Others-to-Worst (OW) is as follows:
   $A_W = (a_{1W}, a_{2W}, \dots, a_{nW})$
   In which the vector a_{jW} suggests the scores from the preference of the criterion *j* over the worst criterion *W*, which can be visualised in Figure 14. It is worth mentioning that this step was carried out for the enablers and barriers.

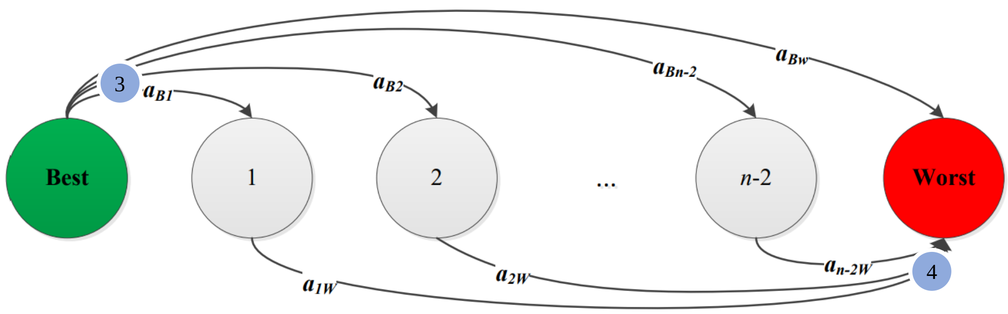

Figure 14: Steps 3 and 4 of the Best-Worst Method. Adapted from (Rezaei, n.d.)

5. In order to find the optimal weights for the criteria (i.e. enablers ad barriers), a linear model of BWM offered by the developer of the method was used. This model enables to increase the efficiency of the process together with a simple calculation and enable to find an optimal solution. With this robust optimization technique, the weights of the enablers and barriers could be obtained, ranging from 0 to 1.

Consistency Ratio (CR)

The Consistency Ratio (CR), which is a robust index ranging from 0 to 1, is used to calculate the consistency level from the obtained results (Rezaei, n.d.). The higher the CR, the less consistent the comparisons are, hence the results are less reliable. The CR has threshold values depending on the number of criteria used and the maximum number used in the pairwise comparison. For instance, in a problem with six criteria (step 1) and the maximum value in the pairwise comparison is 7 (steps 3&4), the threshold is 0.3931. This means that the values of CR obtained below this threshold are acceptable for such a problem. The threshold values can be found in Table 12.

Table 12: Thresholds for CR values. Adapted from (Rezaei, n.d.)

Criteria a_{BW}	3	4	5	6	7	8	9
3	0.2087	0.2087	0.2087	0.2087	0.2087	0.2087	0.2087
4	0.1581	0.2352	0.2738	0.2928	0.3102	0.3154	0.3273
5	0.2111	0.2848	0.3019	0.3309	0.3479	0.3611	0.3741
6	0.2164	0.2922	0.3565	0.3924	0.4061	0.4168	0.4225
7	0.2090	0.3313	0.3734	0.3931	0.4035	0.4108	0.4298
8	0.2267	0.3409	0.4029	0.4230	0.4379	0.4543	0.4599
9	0.2122	0.3653	0.4055	0.4225	0.4445	0.4587	0.4747

4.6.2. Organisation of the workshops

Two workshops were organised with the objective of validating the results obtained from the interviews. The workshops were conducted online and had a duration of approximately one hour each. They were organised in different days and there were five participants in total, from which four participants were contractors which were also interviewed and one participant was an expert on the field of road construction. It is worth mentioning that manufacturers who participated in the interviews were not available for participating in the workshops.

First, a small introduction about the present study was given to the participants. Then, the five steps from the BWM were explained. Afterwards, the participants were asked to perform steps 3 and 4 from the BWM by filling an online survey. Such results served to complete the BWM; hence, the ranking of enablers and barriers could be obtained with the input from experts on the road construction field.

4.6.3. Ranking of enablers and barriers

Two workshops were conducted to obtain the scores of steps 3 and 4 from the BWM for the enablers and barriers. In step 3, the Best enabler/barrier is compared against the remaining enablers/barriers. Whereas, in step 4, the remaining enablers and barriers are compared against the Worst enabler/barrier. A detailed explanation from the BWM for enablers and barriers can be found in Appendix G.

Ranking of enablers

The BWM was applied to the enablers, which enabled determining the weights for the enablers, as Figure 15 shows.

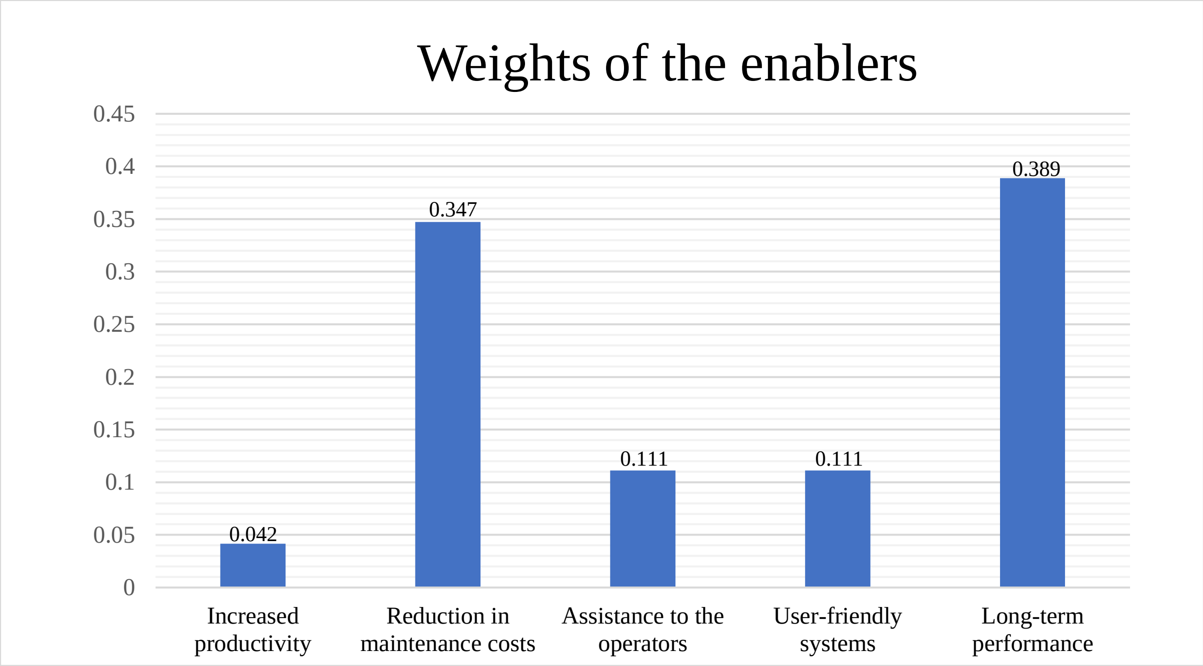

Figure 15: Weights of enablers

The enabler which received the highest weight is *Long-term pavement performance*. Hence this enabler is regarded as the most critical enabler from paving and compaction support systems. Even though *Reduction in reparation costs* was considered the essential enabler at first instance, this changed with the introduction of *Long-pavement performance.* It is worth noticing that *Assistance to the operators* and *User-friendly systems* obtained identical scores. This was also evidenced in the results from the interviews, for which both enablers obtained almost similar scores. *Increased productivity* was the enabler that received the lowest weight, which was also evidenced in the results from the interviews.

The CR value is 0.0972, close to zero, indicating the high reliability of the obtained results. The obtained CR value was below the threshold value of 0.3734. This threshold value was obtained from Table 12, taking into account that there are five criteria and the maximum value (a_{BW}) in the pairwise comparison was seven; hence, the threshold value is 0.3734.

Raking of barriers

The BWM was also applied to the barriers, and the obtained weights are shown in Figure 16.

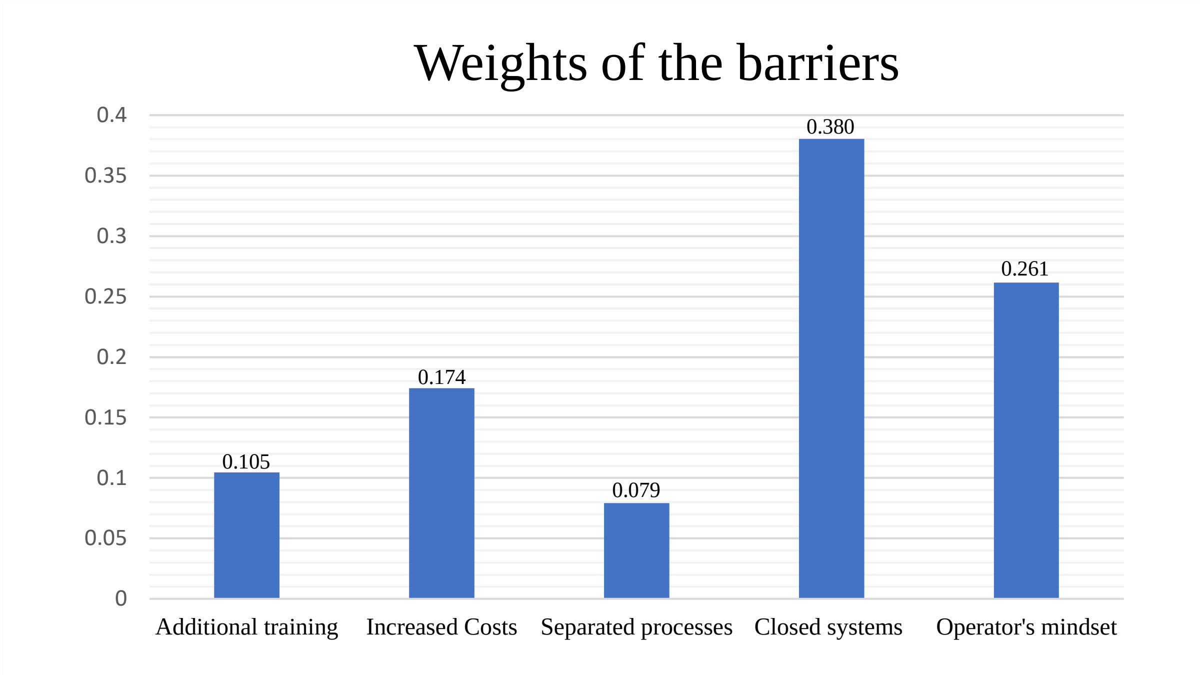

Figure 16: Weights of barriers

The barrier which obtained the highest score was *Closed systems for integration*. Hence this is the most critical barrier. The same result was also evidenced in the obtained average score from the interviews. Another significant barrier is the *Operator's mindset*, and even though this barrier was not identified during the literature review, it was recognised during the interviews. After the application of the BWM, it resulted in a barrier of high importance. *Increased costs* surpassed *Additional training*, which contradicts the results from the interviews. The least essential barrier is *Paving and Compaction are treated as separate processes*, which coincide with the results obtained from the interviews. The obtained CR value is 0.1426. The obtained results are highly reliable since this value is close to zero. Since there are five criteria and the maximum value in the pairwise comparison was 5, the threshold value is 0.3019. The obtained CR valued is below this threshold which supports the reliability of the results.
Summary

4.7.Future developments

In the future, machines will improve the gathering of data, which process improvements will accompany (Kaufmann, n.d.). Hence, the data on how machines previously performed in specific applications and conditions will be available from the start of the project. Hence, the communication among machines from different manufacturers and different phases of the road construction life-cycle will improve to take advantage of the data being gathered. Consequently, the machines without interoperability will be phased out from construction works. The standardization of tools for collecting such information will be necessary for machines to communicate with each other. Hence, the devices from machines of different manufacturers will be a bit different; however, all of them will collect the same data and communicate with each other in real-time. In other words, the hardware will be standardised and integrated into machines.

Another expected development for the future decades is autonomous machines, fundamentally those that do not require an operator (Kaufmann, n.d.). Many exciting developments have already taken place by some of the most recognised manufacturers (e.g. Sakai, Ammann).

However, concerns related to safety will have to be addressed before implementing such machines.

4.8. Results

After performing a literature review about the evolution of paving and compaction support systems and the regulations for road construction in different countries, it was possible to identify the enablers and barriers for the adoption of paving and compaction support systems. The identified enablers were *increased productivity, reduction in maintenance costs*, *assistance to the operators* and *user-friendly systems*. Whereas, the identified barriers were *additional training*, *increased systems costs*, *paving and compaction are treated are treated as separated processes* and *closed systems for integration*. Such enablers and barriers were assessed in structured interviews, from which the interviewees were asked to give a score within a range from 1 to 9 to each enabler and barrier according to their importance. The higher the score, the more important the enabler or barrier. After performing the interviews, *reduction in maintenance costs* and *closed systems for integration* were determined as the most important enabler and barrier respectively. At the same time, the interviews enabled to retrieve other enablers and barriers which were not stated previously. Hence, the enabler *long-term pavement performance* was also considered together with the barrier *operator's mindset*. Since there were additional enabler and barrier considered, it was necessary to validate the previous obtained results. Hence, it could be verified that *long-term pavement performance* and *operator's mindset* are still the most and least important enablers and barriers. This validation was done with the application of the BWM which enabled to obtain weights for the enablers and barriers. Such weights represented the importance from the enablers and barriers. The higher the weight, the more important the enabler/ barrier is. It is worth mentioning that the input for the BWM was obtained from two workshops with experts in the topic, which made the outcomes more reliable. The results after applying the BWM revealed that *long-term pavement performance* is the most important enabler, whereas *closed systems for integration* is the most important barrier for the vast implementation of the intelligent support systems in asphalt construction industry.

5. Conclusions and Recommendations

For many years, traditional equipment and practices generated good results regarding road construction. However, the growing demands from authorities and issues with conventional methods led to developing and implementing systems that can support the paving and compaction processes. The development of such systems started approximately in the 70s. Over the years, such technologies have improved evidently, since they started from the operator having to enter data manually. Nowadays, the equipment gathers, stores, analyses, and documents data from paving and compaction operations in real-time. Available technologies on the market profess numerous benefits. However, such technologies have not been widely implemented. I therefore recommend that the benefits for the use of such technologies regarding the asphalt pavement's quality should be widespread among companies and clients. One way of doing this is to carry out projects using such technologies; hence, companies and clients can learn from the outcomes. Another way of spreading the knowledge about these systems is by supporting organisations committed to the research of new technologies. Hence, such organisations can provide important insights on the feasibility of the adoption of such technologies and the issues that might be encountered when implementing these high-tech solutions.

Much research has been done regarding the use of high-tech solutions for asphalt construction, especially compaction support systems. It is worth mentioning that a common term has not been agreed to use such systems worldwide. The term CCC is generally used in Europe. At the same time, the term IC is employed within North American and South American countries. The performed studies have been principally focused on the correlations among MVs documented by the roller and in situ spot tests of soil and asphalt. From which better correlations have been reported for soil compaction. The inconsistency in correlations in asphalt compaction is caused by several factors: (1) the thickness of the asphalt layers are smaller than the measuring depth from CCC/IC; (2) the MVs continuously change since they depend on the temperature of the asphalt; and (3) the MVs are influenced by parameters such as amplitude or frequency. In consequence, there is a need to standardise the terminology used for advanced paving and compaction systems. At the same time, more research is needed if the asphalt compaction data is to be used for QC and QA purposes instead of spot test data.

CCC/IC has been a topic of discussion in many countries, especially in the US, which is the only country that has implemented such technologies on a large scale for soil and asphalt compaction. Thanks to the efforts from the FHWA through demonstration projects and workshops, some of the issues related to lack of specifications, lack of equipment and technical support, lack of personnel and resources, lack of training and lack of GNSS/GPS validation have been solved. Likewise, Germany and Austria are the only countries that have implemented CCC specifications for soils. Hence, the authorities in charge play an important role in supporting the implementation of innovative high-tech solutions and helping to solve inherent issues related to the adoption of such technologies.

The other analysed countries have not implemented high-tech solutions within their guidelines and specifications. However, two trends were identified among those countries. On the one hand, some countries have adopted other technologies (e.g. FWD, IQRN) or are using traditional methods, and their roads' quality is acceptable. Hence, if due to implemented standards the quality of the new constructed road is good, the contractors and authorities would not be attracted to invest in such technologies. However, since demands for the road infrastructure are increasing, these countries are investing considerably in research and innovation, but they do not focus specifically on paving and compaction support systems. On the other hand, some countries are using conventional systems for road construction, and their roads' quality is poor. These results are obtained since authorities from such countries are using suboptimal practices and equipment for road construction. Overall, both cases show that the implementation of high-tech solutions is highly influenced by the management from the authorities of each country. Therefore, the use of paving and compaction support systems could be promoted within these countries if they are settled in standards and guideline documents. Hence, more contractors will adopt them in different projects. However, in this process, communication between the authorities in charge, contractors and vendors are essential. Furthermore, the technologies are needed to be validated by the competent authorities to guarantee that paving and compaction support systems will bring benefits for road construction. At the same time, a change in contractual forms could influence the adoption of such systems. One clear example was identified in the Netherlands with the DBFM contracts, in which a change in contractual form lead the contractors to look for technologies that can bring better results related to better long-term pavement performance. Since they are not only responsible for the construction but, also for the maintenance of the roads.

Based on the conducted research the most important enabler for the implementation of high-tech solutions for asphalt construction is *Long-term pavement performance*. This is the main reason clients chose to work with such technologies, because they reduce inconsistencies throughout the construction process by gathering data in real-time. Consequently, this results in a longer pavement lifetime. On the other hand, the barrier *Closed systems for integration* refers to systems that cannot be integrated with other systems; they are not interoperable. This is important because telematics and machine control are currently playing an essential role in the data gathering from high-tech solutions in real-time. In general, manufacturers can focus more on overcoming this barrier by opening up their systems and enabling data transfer and communication between differing machine types. As a result, this can give a boost to the adoption of paving and compaction support systems. At the same time, the implementation of such systems can be promoted by realising studies which show how their use contribute to a longer pavement performance. For instance, it can be researched how much the service life of asphalt pavement can been extended by using paving and compaction support systems compared to conventional systems. In order to promote the adoption of paving and compaction support systems it is also important to focus on the other barriers. One of the discussed barriers was the mindset from operators; therefore, these systems should be appealing to them. Since operators play an essential role in achieving the required results for the constructed layers. In this way, they will be willing to use such technologies. Another important barrier was the *additional training* that should be provided to the operators. One way of overcomming this barrier is by providing them with on-site technical assitance and on-site training. Finally, the price of the available solutions represents a barrier, especially for small companies. Hence, it is vital to make the systems more affordable.

6. Discussion

This study aimed to report the status of the implementation of paving and compaction support systems. It was determined that current technologies are going through a technological revolution in which gathering, storing, documenting, and analysing jobsite data in real-time is playing a crucial role. However, more manufacturers are developing new solutions. Hence, the trend among high-tech solutions will keep changing in the coming years. From my perspective, in the future the machines from different manufacturers will have to communicate among each other in order to take advantage from the retrieved data from paving and compaction operations. At the same time, the sensors and devices used would improve to provide better information to the personnel involved in the road construction operations.

A literature review was performed on how high-tech solutions have been implemented in the regulations from some countries over the world. However, some of the specifications were not available due to their privacy, prices or inexistence of on-line copies. For instance, the specifications and guideline documents from France were not analysed. Since the road network of France is managed by different actors and each of them uses private specifications. In some cases old versions from the specifications were analysed. For instance, the RAW specifications from 2020 used the Netherlands were not available. Hence, an old version from the RAW specifications was studied. Generally, the performed literature review offers a good insight into the studied countries' situation with respect to the adoption of high-tech solutions within their regulations. After analysing such regulations it is clear that they play an important role in the adoption of paving and compaction support systems. For instance, the implementation of such technologies in countries such as Austria, Germany and the United States has increased due to the establishment of specifications. At the same time the support offered by the authorities plays an important role in the implementation of such technologies.

After performing the literature review, it was possible to identify enablers and barriers for the adoption of paving and compaction support systems, which were discussed during interviews with experts in the area. It would have been better if more interviews were carried out; hence the results would be more robust. Nonetheless, the interviews offer a good insight into the current situation regarding the implementation of the paving of compaction support systems. Since the information was retrieved from two perspectives: vendor and customer. Hence, I think that in the following years the focus of the academia and industry should be on overcoming of identified enablers and barriers.

Additionally, the results obtained from the interviews were validated by applying the BWM, and the input for such method was retrieved from two workshops with a total of five participants. Nevertheless, it would have been more feasible if all interviewees participated in the workshop. Consequently, every participant could reaffirm the obtained results. After applying the BWM, it was possible to determine that the most important enabler and barrier were *Long term pavement performance* and *Closed systems for integration,* respectively. However, the ranking from the enablers and barriers may be context-dependent. Because, if the same enablers and barriers are ranked in another country, the weights may vary from the obtained. For instance, if the same enablers are ranked in a South American country. The barrier *Increased system costs* would receive a higher score due to the extra costs related to the importation of such machinery. However, this assumption can be researched in a future study.

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Appendices

Appendix A

Compaction Meter Value (CMV)

CMV is determined by employing an accelerometer mounted in the drum to measure g forces of the vibrating drum (Hu, et al., 2019). In principle, the vibration energy is transmitted to the soil by the vibrating drum. The vibration response is detected by the accelerometer. Through a spectral analysis of the measured vertical acceleration, the acceleration amplitude spectrum is attained, then CMV can be calculated as follows:

$$CMV = C \times \frac{A_{2\Omega}}{A_{\Omega}} \quad \text{Equation 1}$$

Where:

C = constant (i.e. 300)

$A_{2\Omega}$ = acceleration amplitude of the first harmonic component of the vibration

A_{Ω}= acceleration amplitude of the fundamental component of the vibration

Compaction Control Value (CCV)

CCV is based on the concept that has the ground stiffness increases, the roller enters into a different motion state, which causes in vibration accelerations at several frequency components (Xu & Chang, 2013). This value is calculated by using the acceleration data of amplitudes as s

$$CCV = \left[\frac{A_{0.5\Omega}+A_{1.5\Omega}+A_{2\Omega}+A_{2.5}+A_{3\Omega}}{A_{0.5\Omega}+A_{\Omega}}\right] \times 100 \quad \text{Equation 2}$$

Where:

$A_{0.5\Omega}$ = acceleration amplitude of the first sub-harmonic component of the vibration

A_{Ω}= acceleration amplitude of the fundamental component of the vibration

$A_{1.5\Omega}, A_{2\Omega}, A_{2.5}, A_{3\Omega}$ = acceleration amplitude of higher-order harmonic components of the vibration

The vibration acceleration signal is transformed through the Fast Fourier Transform method. Afterwards, the signal is filtered in order to detect the acceleration amplitude spectrum.

Vibratory Modulus (E_{VIB})

The E_{VIB} value uses the interaction of the acceleration from the roller drum and the stiffness of the soil. It follows the principle that as the compaction increases the stiffness will also increase which relates to the dynamic load plate. The set of values 45, 80, 100 and 120 MN/m^2 can be visualised by the operator a step change. Which allows to see the achieved target quickly (Bomag, n.d.).

Roller Integrated stiffness (kB)

The roller integrated stiffness (kB) was introduced in the late 90s by Ammann which considered a lumped parameter with two degrees of freedom spring-mass-dashpoint system.

This system has effectively represented the interaction between the drum and the ground. The kB value can be determined when there is constant contact between the drum and soil. It is strongly associated to the plate loading tests results (White & Vennapusa, 2010).

Machine drive power (MDP)

This value essentially defines the amount of additional power needed (in kJ/s) by the roller to compact granular or cohesive soil over the power needed to compact a calibration layer (Cai et al., 2017). In this sense, a positive MDP relates to the layer being compacted has not reached the level of compaction associated with the calibration layer. In the same way, a negative MDP relates to the fact that the layer being compacted has reached more compaction that the calibration layer. This value follows the principle that working over soft soil will require more energy than working over stiff soil. MDP can be calculated with the following equation:

$$MDP = P_g - WV\left(sin\,\theta + \frac{a}{g}\right) - (mV + b) \qquad \text{Equation 3}$$

Where:

P_g = gross power needed to move the roller

W = roller weight

V = roller velocity

θ = slope angle

a = machine acceleration

g = acceleration of gravity

m & b = internal loss coefficients specific from a particular machine.

Appendix B

Table 13: Considered European countries in the study. Adapted from (EUR-Lex, n.d.; World Population Review, 2021)

Country	Area (km^2)	Region
France	551,695	Western Europe
Spain	505,992	Southern Europe
Germany	357,114	Western Europe
Italy	301,336	Southern Europe
United Kingdom	242,900	Western Europe
Greece	131,990	Southern Europe
Portugal	92,090	Southern Europe
Austria	83,871	Western Europe
Netherlands	41,850	Western Europe

Appendix C

Table 14: Available IC specifications in the US. Adapted from (The Transtec Group, 2021).

Agencies	Asphalt IC Specifications	Soil IC Specifications
FHWA	Asphalt	Soils
AASHTO	Asphalt-Soils Combined Spec	Asphalt-Soils Combined Spec
Central Federal Land HD	Asphalt	
Eastern Federal Land HD	Asphalt	
Alabama DOT	HMA	
Alaska DOT	HMA	
Arizona DOT	HMA	
California DOT	HMA,CIR	
Connecticut DOT	HMA	
DC DOT	HMA	
Georgia DOT	Asphalt	Soils
Indiana DOT		Soils
Iowa DOT	Asphalt	Soils
Kentucky Transportation Cabinet	Asphalt	Soils
Michigan DOT		Soils
Massachusetts DOT	HMA	
Minnesota DOT	Asphalt-Soils combined, Thermal profiles	Asphalt-Soils combined
Missouri DOT	Asphalt, Thermal profiles	
Nevada DOT	Asphalt	
New Jersey DOT	Asphalt 1 (draft), Asphalt 2 (draft)	
New Mexico DOT	Asphalt (draft)	
North Carolina DOT	Asphalt (draft)	
North Dakota DOT	Asphalt (draft)	
Oklahoma DOT	Asphalt	
Oregon DOT	Asphalt and thermal profiles	
Pennsylvania DOT	Asphalt, RCC, Embankment, subbase	
Rhode Island DOT	HMA	
Tennessee DOT	HMA	
Texas DOT		Soils, Approved IC rollers
Utah DOT	Asphalt	
Vermont Agency of Transportation	Asphalt	Subbase

Appendix D

Table 15: Summary of state IC specifications

State	Description
Alaska (The Transtec Group, 2021)	• The use of approved IC systems (i.e. Bomag, Sakai, Wirtgen/Hamm, Trimble) • The quality control personnel consists of: IC Plan Administrator, IC Quality Control Technician and IC Roller Operators. • The years of experience for the IC Plan Administrator are stated. • If there are ineffective or unqualified equipment personnel. It is required that construction operations stop until corrective actions are taken, and no additional contract time or additional compensation will be allowed. • The training shall be provided by a representative of the manufacturer which provided the IC equipment. • The payment will be done at the contract lump sum price.
Massachusetts (The Transtec Group, 2021)	• The use of IC systems (i.e. Bomag, Sakai, Wirtgen/Hamm) is recommended. • There are two options for comparing roller and rover coordinates: (1) GPS measurements shall be conducted when the IC roller is static by placing the rover above the GPS from the roller; (2) First, a location is marked on the ground, then the IC roller and rover are used to measure the position of the mark. • The quality control personnel is not specified, but there tasks for the Quality Control Technician are described. • A Construction Quality Meeting should be held with the DOT, before starting any associated activity with HMA pavement construction. • The length of the pre-paving mapping should be approximately 500 ft (150m). • The method of measurement and basis of payment are not specified.
North Dakota (The Transtec Group, 2021)	• The type of roller to be used is not stated • The retrieved data can be transferred by USB and cellular connection. • There specifications about the accuracy for the speed, frequency, amplitude and temperature. • GPS and Global Navigation Satellite System may be used simultaneously and the minimum coverage of the project site is 90%. • The accuracy for the roller and rover is $\pm$0.2 ft and $\pm$0.1 ft respectively, in the X and Y direction. • A calibration of the IC rollers and rover should be performed daily. • In case of an equipment malfunction it is necessary to make a written documentation. • The data should be summitted every day to the cloud storage in intervals of 15 minutes when there is no cellular coverage. • The payment will be done at the contract lump sum price.

Vermont (The Transtec Group, 2021)	• The minimum information required for the Quality Control Plan is related to the QC personnel and their duties, machinery to be used, sequence of use of the machinery and limitations. • Additional information about best practices should b provided by the Contractor. • There is no specific information about the quality control personnel. • The length of the pre-paving mapping should be approximately 500 ft (150m). Corrective actions should be taken when the density results the specification limits of the Agency of Transportation of Vermont. • The payment will be done on a lump sum basis.
Alabama (The Transtec Group, 2021)	• IC roller should be provided by the original roller manufacturer. • The display unit should enable the transmission of data by USB port and/or wireless transmission to the Cloud. • The data should be stored by an external computer and/or cloud storage. • The quality control personnel consists of: quality control manager and the responsible for operating the IC rollers and attached IC equipment. • The magnitude of the evaluation area shall be at least 1500 linear feet. • The onsite training shall be provided by representatives from The Transtec Group. • Within the IC operations criteria, a 70% of the individual construction shall meet or exceed the optimal number of roller passes and ICMV values. The areas which do not meet these criteria shall be investigated. • The contractor may receive a bonus pay if 90% coverage by IC is achieved on the established roller pattern and the thermal profile differential is 70 % in the Good category. • The payment will be made partially according to a schedule.
Arizona (The Transtec Group, 2021)	• IC rollers may be manufactured rollers or rollers which are retrofitted with IC equipment. • The display unit should enable the transmission of data by USB port or wireless transmission to a web-based interface, known as the “cloud”. • The UTM coordinate system may be used when State Plane Coordinate System is not available. • The quality control personnel consists of: IC Quality Control Technician and IC roller operators. • There are specifications for establishing the target ICMV and optimum roller pattern for the breakdown and intermediate phase. • Analysis of IC data should indicate complete and uniform coverage form the rollers and be consistent. Otherwise, the cause for this should be investigated and a corrective action taken. • If there is not a reasonably correlation among quality control tests and IC information, such areas may be investigated. • Within the IC operations criteria, a 75% of the individual construction shall meet or exceed ICMV values.

	• The payment is done in accordance with four categories (i.e. proper implantation, daily submittal of data, weekly IC reports and comprehensive IC report).
New Mexico (The Transtec Group, 2021)	• The use of known IC systems (i.e. Bomag, Sakai, Wirtgen/Hamm). • The measurements derived from IC shall not be used for the acceptance of HMA or WMA, they shall be used for information purposes only. • The minimum operator qualifications (i.e. years of experience) are stated. • There is no specific mention about the Quality Control Plan. • The length of the pre-construction mapping should be approximately 500 ft (150m). • The item will be paid as an allowance for providing IC in the project.

Appendix E

Table 16: Considered South American countries in the study. Adapted from (EUR-Lex, n.d.; World Population Review, 2021)

Country	Area (km^2)
Brazil	213,993
Colombia	51,265
Argentina	46,605
Peru	33,359
Venezuela	28,704
Chile	19,212
Ecuador	17,888
Bolivia	11,832
Paraguay	7,219

Appendix F
Specific Questions

- Has the company in which you are working on adopted/developed paving and compaction support systems, and why?
- Why do you think that paving and compaction support systems have not been widely implemented?
- How can the implementation of pavement and compaction support systems be promoted so they can be standardised in the future?

Specifications and Guidelines

- What role do specifications and guideline documents play for constructing roads in the implementation of paving and compaction support systems?
- Why do you think that countries such as the USA have included paving and compaction support systems (i.e. Intelligent Compaction) within the specifications and guideline documents for constructing roads and other countries such as Spain have not?

Enablers and Barriers

Enablers

Through a literature review, some enablers for the adoption of paving and compaction support systems could be identified. On a scale from 1(least important) to 9 (most important), to what extent do you consider the importance of each enabler and why?

- Increased productivity: An efficient paving and compaction process is carried out when the work is achieved in less time, which minimises fuel consumption and machinery wear and tear.
- Reduction in reparation costs: These systems document inconsistencies throughout the compaction and paving process. This information can be used to reduce quality-related faults. Thus, they help reduce the expenditures in rectifications of defects and prevent claims and complaints, together with an extended pavement lifetime.
- Assistance to the operators: The systems document and analyse each stage of the work instantaneously and continuously. In this way, operators can improve their working strategies when it comes to paving and compaction. Therefore, the improved final quality of the asphalt layer can be achieved.
- User-friendly systems: These systems are designed with simple and intuitive interfaces, which are also combined with easy installation and set-up.
- Do you think that any of the enablers for implementing support systems are missing or misplaced? If so, on a scale from 1 (least important) to 9 (most important), to what extent do you consider the importance of the enabler/s and why?

Barriers

Through a literature review, some barriers to the adoption of paving and compaction support systems could be identified. On a scale from 1 (least important) to 9 (most important), to what extent do you consider the importance of each barrier and why?

- Additional training: The roller's operator and construction supervisor should learn how to handle these new technologies.
- Increased systems cost: There is a significant concern related to acquiring these new systems due to their increased cost compared to conventional compaction systems.
- Paving and Compaction are treated as separated process: The solutions presented by manufacturers and academia treat both processes as separated, which leads to inaccurate assumptions about the actual temperature of the asphalt mat.
- Closed systems for integration: In order to control the obtained data from construction operations and the road lifecycle, several solutions have to be used by the customer.
- Do you think that any of the barriers for implementing support systems are missing or misplaced? If so, on a scale from 1 (least important) to 9 (most important), to what extent do you consider the importance of the barrier/s and why?

- Do you think that the barriers overcome the enablers from these technologies or vice versa and why?

Future developments

There are two suggested developments for the future of paving and compaction support systems. Do you agree with each statement, and why?

- One of the future developments relates to connecting more machines within the process of road construction (e.g. asphalt plant, paver, compactor).

- In the years to come, autonomous machines, essentially those that do not require an operator, are on the horizon.

- Can you suggest any other developments for the future of asphalt and paving support systems that were not mentioned in this interview?

Appendix G
Best-Worst Method Results

Enablers

Step 1: Identify the enablers

Table 17: Enablers for the implementation of high-tech solutions for asphalt construction

Enablers
Increased productivity
Reduction in maintenance costs of roads
Assistance to the operators
User-friendly systems
Long-term pavement performance

Step 2: Identify the Best and Worst enablers

The Best and Worst enablers were determined by considering the average scores obtained from the interviews. Hence, the enabler which obtained the highest score was *Reduction in maintenance costs of roads*. Whereas, the enabler which obtained the lowest score was *Increased productivity*.

Table 18: Best and Worst enabler

Best enabler (Most important)	Worst enabler (Least important)
Reduction in maintenance costs of roads	Increased productivity

Step 3: Best enabler over all other enablers

In the workshop each participant was asked to give an score in a scale from 1 to 9 as showed in Table 19. The score is used to express the preference of each participant on the 'Best enabler over all other enablers'. For instance, the participant can express that *Reduction in maintenance costs of roads* is strongly more important than *Increased productivity*. Therefore, a score of 5 should be assigned to this comparison.

Table 19: Scale used for the BWM

The meaning of the numbers 1-9:
1: Equal importance
2: Somewhat between Equal and Moderate
3: Moderately more important than

4: Somewhat between Moderate and Strong
5: Strongly more important than
6: Somewhat between Strong and Very strong
7: Very strongly important than
8: Somewhat between Very strong and Absolute
9: Absolutely more important than

The scores assigned by each participant are showed in Table 20.

Table 20: Results from the workshops 'Best enabler over all other enablers'

Participant	Reduction in maintenance costs to Increased productivity	Reduction in maintenance costs to Reduction in maintenance costs	Reduction in maintenance costs to Assistance to the operators	Reduction in maintenance costs to User-friendly systems	Reduction in maintenance costs to Long-term pavement performance
First	9	1	5	4	1
Second	3	1	5	4	3
Third	2	1	1	1	1
Fourth	7	1	5	2	1
Fifth	8	1	4	9	1
Average	5.8	1	4	4	1.4

After obtaining the scores determined by each participant, the average values were determined, these values were rounded since step 3 from the BWM require whole numbers.

Table 21: BWM Step 3 enablers

Best to Others	Increased productivity	Reduction in maintenance costs of roads	Assistance to the operators	User-friendly systems	Long-term pavement performance
Reduction in reparation costs	6	1	4	4	1

Step 4: All other enablers over the Worst

The same scale used for step 3 was applied for comparing the 'All other enablers over the Worst'. The scores assigned by the participants are showed in Table 22.

Table 22: Results from the workshop 'All other enablers over the Worst'

Participant	Increased productivity to Increased productivity	Reduction in maintenance costs to Increased productivity	Reduction in maintenance costs to Assistance to the operators	Reduction in maintenance costs to User-friendly systems	Reduction in maintenance costs to Long-term pavement performance
First	1	9	7	7	9
Second	1	3	3	5	6
Third	1	2	1	3	5
Fourth	1	2	3	6	7
Fifth	1	7	2	4	7
Average	1	5.6	3.2	5	6.8

After obtaining the average scores, they were rounded and these values were used in step 4, as Table 23 shows.

Table 23: BWM Step 4 enablers

Others to the Worst	Increased productivity
Increased productivity	1
Reduction in maintenance costs of roads	6
Assistance to the operators	3
User-friendly systems	5
Long-term pavement performance	7

Step 5: Find the weights for each enabler

The model provided by the developer of the method was used to obtain the weights for each enabler.

Table 24: Weights enablers

Enablers	Weights
Increased productivity	0.042
Reduction in maintenance costs of roads	0.347
Assistance to the operators	0.111
User-friendly systems	0.111
Long-term pavement performance	0.389

Barriers

Step 1: Identify the barriers

Table 25: Barriers for the implementation of high-tech solutions for asphalt construction

Barriers
Additional training
Increased system costs
Paving and compaction are treated separately
Closed systems for integration
Operator's mindset

Step 2: Identify the Best and Worst barriers

The Best and Worst barriers were determined by considering the average scores obtained from the interviews. Hence, the barrier which obtained the highest score was *Closed systems for integration*. Whereas, the enabler which obtained the lowest score was *Paving and compaction treated separately*.

Table 26: Best and Worst barrier

Best barrier (Most important)	Worst barrier (Least important)
Closed systems for integration	Paving and compaction treated separately

Step 3: Best barrier over all other barriers

The same procedure applied for Step 3 of the enablers was applied for Step 3 of the barriers. The scores and averages can be visualised in Table 27.

Table 27: Results from workshops 'Best enabler over all other enablers'

Participant	Closed systems for integration to Additional training	Closed systems for integration to Increased system costs	Closed systems for integration to Paving and compaction treated separately	Closed systems for integration to Closed systems for integration	Closed systems for integration to Operator's mindset
First	3	1	1	1	1
Second	6	2	1	1	2
Third	7	1	5	1	1
Fourth	5	7	5	1	3
Fifth	6	5	4	1	2
Average	5.4	3.2	3.2	1	1.8

The obtained average scores were rounded as shown in Table 28.

Table 28: BWM Step 3 barriers

Best to Others	Additional training	Increased system costs	Paving and compaction treated separately	Closed systems for integration	Operator's mindset
Closed systems for integration	5	3	3	1	2

Step 4: All other barriers over the Worst

The same procedure applied for Step 4 of the enablers was applied for Step 4 of the barriers. The scores and averages can be visualised in Table 29.

Table 29: Results from barriers 'All other barriers over the Worst'

Participant	Additional training to Paving and compaction treated separately	Increased system costs to Paving and compaction treated separately	Paving and compaction treated separately to Paving and compaction treated separately	Closed systems for integration to Paving and compaction treated separately	Operator's mindset to Paving and compaction treated separately
First	3	7	1	3	5
Second	5	4	1	5	4
Third	1	1	1	1	1
Fourth	3	1	1	7	1
Fifth	1	3	1	4	3
Average	2.6	3.8	1	4	2.8

The rounded average scores are shown in Table 30.

Table 30: BWM Step 4 barriers

Others to the Worst	Paving and compaction treated separately
Additional training	3
Increased system costs	4
Paving and compaction treated separately	1
Closed systems for integration	4
Operator's mindset	3

Step 5: Find the weights for each barrier

The model provided by the developer of the method was used to obtain the weights for each barrier.

Table 31: Weights barriers

Barriers	Weights
Additional training	0.105
Increased system costs	0.174
Paving and compaction treated separately	0.079
Closed systems for integration	0.380
Operator's mindset	0.261