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CONSISTEND: A tool to assess the impact of construction process quality on the performance of pavements and its implementation in tenders

Report on applicability and quantified influence on quality control

Deliverable D3.1
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The Netherlands Organisation for Applied Scientific Research (TNO)
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Executive summary

The aim of this Deliverable is to gather information on quality control methods which can be used to manage the construction parameters during transport, laying and compaction of asphalt surface course. The information gathered will be used as input to the quality assessment tool (Deliverable D2.1) to quantify the effect of quality control on the construction parameters and hence the service life.

Methods which are commercially available and “ready to use” are primarily examined as they are of most interest to roads authorities. However, other methods which are under development are also mentioned. The information was gathered on these methods through an extensive literature review, consultation with industry experts and consultation with road authorities. Information on all aspects of the methods was not always available and in some cases assumptions are made but the source of all information is clearly stated in the report.

The following aspects of each quality control method are examined:

- Description of method.
- Reduction in the variability of construction parameters which can be achieved with this method.
- Energy efficiency and cost are examined to determine the additional energy required to implement the methods and the associated cost.
- Applicability in practice is investigated to identify how suitable the method is in practice and under different circumstances.

As part of the review of the available methods, it was found that there are two types of quality control method. The first group measures the construction parameters (temperature, compaction, location, etc) but does not directly influence any of the parameters. These methods generally aim to provide extensive real time information to equipment operators while also saving a permanent record of the construction parameters. These measuring methods require further action to be taken based on the measurements in order to influence the quality and hence the service life of the pavement. The second group of methods directly physically influences the construction parameters (temperature, joints, etc.). The effect of these methods on the construction parameters, and hence the service life, is easier to quantify.

The information gathered indicates that monitoring and controlling temperature is the focus of many of the quality control methods. The aim is to keep the material in the appropriate temperature range throughout the transport, laying and compaction phases. Compacting the material in the appropriate temperature range increases the likelihood of the material achieving the target density, and therefore achieving the optimal service life.

1 Introduction

1.1 Background

Quality control during the construction process is, next to road design and material selection, an important factor that determines the service life of an asphalt road. A longer functional life of a road has an enormous impact on its carbon footprint because it minimizes the use of materials and energy during the life cycle. The road construction sector faces a number of changes that have an impact on quality control. Under the impact of new types of contracts like Design, Build, Finance and Maintain (DBFM), the responsibility for quality control moves from road owner to contractors and investment in advanced techniques for quality control has now become rewarding for contractors. The workforce of construction companies is also changing more frequently. Subsequently, road construction teams are subjected to frequent changes, which reduce the total knowledge of the team. This lack of continuity has a negative effect on the service life and performance of a road.

New technologies have become available over the past decades which can help take quality control to a whole new level. With the help of these technologies a wide selection of parameters can now be monitored during construction in real time. However, at this time an important challenge is the limited knowledge available on the influence of these construction parameters on the service life of pavements. This is largely due to traditional and empirical knowledge of road materials and construction.

The CONSISTEND project aims to combine available data on the influence of construction parameters on service life with the knowledge of experts of different EU member states to determine the parameters that are most important to monitor and manage during construction. It aims to incorporate this data into a tool that can perform real time predictions of the service life of the pavement and the effect of quality control measures on this service life. As part of the CONSISTEND project, this deliverable identifies available quality control measures and examines their effect on the construction parameters and their applicability and influence under different circumstances.

1.2 Objectives and scope

This report identifies quality control methods which can be used during the transport, laying and compaction of asphalt surface course. Methods which apply to other asphalt courses or methods which are used after compaction is complete (e.g. testing of cores) are beyond the scope of the CONSISTEND project. This report primarily aims to quantify the effect of these methods on the variability of the construction parameters. Quality control methods are also examined in terms of their cost, their associated energy and their applicability in different circumstances. The aim is to identify methods which are commercially available and ready to use. This information will be used in the CONSISTEND tool which will quantify the effect of these methods on the service life of asphalt surface course. This tool will be described in CONSISTEND Deliverable D2.1.

Different methods target different construction parameters, e.g. temperature, compaction, joints. As part of the CONSISTEND project, only the influence of a certain number of construction parameters is being examined. These parameters are the focus of this work and quality control methods which affect other parameters, although mentioned in some cases, are not the focus of this report. The relevant parameters for CONSISTEND are:

- Temperature of material
- Weather (Ambient Temperature, Wind Speed, Rainfall)
- Compaction (Void Content (%), Number of roller passes)
- Workmanship
- Travel time and delays
- Joints (longitudinal joints)
- Interlayer bond

Information on the effect of these parameters on lifespan was gathered from industry experts and is presented in CONSISTEND Deliverable D1.1.

The information contained in this report was obtained from an extensive literature review along with information gathered from industry experts, roads authorities in partner countries and equipment suppliers. In some cases where information was not available, assumptions were made. However, the source of all information is clearly stated throughout the document.

1.3 Report outline

All commercially available quality control methods are presented in Section 2. For each method a general introduction is given as well as a description of how it influences the relevant construction parameters.

Section 3 aims to quantify the effect of each method on the relevant construction parameters. The aim is to accurately quantify the reduction in variability of the construction parameters with the method so that the information can be used as an input for the CONSISTEND tool which will model the lifespan of the material. It is not always possible to obtain the required information and in such cases assumptions about the influence of the method may need to be made. If assumptions are made they are clearly stated in the report.

Section 4 aims to quantify the cost and energy associated with each method. This information will be useful to road owners or contractors who want to examine the long term monetary and energy saving that can be made.

Section 5 describes the applicability in practice of each quality control method. Not all methods are suitable in all circumstances. The implementation issues associated with each method are highlighted. These relate to issues such as set up time and space required to implement an approach.

The CONSISTEND project is only interested in methods which are commercially available and currently ready for use by contractors. However, other methods may be currently under development and may be ready for use in the near future. Section 6 describes some of these methods which were identified as part of literature review.

Section 7 provides an example of how the information gathered on variability might be used as inputs for the quality assessment tool (Deliverable D2.1). As work is still in progress on the quality assessment tool, the final inputs will be presented in Deliverable D2.1.

2 Description of Available Quality Control Methods

This section describes all the available quality control methods. The primary aim is to identify methods which can influence the construction parameters which are being examined by the CONSISTEND project – see Deliverable D1.1. However, other methods are also identified and described.

The CONSISTEND project is concerned with the transport, laying and compaction of asphalt surface course. As such, quality control methods are examined independently for each of these phases of construction. In addition, methods which can be used for all three phases are examined separately.

Commercially available methods which are ready to use on site are of interest to this project. Other methods which are currently being researched or developed are not discussed in this section but there is some discussion of these methods in Section 6.

2.1 Transport

2.1.1 Insulated truck

Truck bodies are generally insulated and covered to minimise temperature loss during transportation of asphalt to site. The use of these trucks is required to meet national specifications, for example, BS594987 (2010) and TSC 06.300/06.410 (2009).

2.1.2 Asphalt Logistics Information System

The Asphalt Logistics Information System (ALIS) was developed in the Netherlands to increase the efficiency of supplying asphalt to site. The system consists of an iPhone/iPad application coupled with GPS and other equipment to monitor the manufacturing and delivery process – see Figure 1.

The parameters that are monitored by the system include:

- Temperature of asphalt when loaded into the truck.
- Location of trucks and the amount of asphalt that is en route to the site.
- Quantity and type of material in each truck.
- Expected arrival time of trucks at the paver and at the asphalt plant.
- Temperature of material when loading paver.
- Wait times to unload at paver.
- Wait times at the asphalt plant.
- Capacity of the plant. How much asphalt has been processed and the capacity to process additional asphalt.

Some of the benefits of the system include:

- Reduces wait times on site and at the asphalt plant which helps ensures the material arrives on site at the correct temperature.
- Can adjust paving speed to match the arrival time of the next load. This can reduce cold spots due to paver stops.
- Exact details of the mix are known before it arrives at the paver.
- The asphalt supplier can monitor the speed of different jobs throughout the day and reallocate trucks if required.
- Less material is unnecessarily sent to site and wasted.

Figure 1. Example of information given by ALIS iPhone/iPad application.

2.1.3 RFID tag on truck

Asphalt trucks can be fitted with a radio frequency identification (RFID) tag which carries the information for the material in the truck. This tag is automatically read by the paver at delivery. This information can then be uploaded to a cloud based system using the mobile phone network. This system saves time collecting delivery tickets on site and results in less data corruption. These systems are being trialled in the UK.

Studies have been performed to examine the feasibility of this approach. A Federal Highway Administration (FHWA) in Alaska instrumented 10 trucks with RFID tags and placed readers at the weigh bridge and on the paver (Henrie & Ronchetti 2010). It was found that the equipment worked as expected. The project collected much information, including:

- Truck ticket number
- Weight of truck
- Date and time that truck entered the plant, was loaded, exited plant, arrived at site, loaded paver and left site.
- GPS location of paver when trucks were first detected by paver.

2.2 Laying

2.2.1 Monitoring systems on board the paver

These systems generally consist of a Global Positioning System (GPS) linked to infrared (IR) sensors. They primarily monitor the temperature of the material just behind the paver and link all temperature measurements to the location on the road. It can also use infrared sensors to monitor the temperature in the hopper and at the auger. The aim is to determine if there is an even temperature distribution in laid material. Some agencies require contractors to monitor temperature behind the paver (Bijleveld 2015).

Most systems use IR line scanners to record the temperature behind the paver. These systems record many points (typically hundreds) transversely along a line behind the paver and are best for producing real-time temperature contours on the paver as well as storing the records. Figure 2 shows a temperature contour plot from the Slovenian test site which is discussed in detail in Deliverable D4.1. IR cameras can also be used but these record thermal images of the material behind the paver which make it more difficult to produce high resolution contour plots of temperature. Both approaches are compared in Huerne et al. (2009) and their finding are summarised below:

- Both systems can be easily mounted on the paver.
- IR camera and IR line scanner are similarly priced.
- Processing of data for visualisation is most easily done with IR line scanner.
- The angle of view is important to capture all the material which has been laid. IR line scanners typically have a better angle of view.

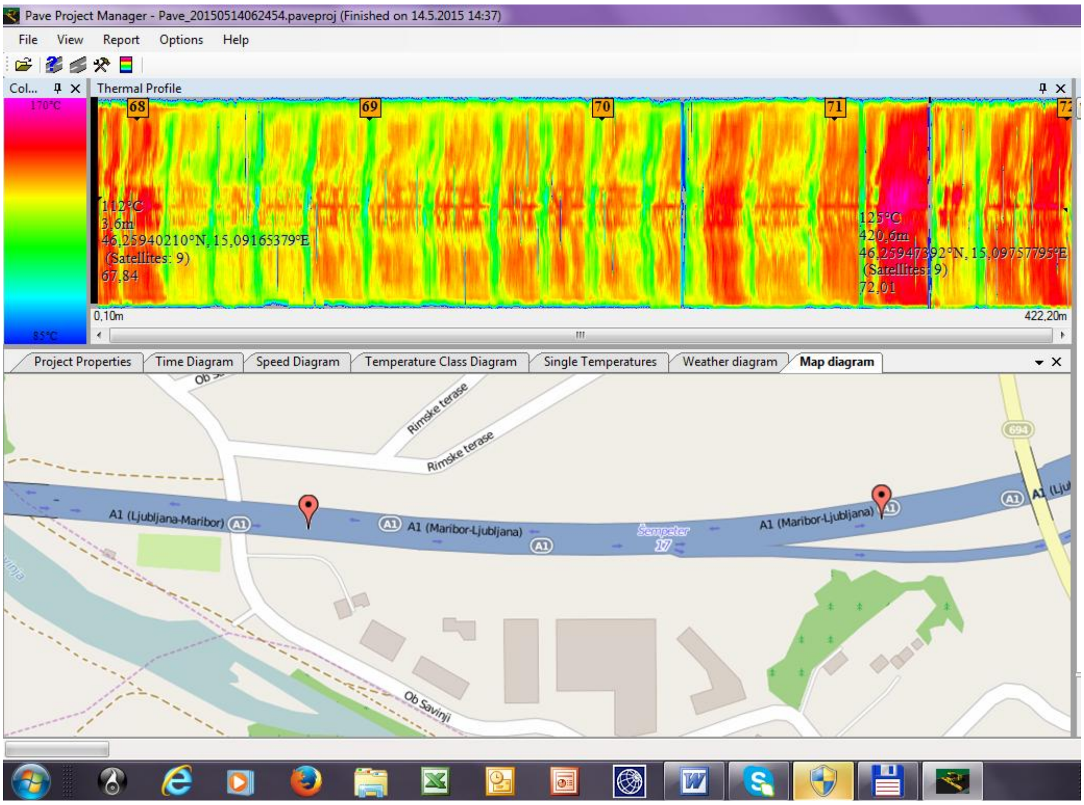

Figure 2. Temperature contour from Slovenian test site.

These systems can also be linked to other monitoring systems. Weather stations can monitor temperature, wind speed and rainfall. The sensors are shown in Figure 3 and the onboard display is shown in Figure 4. The GPS system can also be used to monitor the number of paver stops. If the use of GPS is not possible (e.g. in a tunnel), other systems can be used to monitor paver stops. Stops are important for quality control as they can produce cold patches in the asphalt which as a result may not be compacted at the correct temperature.

Bijleveld (2015) notes that some agencies are starting to require contractors to monitor paver stops and are penalising them for stops.

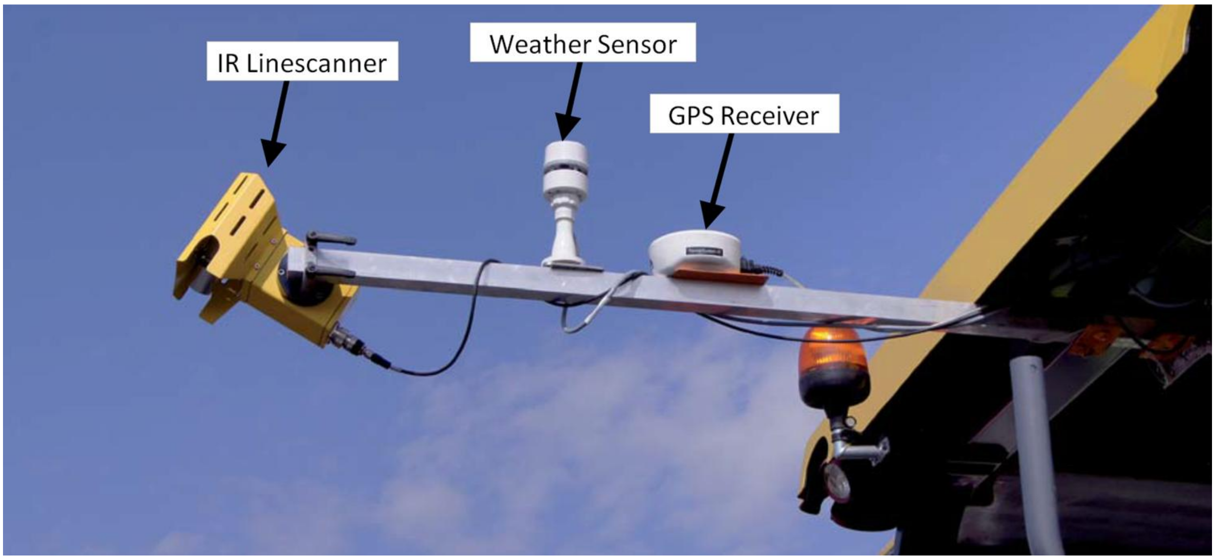

Figure 3. Monitoring equipment attached behind paver (www.moba-automation.com).

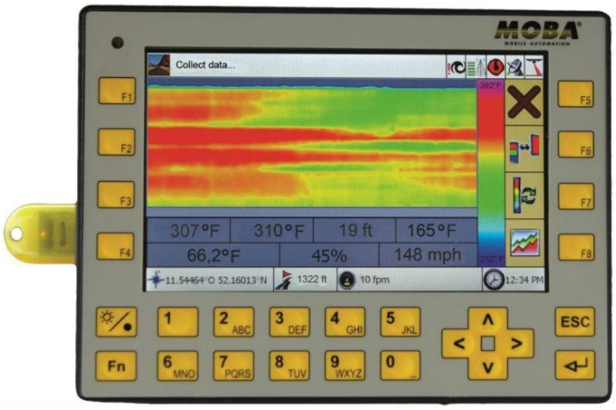

Figure 4. Real time display on paver of laying temperature (www.moba-automation.com).

2.2.2 Shuttle buggy

Shuttle buggies are used to remix the asphalt between the truck and the paver – see Figure 5. A shuttle buggy is not a quality control measure such as the other measuring methods in this document as it does not measure the construction parameters. However, it improves quality and so it is deemed relevant to this work.

The aim of the shuttle buggy is to eliminate segregation. Thermal segregation as well as segregation of aggregate can occur while the material is being transferred to site. Producing an asphalt layer without any deviations in temperature helps reduce any variations in compaction.

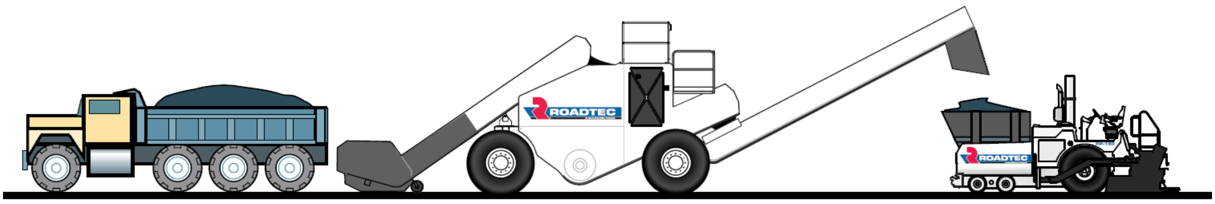

Figure 5. Diagram showing how shuttle buggy supplies paver (www.roadtec.com).

Shuttle buggies also store material. This helps ensure a continuous paving process with less stops. Paver stops can affect quality and evenness of the finished surface. The storage also means that two pavers can be supplied from one shuttle buggy. This can be particularly useful for echelon paving – see Section 2.2.7. The shuttle buggy also never touches the paver so the problems associated with trucks bumping the paver are eliminated.

Bijleveld (2015) examined many aspects of the asphalt construction process. His findings recommend that shuttle buggies be used to reduce temperature differentials and to allow a continuous construction process. Discussion with contractors suggested that this was particularly important for thin surfaces which are of particular interest to CONSISTEND. A shuttle buggy can be seen in operation in Figure 6.

Figure 6. Diagram showing shuttle buggy in operation (www.astec-europa.com).

2.2.3 Rate of application of bond coat

Bond coats are applied between asphalt layers and they are required by national specifications (BS594987 2010; TSC 2009; CROW 2010). They are generally applied using spray tankers and BS594987 (2010) specifies that “calibrated metered mechanical spraying equipment” should be used to ensure the correct rate of application. Spraying trucks generally use computer controlled spraying equipment. Although no evidence was found of the rate of application being linked to GPS coordinates, it would seem that this may be a straightforward addition in the future.

The rate of application can also be tested by placing a tray in the path of the sprayer and then weighing the tray after the sprayer has passed in order to determine the amount of bond coat that has been applied. As the area of the tray is known, the rate of application can be calculated.

2.2.4 Visual inspection - joints

Joints often represent a weak point in the pavement. Poorly constructed joints can cause cracking and ravelling. Visual inspection of joints is used to ensure that they are constructed correctly. BS594987 (2010) specifies that all surface course joints should be cut back to a vertical edge and painted with a bond coat or hot bitumen. Parallel joints between layers should also be offset (CROW 2010). Visual inspection can ensure that these joints are constructed correctly.

2.2.5 Visual inspection - condition of underlying layers

The inter-layer bond is affected by the condition of the underlying layer. To obtain an effective bond, the underlying layer should be free of loose material, detritus, etc. Visual inspection prior to laying can ensure that the underlying layer is in appropriate condition and if not that it is cleaned prior to laying. An example of the surface contamination that can occur is given in Figure 7.

Figure 7. Example of contamination of underlying layer.

2.2.6 Measure layer thickness

Measurement of the layer thickness can ensure that there is adequate material depth. The material depth can be easily measured at the edge of the mat – see Figure 8. The required layer thickness is usually specified in the contract documents but national standards also give guidance for minimum depths for different materials. For example, minimum values are given for different materials in BS594987 (2010) and TSC 06.300/04.410 (2009). As layer thickness is not among the construction parameters being examined in the CONSISTEND project, it will not be discussed further in this report.

Figure 8. Layer thickness can be measured at the edge of the layer.

2.2.7 Echelon paving

The joint construction process can be improved by using echelon paving. This consists of paving with two or more pavers side-by-side and slightly offset – see Figure 9. With this process, both mats are hot during compaction of the road and rollers can pass over the joint before either side has cooled. The result is a hot joint with a much improved joint quality. This method is not a quality control measure like the other measuring methods in this document as it does not measure the construction parameters. However, it improves quality and so it is included as it is relevant to this work.

Figure 9. Echelon paving with three pavers side-by-side (www.aggbusiness.com).

2.2.8 Sonic sensor control of grade and slope

Sonic sensors can be attached to the paver to control the slope, grade and smoothness during laying. The system consists of a number of multi-sensor detectors placed on a beam which measure the distance to the road surface. The beam extends in front and behind the paver for improved detection – see Figure 10. It detects any large-scale and small-scale bumps in the pavement and the paver automatically reacts to smooth these bumps. As grade and slope are not among the construction parameters being examined in the CONSISTEND project, they will not be discussed further in this report.

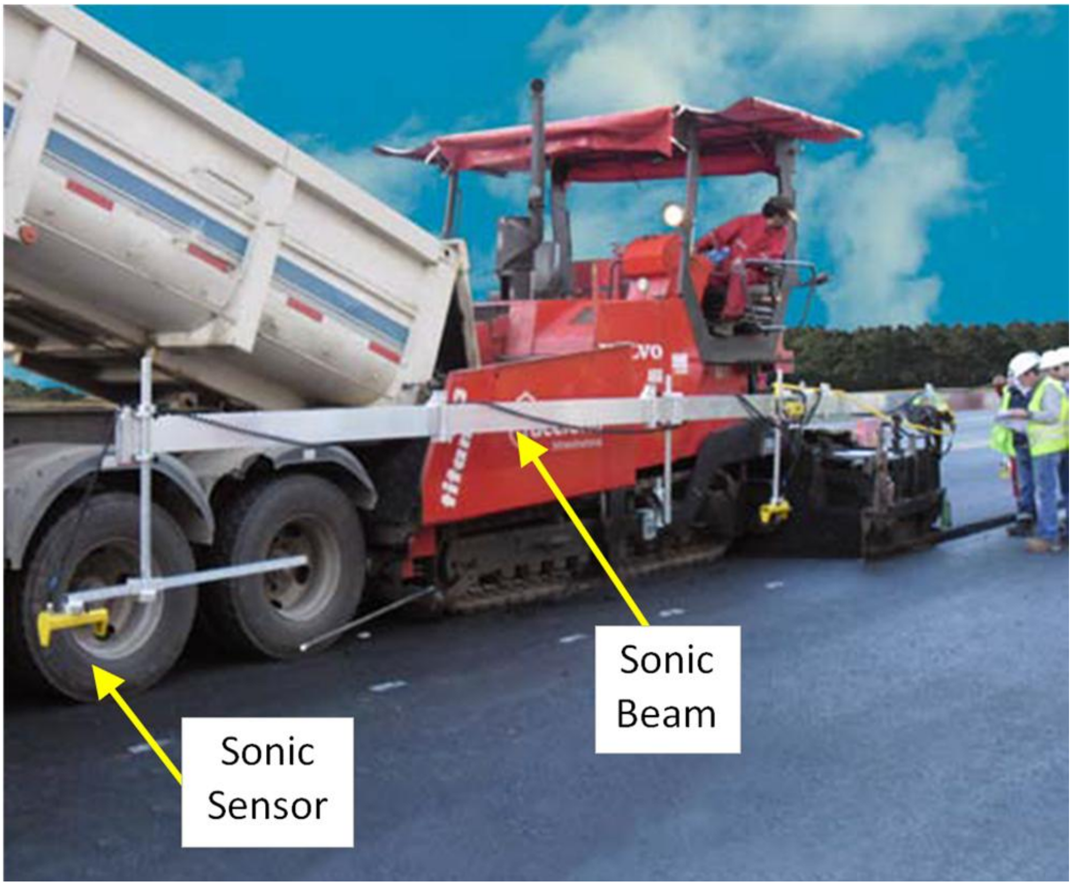

Figure 10. Sonic sensors for control of layer thickness (www.moba-automation.com).

2.3 Compaction

This section discusses quality control methods which can be used during compaction, of which intelligent compaction dominates. Intelligent compaction is a term which refers to a vibratory roller equipped with a range of advanced methods for monitoring the construction parameters. The aim of these methods is to capture the complete compaction history of the pavement while providing the roller operator with real time information on the compaction process via an on-board display. Intelligent compaction methods are discussed here as well as non roller based methods.

2.3.1 GPS on roller

Adequate compaction is required in order to obtain the target asphalt density. This target density is important as under compaction can result in rutting of the material over time and over compaction can cause the material to lose its stability. The final density of the material is affected by many factors but the number of roller passes is a key factor. In the busy onsite environment it can be difficult to keep track of the degree to which each point on the mat has been compacted. GPS based monitoring can be installed on rollers to show the number of roller passes at all locations on the mat. The GPS equipment is usually placed on top of the cab of the roller – see Figure 11. This information is available to the roller operator on an in-cab display which can take into account information from multiple rollers with this system. The in-cab display is shown in Figure 12 with the information on the number of roller passes shown on the left. The display also shows the asphalt temperature and this is further discussed in Section 2.3.2. Chang et al. (2011) found that GPS systems are particularly useful in low visibility conditions such as night paving.

Figure 11. GPS equipment on roller (Chang et al. 2011).

Figure 12. Real time display in the roller cab showing the number of roller passes and the temperature of the material being compacted (www.moba-automation.com).

2.3.2 Roller infrared sensor

The required compaction effort is dependent on the temperature of the asphalt. There are different stages in the compaction process (breakdown rolling, intermediate rolling and finishing rolling) and ideal temperatures exist for different stages of the rolling process. Temperature of the material can vary across the mat due to different factors such as paver stops, material from different trucks, weather conditions, etc. The cooling rate of the asphalt layer is very dependent on the thickness of the layer (Bijleveld 2015). As a result, surface courses, which are relevant to CONSISTEND, cool very quickly and temperature information is of increased importance. IR sensors on the roller supply the operator with visual representations of the temperature of the material being compacted – see Figure 12. If the operator is aware of the temperature at different locations on the mat they can vary their rolling strategy accordingly. The system also records the rolling temperatures for future reference. IR sensors can be fitted to one or more locations on a roller. An example is shown in Figure 13.

Figure 13. Infrared temperature sensor on a roller (Chang et al. 2011).

2.3.3 On-board measurement of compaction

Many modern rollers can be purchased (or sometimes retrofitted) with systems for measuring the level of compaction. These systems generally use accelerometers on the roller drum to measure its dynamic response during compaction. This is used to calculate the stiffness of the material and hence the degree of compaction. Other systems calculate the degree of compaction based on the rolling resistance of the material (Chang et al. 2011). Chang et al. (2015) performed detailed research to establish if these systems could be used as a substitute to traditional testing of cores taken after construction. The results concluded that the final compaction values given by these on board systems did not correlate well with core testing. It is suggested that this is likely caused by the difference in measurement depth and footprint with cores and on-board measurements. It may also be due to drum rebound changing when the asphalt temperature drops below a certain threshold (e.g. glassy temperature).

It was found that these systems do have benefits. The measurements correlated well with nuclear density gauge measurements during breakdown compaction (Chang et al. 2015) and can identifying weak spots in the support layer (Chang et al. 2011). A disadvantage of these systems, which is particularly relevant to the surface courses focused on in the Consistend project, is that vibratory rolling cannot be used for some surfaces courses (e.g. stone mastic asphalt (SMA) and porous asphalt) or for finish rolling (NRA 2015).

2.3.4 Density gauge

Nuclear density gauges are an indirect method of measuring the density of asphalt. They use a radioactive isotope to determine the density of the material examined. The denser the material the harder it will be for the radioactivity to pass through it. The gauges do not directly measure density and must be initially calibrated against cores taken from the asphalt in order to establish a relationship between the gauge reading and the true density (BS594987 2010). Nuclear density gauges are usually used following final compaction of the layer but they can be used during compaction to monitor the density of the material (Bijleveld 2015). Figure 14 shows a nuclear density gauge in use.

Figure 14. Nuclear density gauge (www.pavementinteractive.org)

Non-nuclear alternatives for measuring density also exist. Rather than using a radioactive isotope, these systems use other methods such as measuring the electrical impedance of the material or methods based on measuring dielectric properties. The advantage of these systems is that they do not contain any radioactive materials and as a result do not have any special licensing or training requirements. They are also quicker and can also allow more locations to be tested in the same time period.

2.3.5 Using a cooling model to predict optimal rolling start/stop times.

Optimal temperature ranges exist for the compaction of asphalt. However, start and stop times for rolling are generally chosen based on the experience of the roller operator. Different programmes exist which aim to predict the asphalt cooling rate in order to optimise the rolling schedule. For example, the PaveCool software (Chadbourn et al. 1998) was developed in Minnesota in the 1990s to aid in laying asphalt in adversely cool weather, which is often required due to Minnesota's climate. It outputs a cooling curve which identifies the optimal start and stop times for rolling – see Figure 15. Similar software, known as CalCool was also developed by Timm et al. (2001). As part of the ASPARi project, both PaveCool and CalCool were used and were found to be suitable for use with Dutch asphalt mixtures (Bijleveld

2015). It was found that predictions of the rate of cooling of the material help in providing roller operators with clear instructions.

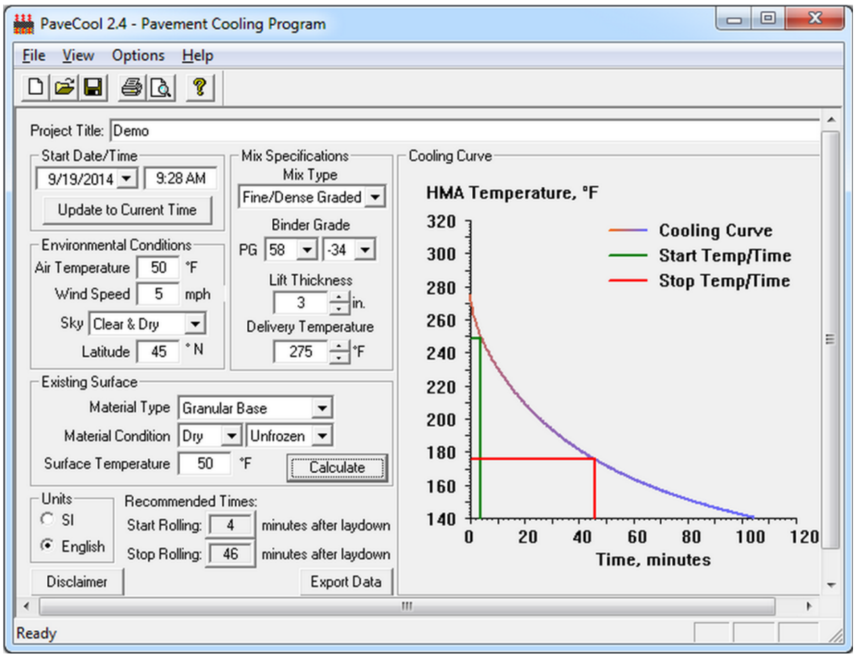

Figure 15. PaveCool program (www.dot.state.mn.us/app/pavecool/)

2.3.6 Rate of application of HRA chippings.

The rate of application of chippings is only relevant to hot rolled asphalt (HRA) and not to any of the other asphalt mixes examined. The precoated chippings are applied to the surface of the HRA using a spreader – see Figure 16(a). The rate of application of the precoated chippings can be measured by placing trays of known area in the path of the spreader and weighing the aggregate that land on the tray – see Figure 16(b). This procedure is detailed in BS 598-1:2011.

(a) HRA chippings spreader with testing trays.

(b) Weighing test tray.

Figure 16. Testing rate of application of HRA chippings.

2.4 Parameters relevant to transport, laying and compaction

2.4.1 Weather station

Weather stations can be used to record the weather during all phases of the asphalt construction process. Weather stations are used as part of the PQi-framework used in the ASPARi project (Bijleveld 2015). In that project they monitor ambient temperature, wind speed, humidity and solar radiation. The weather conditions can have a considerable impact on the rate of cooling of the asphalt and national standards generally outline acceptable weather conditions for laying asphalt, e.g. Standaard RAW bepalingen (CROW 2010) and (NRA 2015). The weather conditions can also be recorded using sensors on the paver – see Section 4.

Figure 17. Portable weather station (www.envirotech-online.com).

2.4.2 Handheld thermometer

Regular handheld thermometers or infrared handheld thermometers can be used to monitor the temperature of the material during the construction process. They can be used to monitor the temperature in the truck, in the hopper, at the screed or during and after compaction. IR thermometers will give the surface temperature whereas the probes on regular electronic thermometers can be inserted into the material to get the temperature below the surface. Examples of these thermometers are given in Figure 18.

(a) Regular thermometer

(b) IR thermometer (www.surveyorsequipment.co.uk)

Figure 18. Handheld thermometers

2.4.3 Experience of staff and on site supervision

The experience of the personnel on site is a key parameter which affects the construction process. Although it is difficult to quantify, its importance is acknowledged by BS594987 (2010) which specifies that "trained and experienced personnel" should be used. Supervision of the construction process is also recommended to ensure that best practice is being followed and to ensure that any quality control measures are being implemented correctly.

2.4.4 Quality plan

The Quality Plan is written to ensure that all the relevant data required for a contract is collected by the required people at the required time. It will specify what information needs to be recorded, by whom, when and in what format This may vary from contract to contract depending on what materials are being laid and what is specified in the contract for testing requirements. In the UK there is a basic amount of information required for a contractor to comply with the requirements of Sector Scheme 16 (NHSS 2014) which is a pre-requisite for all major and public procurement contracts.

The following information should be outlined in the Quality Plan:-

- Inspection and Test Plan
- Training and Competency requirements for all personnel
- Copies of the documents to be used
    - Laying records
    - Test reports
    - Diary sheets
    - Dip sheets
    - Permission to proceed sheet

2.4.4.1 Inspection and Test Plan (ITP)

There will be an ITP for each material which will lay out the specific testing requirements to be complied with in the contract when that material is laid

2.4.4.2 Records

2.4.4.2.1 Laying records

These should include the following:-

- Visual inspection of the material
- Temperature at delivery, laying (behind the screed) and after final rolling for each load
- Wind speed
- Air temperature
- Rain
- Chainage for load start
- Chainage for load finish
- Photographs
- Details of equipment used

2.4.4.2.2 Test Reports

These can either be internally generated or third party documents which are the results of all the testing undertaken and will vary depending on the material being used.

2.4.4.2.3 Diary Sheets

This would normally be the record of the supervisor and would contain his comments on any issues that may have arisen which could have an influence on the contract.

2.4.4.2.4 Dip sheets

This is the record that the area has been surveyed before any material is laid so that the operatives know the thickness of the material to be laid at any given location

2.4.4.2.5 Permission to Proceed

This will record the visual inspection of the area to be laid prior to surfacing to ensure that it is in a fit condition to be over laid. This will often be counter signed by the client to indicate his acceptance.

3 Reduction in Variability of Construction Parameters

The quality assessment tool which will be created as part of the CONSISTEND project will link the lifespan of surface course with variability in the construction parameters. The variability of many of the construction parameters can be reduced by using quality control methods. This section quantifies, where realistically possible, the reduction in variability that can be achieved with various quality control methods, see Table 1 – Table 4. Information on the effect of all methods is not always available and in some cases the effect has to be estimated or assumed. In all cases, the source of the information is clearly stated.

Table 1. Reduction in variability of construction parameters during transport.

Method	Reduction in Variability	Reference/Source
Insulated truck	Experience of industry experts indicates that there is very little loss of temperature with an insulated and sheeted truck. Losses are typically in the range of -5°C.	Industry experts.
Asphalt Logistics Information System (ALIS)	The improved management of asphalt supply trucks helps reduce/eliminate stops while waiting for the next truck to arrive. It should also reduce truck waiting times on site which should also improve laying temperatures. In Bijleveld (2015), all contractors concurred that it is important to organise the delivery logistics to avoid temperature differentials during laying.	ALIS website (http://www.kws.nl/nl/producten/detail/asfalt-logistiek-informatie-systeem-alis) PhD thesis from ASPARi project (Bijleveld 2015).
RFID tag on truck.	Saves time on site as details of asphalt are recorded automatically. However, no information to quantify the reduction in delays was found. Data corruption is also reduced.	Industry expert.

Table 2. Reduction in variability of construction parameters during laying.

Method	Reduction in Variability	Reference/Source
Paver with GPS and infrared temperature monitoring	Doesn't influence temperature itself but facilitates better control of temperature. No information was found to quantify the effect of monitoring temperature.	CONSISTEND conclusion
Monitor paver stops	This is a measurement technique which does not directly influence paver stops. If this knowledge is acted upon there may be an indirect influence which reduces paver stops.	n/a
Shuttle buggy	For a single field study, a Shuttle Buggy reduces the standard deviation of the temperature behind the screed from 15 °C to 5 °C. However, it	PhD thesis from ASPARi project (Bijleveld 2015).

Method	Reduction in Variability	Reference/Source
	reduces the overall temperature of the mix by 5-20 °C. Examination of IR images supplied by manufacturers would suggest that thermal segregation is eliminated. Helps enable a continuous process. Very positive for reducing segregation, inhomogeneity, stops, bumps and transverse joints.	 Equipment supplier. Bijleveld (2015) Industry experts.
Rate of application of bond coat	If calibrated metered spraying equipment is used and the rate of application tested on site then the rate of application should closely match the target value.	CONSISTEND assumption
Echelon paving	With echelon paving, longitudinal joints go from cold matched to hot matched. As such, quantifying the reduction in variability is not applicable here.	CONSISTEND Deliverable D1.1
Visual inspection - longitudinal joints	If visual inspection of joints is performed, it can ensure that joints are constructed correctly. If there is no visual inspection it cannot be assumed that joints are constructed correctly. However, no information was found to quantify the reduction in variability of joint construction when visual inspections take place.	CONSISTEND Deliverable D1.1
Visual inspection - condition of underlying layers	If visual inspection of joints is performed, it can ensure that there is no contamination of the underlying layer. However, no information was found to quantify the reduction in variability in the condition of the underlying layer when visual inspections take place.	CONSISTEND Deliverable D1.1

Table 3. Reduction in variability of construction parameters during compaction.

Method	Reduction in Variability	Reference/Source
GPS on roller	GPS measures the number of roller passes and colour coded maps show when the adequate number of passes has been achieved. Doesn't directly influence the number of passes but facilitates better control of the number of roller passes. No information was found to quantify the effect of this method on the construction parameters during compaction.	n/a
Roller infrared sensor	This is a measurement technique which does not directly influence temperature. If this knowledge is acted upon there may be an indirect influence on temperature of the material. No information was found to quantify the effect of this method on the construction parameters during compaction.	n/a
Using a cooling model to predict optimal rolling start/stop times	Doesn't directly influence temperature itself but facilitates compaction at the most appropriate temperature. No information was found to show the variability in construction parameters when this method is used.	CONSISTEND assumptions
Density gauge	This method can be used during compaction. No information was found to show the variability in the construction parameters when this method is used.	PhD thesis from ASPARi project (Bijleveld 2015).
Rate of application of HRA chippings	No information was found to show the variability in the rate of spread when this method is used.	n/a
On-board measurement of compaction	No information was found to show the variability in the final void content when this method is used.	n/a

Table 4. Reduction in variability of construction parameters during transport, laying and compaction.

Method	Reduction in Variability	Reference/Source
Weather station	Provides accurate weather information which can be used to determine if the conditions are appropriate for laying. As such it reduces the risk of laying in adverse weather conditions. No info was found to quantify the variability of the construction parameters when using this method.	Industry expert.
Handheld thermometer	Handheld thermometers which can be inserted into the asphalt give more accurate measurements of the temperature at the centre of the asphalt layer than IR thermometers which give the surface temperature. The surface temperature can be significantly lower depending on the weather conditions. Measuring temperature has no direct influence on the construction parameters. No information was found to show the variability in construction parameters when temperature is monitored. Compaction should occur at the correct temperature if temperature is being monitored.	Industry expert. CONSISTEND assumption CONSISTEND assumption
Recording details of laying in quality plan	Doesn't directly influence the variability in construction parameters but has an indirect effect as helps implement measures that do. No information was found which can quantify the variability of the construction parameters when a quality plan is used.	CONSISTEND assumption
Experience of staff and on site supervision	No information was found to quantify the variability of the construction parameters when experienced staff or site supervision are used.	n/a

4 Energy Efficiency and Cost

To implement a new quality control measure, additional energy and cost is required. Costs may be in the form of additional staff, acquiring new equipment, fuel costs, etc. With the carbon emissions associated with road construction becoming increasingly relevant, the carbon cost of any new methods must also be considered. This section aims to quantify some of these costs – see Table 5 - Table 8. For many of the methods, information is not readily available and estimates have to be made. In each case, the source of the information is clearly stated for the reader.

Table 5. Energy Efficiency and Cost of QC methods used during transport.

Method	Energy Efficiency and Cost	Reference/Source
Insulated truck	Increases energy efficiency as reduces heat loss during transport. Insulated trucks are used as standard practice so no additional investment is required.	CONSISTEND assumption
Asphalt Logistics Information System (ALIS)	Can increase energy efficiency by reducing the amount of downtime of the paver and reducing wasted material. Operating energy is minimal.	System supplier CONSISTEND assumption
RFID tag on truck.	Although the tags themselves are relatively low cost, the software required for data management can be expensive, in the range of \$50,000 - \$100,000 US dollars. It should be noted that the cost of this software may have changed since this information was published in 2004.	O'Connor (2004)

Table 6. Energy Efficiency and Cost of QC methods used during laying.

Method	Energy Efficiency and Cost	Reference/Source
Paver with GPS and infrared temperature monitoring	Equipment supplier indicated that a system consisting of GPS, IR linescanner, weather sensor, paver stop recording and data acquisition system costs in the region of €35,000. IR cameras and line scanners are about the same price and 3-5 times more than handheld IR. Minimal operating energy relative to paver fuel costs. These systems can save energy if they reduce abortive work and/or help pavement last longer. There is additional set up time associated with these systems which may delay the construction	Equipment supplier Huerne et al. (2009) CONSISTEND assumption Industry expert. CONSISTEND assumption

Method	Energy Efficiency and Cost	Reference/Source
	and/or require additional staff. Once the system is mounted on a paver there is practically no additional time needed for data acquisition. However, data analysis needs some time and a trained engineer.	Industry expert.
Monitor paver stops	Equipment supplier indicated that a system consisting of GPS, IR linescanner, weather sensor and data acquisition system costs in the region of €35,000. Minimal operating energy relative to paver fuel costs. These systems can save energy if they reduce abortive work and/or help pavement last longer. There is additional set up time associated with these systems which may delay the construction and/or require additional staff.	Equipment supplier CONSISTEND assumption Industry expert. CONSISTEND assumption
Shuttle buggy	Shuttle buggies are powered by a 224kW diesel engine. The estimated cost of buying a new shuttle buggy is in the region of €300,000 with second hand available for <€100,000. Can save energy by making the construction process more efficient and by helping to construct pavements which last longer. An additional driver is required to operate the shuttle buggy.	Manufacturer (https://www.roadtec.com/images/uploads/productdocs/SB-2500e%3Aex.pdf) Online search of shuttle buggies for sale. Manufacturer and industry expert. CONSISTEND assumption
Rate of application of bond coat	Testing the rate of application does not require expensive equipment but additional staff/time may be required to perform the tests.	CONSISTEND assumption
Echelon paving	This may save energy as additional preparation of cold joints is not required. Although the gross energy required is similar, twice as much equipment, workers and mill capacity are	CONSISTEND assumption CONSISTEND assumption

Method	Energy Efficiency and Cost	Reference/Source
	required. Can save energy in the long term by constructing pavements which last longer.	 Industry expert.
Visual inspection - joints	Costs are associated with having staff on site to inspect joints. Additional energy associated with performing this task is minimal. Can save energy in the long term by constructing pavements which last longer.	CONSISTEND assumption CONSISTEND assumption CONSISTEND assumption
Visual inspection - condition of underlying layers	Same as above	Same as above
Layer thickness measurements	Same as above	Same as above

Table 7. Energy Efficiency and Cost of QC methods used during compaction.

Method	Energy Efficiency and Cost	Reference/Source
GPS on roller	Minimal operating energy. Can reduce energy by making roller movements more efficient. Equipment supplier indicated that a system consisting of GPS, IR sensor and data acquisition system costs in the region of €11,000.	CONSISTEND assumption Equipment supplier. Equipment supplier.
Roller infrared sensor	Minimal operating energy. Equipment supplier indicated that a system consisting of GPS, IR sensor and data acquisition system costs in the region of €11,000. IR temperature data helps operator compact during the correct temperature range when compaction can be performed more efficiently. This may avoid the need for additional roller passes.	CONSISTEND assumption Equipment supplier. CONSISTEND assumption

Method	Energy Efficiency and Cost	Reference/Source
Using a cooling model to predict optimal rolling start/stop times	Software for generating a cooling model is available online for free download. Minimal energy required. There will be some staff costs associated with preparing the model. May save energy by enabling more efficient use of rollers. Can save energy in the long term by constructing adequately compacted pavements which last longer.	(*http://www.dot.state.mn.us/app/pavecool/*) CONSISTEND assumption CONSISTEND assumption CONSISTEND assumption CONSISTEND assumption
Density gauge	The costs associated with these systems were estimated by an industry expert as: Purchase costs ≈ €15 000; Providing appropriate storage equipment ≈ € 5000; Training/refresher course costs for 1 day per employee per 3 years ≈ € 1500; Within the company, at least one person must have had ionizing radiation training ≈ € 5000; Cost associated with maintenance and calibration per unit per year ≈ € 3000; Some authorities do not allow their use due to the associated risks.	Industry expert Industry expert
Rate of application of HRA chippings	Testing the rate of application does not require expensive equipment but additional staff may be required to perform the tests.	CONSISTEND assumption
On-board measurement of compaction	Information on cost of this equipment was not found. Can save energy in the long term by constructing adequately compacted pavements which last longer.	CONSISTEND assumption

Table 8. Energy Efficiency and Cost of QC methods used during transport, laying and compaction.

Method	Energy Efficiency and Cost	Reference/Source
Weather station	Online research suggests that fully portable weather stations can be purchased for less than €1,000. Combined handheld anemometer and thermometer can be purchased for less than €100. If it eliminates pavement construction during adverse weather conditions then the pavement lifetime may be increased which results in increased energy efficiency and maintenance cost savings. Minimal operating energy. Staff costs associated with set up and monitoring of weather conditions.	Online search of thermometers for sale. CONSISTEND assumption CONSISTEND assumption CONSISTEND assumption
Handheld thermometer	Both normal and IR thermometers are low cost (< €200).	Online search of thermometers for sale
Recording details of laying in quality plan	There are staff costs associated with preparing a quality plan. It would normally take 4 or 5 days to put together a quality plan and possibly more for larger contracts. Once the contract is running, personnel time is needed check for compliance on site and to collate the paperwork generated and to submit it the client. Any Non Conformance Reports need to addressed and corrective action agreed with the client. Depending on the size of the contract this may be in the region of 2 -5 days per week. The contract and laying crews should also be audited internally at least once per year which may take approximately 5 man days	Industry expert
Experience of staff and on site supervision	Although experienced workers are generally more expensive, they may be more efficient. If experience of staff or on site supervision results in improved construction quality, then the pavement lifetime may be increased which results in increased energy efficiency and maintenance cost savings.	CONSISTEND assumption CONSISTEND assumption

5 Applicability in Practice

Some quality control methods are also more commonly used than others or have been on the market for longer. There is less risk associated with using a well established method that is commonly available. Additionally, not all quality control methods are applicable in all circumstances. This should be kept in mind when specifying these methods. The applicability of these methods can depend on factors such as:

- Available space
- Budget
- Scale of job (set up time compared with paving time)
- Location: manmade or natural structure which might affect GPS signals.

Roads authorities who have not used these methods before are reluctant to implement new advanced quality control on small scale projects. Road authorities are more likely to start using these methods on a major project.

Table 9 - Table 12 provide information on how applicable each quality control method is in practice. As with the previous sections, the source of all information is clearly stated.

Table 9. Applicability in Practice of QC methods used during transport.

Method	Applicability in Practice	Reference/Source
Insulated truck	Very applicable in all circumstances.	CONSISTEND assumption
Asphalt Logistics Information System (ALIS)	Requires a mobile internet connection to operate the application.	CONSISTEND assumption
RFID tag on truck.	No information on its applicability in different circumstances was found.	n/a

Table 10. Applicability in Practice of QC methods used during laying.

Method	Applicability in Practice	Reference/Source
Paver with GPS and infrared temperature monitoring	IR linescanner seem to be more widely used than IR cameras. They are easier to implement with respect to data processing for visualisation. IR cameras can be used as an alternative but they are not as easily implemented. Transport Infrastructure Ireland indicated that these systems are not being used in Ireland and are unlikely to be used in the near future due to the scale of current paving jobs. MOBA indicated that there is some set up time with the paver system which means it may not always be suitable for small jobs.	Huerne et al. (2009) National roads authority Equipment supplier

Method	Applicability in Practice	Reference/Source
	IR gives surface temperature which can be very different to the temperature at the centre of the asphalt layer. GPS signal can be affected by manmade or natural structures. Although on site base stations are not required, they can improve GPS signal. GPS systems cannot be used in tunnels.	Industry expert Chang et al. (2011)
Monitor paver stops	As these systems are generally linked to the paver GPS systems mentioned above, the same issues are likely.	CONSISTEND assumption
Shuttle buggy	The shuttle buggy often runs on the free lane adjacent to the one being paved. This requires this lane to be free of traffic. However, it can run on the lane being paved. The shuttle buggy can mix different truck loads making it difficult to track where each load of material is laid on the road.	Industry expert. Schwartz et al. (2014)
Rate of application of bond coat	No information on the applicability in practice of this method was found.	n/a
Echelon paving	Will not be possible if road is still open and paving one lane with traffic on the other. If it is an overlay job, it requires the whole road to be closed. This is not a problem with new roads.	Industry expert
Visual - joints	Additional staff required to perform visual inspections.	CONSISTEND assumption
Visual inspection - condition of underlying layers	Additional staff required to perform visual inspections.	CONSISTEND assumption
Visual inspection - layer thickness	Additional staff required to perform visual inspections.	CONSISTEND assumption

Table 11. Applicability in Practice of QC methods used during compaction.

Method	Applicability in Practice	Reference/Source
GPS and Infrared on roller	Validation of GPS prior to commencement of construction is critical to ensure measurements are consistent.	Chang et al. (2015)
	GPS signal can be blocked by "shadows" caused by objects such as trees or overpasses. Options exist to make GPS reception more reliable. Onsite GSP base stations, virtual reference stations (VRS) and internet-based correction signals can be used to help ensure high precision positioning. Alternatively, laser-based methods (Total Station) can supplement the positioning measurements.GPS cannot be used in tunnels.	(Chang et al. 2015; Chang et al. 2011)
	Systems which are not factory installed should be fitted to the roller at least one day in advance of construction. A trial run should be performed and data storage and transfer checked as well quality checks of the data performed.	Chang et al. (2015)
	It is recommended that all data should be transferred from the system and saved on a daily basis.	Chang et al. (2015)
	All GPS devices on site should be checked to ensure that they are using the same GPS coordinate system.	Chang et al. (2015)
	Offset between the GPS antenna and the front drum must be inputted and verified.	Chang et al. (2011)
	MOBA indicated that set up time is short so it is appropriate for small as well as large jobs.	Equipment supplier
	The MOBA system does not require a base station.	Equipment supplier
Roller infrared sensor	The IR sensors will give the surface temperature which can be very different to the temperature at the centre of the asphalt layer, which is the most relevant temperature for compaction. The roller operator then has to guess the temperature at the centre based on the surface temperature reading which is quite difficult.	Huerne et al. (2009)
Using a cooling model	It can be difficult to accurately predict the rate of cooling in advance as the exact layer thickness	PhD thesis from ASPARi project

Method	Applicability in Practice	Reference/Source
to predict optimal rolling start/stop times	and weather conditions are not known. Wind speed and solar radiation significantly affect the cooling rate.	(Bijleveld 2015).
Density gauge	Nuclear density gauges contain radioactive material and as a result operators need radioactive materials license, special training and special storage arrangements must be made. Non-nuclear density gauges can collect more data than nuclear density gauges in the same time period. However, more non-nuclear density gauges may need more samples to achieve a similar level of confidence in the results. Non-nuclear density gauges have been found to consistently read lower than the nuclear density gauges. Non-nuclear gauges have significantly less battery life than nuclear gauges. The study conducted by Schmitt et al (2006) found that non-nuclear density gauges were best calibrated with nuclear density gauges. If this approach is used, the advantages of removing nuclear density gauges from site would not be realised. Some authorities do not allow the use of nuclear density gauges due to the associated risks. An impractical case is required for transport.	Schmitt et al. (2006) Schmitt et al. (2006) Schmitt et al. (2006) Schmitt et al. (2006) Schmitt et al. (2006) Industry expert Industry expert
Rate of application of HRA chippings	No information on the applicability in practice of this method was found.	n/a
On-board measurement of compaction	On-board measurement of compaction has been found to correlate well with nuclear density gauge readings during breakdown compaction. However, they do not correlate as well with core densities. As a result, on-board measurement is not recommended as a replacement to using cores for acceptance. Most on-board systems which measure compaction require the roller to be operating in vibratory mode but a vibrating roller cannot be used for finish rolling or for some types of surface courses, e.g. SMA and porous asphalt.	Chang et al. (2015) (Chang et al. 2011; NRA 2015)

Table 12. Applicability in Practice of QC methods used during transport, laying and compaction.

Method	Applicability in Practice	Reference/Source
Weather station	Handheld anemometers, rather than full weather stations, are often used to measure wind speed.	CONSISTEND assumption
Handheld thermometer	IR thermometers can be quicker and easier to use but they give the surface temperature, which can be significantly different to the temperature at the centre of the asphalt layer depending on the weather conditions. When using an IR thermometer, BS 598-1:2011 recommends, where possible, to remove 50 – 100 mm from the surface of the material and immediately taking the temperature.	Industry expert BS598-1 (2011)
Recording details of laying in quality plan	Technician is required for every paving machine to record all the temperatures.	Industry expert
Experience of staff and on site supervision	Regular Toolbox talks should be given and attendees recorded.	Industry expert

6 Quality Control Methods Under Development

During the literature study, a number of methods were found which are currently being tested or are under development. These methods are not currently commercially available and “ready to use” but are mentioned here as they may become more prevalent in the future.

Some of the methods were part of a German project titled “Process secure automated road construction”. The project examined the paving process and identified weak spots (Lipke & Ripke 2011). Segregation of aggregate was identified as one of the weak spots. Vibration-dampening systems have been developed for the trucks during transport. They consist of a mass-spring system which is installed on the chassis of the truck. Results of the effectiveness of the system are not given in the paper.

The study also looks at segregation within the paver. As the material is being moved laterally by the auger within the paver, the aggregate can become segregated. This segregation was significantly reduced by installing a half-shell shaped transport channel around the auger.

Passive transponders which measure temperature were also installed within the asphalt layer to help facilitate compaction at the appropriate temperature. These sensors can be more beneficial than IR sensors as they provide the temperature at the centre of the asphalt layer rather than the surface temperature. These sensors can provide the roller operator with an in-cab display of the temperature. Another advantage of the passive transponders which are buried in the asphalt layer is that they have a long service life and can be used throughout the lifespan of the pavement (Lipke & Ripke 2011). This is useful in cold weather to trigger alerts when the road temperature drops below a certain level and in prolonged hot weather when lanes could be closed to prolong the service life of the road.

Low cost expendable RFID tags were also examined in a FHWA research project in the United States (Schwartz et al. 2014). The technology was used to track the spatial location of truckloads of hot mix asphalt. A high survivability rate (60-80%) was found based on RFID tags added to the asphalt at different stages of the construction process. It was concluded that the concept was commercially viable. Thermally sensitive RFID technology was also investigated in the study to monitor the cooling rate of the material during compaction. Although this showed potential, it was found that it required further refinement before it becomes commercially viable. A Transport Research Laboratory report (Cook & Crabb 2014) also examined RFID tags added to the material at the asphalt plant would survive the mechanical and thermal damage that they would be subjected to. It was found that 60% of the tags were readable after compaction on site was completed.

It should be noted that the technologies discussed in this section were only found to be used as part of research projects and so may not be ready for widespread commercial application. As such they are not discussed further in this report.

7 Outputs for CONSISTEND Service Life Model

Based on the information gathered in this deliverable, a sample of possible inputs for the service life model is proposed. This form of inputs can be used to calibrate the quality assessment tool (Deliverable D2.1) which will calculate the effect of quality control methods on the service life of the pavement. The work on the model is still in progress and further refinement of these values will be provided in Deliverable D2.1 along with the actual values used.

Only the construction parameters which are examined as part of the questionnaire in Deliverable D1.1 and which are considered in the quality assessment tool (Deliverable D2.1) are examined here. Other construction parameters and quality control methods which were discussed previously in this deliverable and which are beyond the scope of the tool are not considered here.

Some methods directly affect the construction parameters (temperature, compaction, etc) while other methods measure, but do not directly influence, the construction parameters. The effect of both types of methods is presented in the subsequent tables. For each quality control method, the bandwidth associated with its variability is quantified. The bandwidth is presented in terms of '±'. These figures represent the 5^{th} and 95^{th} percentile lower and upper bounds. The bandwidth gives values from the two different perspectives for which the tool can be used. The bandwidth reflects either the assumed value (in the design or pre-construction phase of a project) or the measured value (after completion of the pavement).

Information on variability was not always available in the literature or from the industry experts and as a result some assumptions had to be made based on engineering judgement. However, the source of all information is clearly stated in the tables.

7.1 Temperature of material

Table 13. Effect of quality control methods on the temperature of the material during transport.

Method	Bandwidth	Reference/Source
No insulation on truck	● warm weather conditions; reduction of target temperature / mean measured value of up to 30 °C ● cold weather conditions; reduction of target temperature / mean measured value of up to 60 °C	Consistend Assumption
Insulated truck	● warm weather conditions; reduction of target temperature / mean measured value of up to 10 °C ● standard weather conditions; reduction target temperature / mean measured value of up to 20 °C ● cold outside conditions; reduction of target temperature / mean measured value of up to 30 °C ● very cold weather conditions; reduction of target temperature / mean value of measurements of up to 40 °C	Consistend Assumption

Table 14. Effect of quality control methods on temperature variability during laying and compaction.

Method	Bandwidth[1]	Reference/Source
No method	● warm weather conditions; target / mean measured temperature ± 30 °C ● standard weather conditions; target / mean measured temperature ± 50 °C ● cold weather conditions; target / mean measured temperature ± 70 °C	● Temperature can vary by up to 90 °C between first and last roller pass temperature (Bijleveld 2015). ● Questionnaire results in Deliverable D1.1 suggest that the temperature for HRA ranges from 100 - 190 °C during laying and 80 – 190 °C during compaction.
ALIS - Asphalt Logistics Information System	● warm weather conditions; target / mean measured temperature ± 10 °C. ● standard weather conditions; target / mean measured temperature ± 20°C ● cold weather conditions; target / mean measured temperature ± 30°C	Consistend Assumption

Method	Bandwidth[1]	Reference/Source
Shuttle buggy	● warm weather conditions; target / mean measured temperature ± 10 °C. ● standard weather conditions; target / mean measured temperature ± 20 °C ● cold weather conditions; target / mean measured temperature ± 30 °C	For a single field study by (Bijleveld 2015), a Shuttle Buggy reduces the standard deviation of the temperature behind the screed from 15 °C to 5 °C. However, it reduces the overall temperature of the mix by 5-20 °C. 5 °C standard deviation value corresponds to ± 8.2 °C.
Roller with IR	No influence on temperature	Consistend assumption. (No direct effect. Likely be rolled at correct temperature if temperature of the mat is being monitored.)

[1] Consistend assumption is that the distributions in this table should be asymmetrical with a smaller bandwidth for temperatures above the target or measured temperature (for example +30°C /-60°C). As only normal and lognormal distributions are applied in the current version of the CONSISTEND tool, this bandwidth is taken to be symmetrical.

Table 15. Accuracy of methods which measure the temperature of the material.

Method	Bandwidth	Reference/Source
No method	Target / mean measured (human estimate) temperature ± 50 °C	Consistend Assumption
Point measurement of temperature	● best achievable considering optimal conditions; target / mean measured temperature ±15°C ● normal practise; target / mean measured temperature ± 25°C ● difficult conditions; target / mean measured temperature ±35°C ● min achievable considering very extreme conditions; target / mean measured temperature ± 50°C	Consistend Assumption
Handheld IR Camera	● max achievable considering optimal conditions; target / mean measured temperature ±15°C ● normal practise; target / mean measured temperature ± 25°C ● difficult conditions; target / mean measured temperature ±35°C ● min achievable considering very extreme conditions; target / mean measured temperature ± 50°C	Consistend Assumption
Paver IR&GPS	● very low thermal segregation; target / mean measured temperature ±5°C ● low thermal segregation;	Consistend Assumption

Method	Bandwidth	Reference/Source
	target / mean measured temperature ± 10°C ● medium thermal segregation; target / mean measured temperature ±15°C ● large thermal segregation; target / mean measured temperature ±20°C ● very large thermal segregation; target / mean measured temperature ±25°C ● extremely large thermal segregation; target / mean measured temperature ±30°C	

7.2 Weather

Table 16. Accuracy associated with different temperature measurement methods.

Method	Bandwidth	Reference/Source
No data (Assumption) or Very bad conditions (Measurement)	Temp: Estimated temperature / mean value of measurements ± 10 °C Wind: Estimated wind speed / mean value of measurements ± 20 km/h	Consistend assumption
Based on forecasts given at an earlier time (Assumption) or Moderate conditions (Measurement)	Temp: Estimated temperature / mean value of measurements ± 7 °C Wind: Estimated wind speed / mean value of measurements ± 15 km/h	●The UK Met Office indicates that about 90% of 1-day temperature forecasts are accurate to ± 2 °C. However, this may not be allowing for temperature variations due to the site elevation etc. (*http://www.metoffice.gov.uk/about-us/who/accuracy/forecasts*). ● For 12-hour forecasts, a UK Met Office report would suggest that for predictions of wind speed, the standard deviation of the accuracy will be about 2.5m/s (9km/hr) (*http://www.hse.gov.uk/research/othpdf/400-499/oth483.pdf*). However, this report was prepared for oil rigs so it is likely that it is not allowing for the local geographical location of the asphalt site.
Current reading for area from national meteorological organisation (Assumption)	Temp: Estimated temperature / mean value of measurements ± 5 °C Wind: Estimated wind speed / mean value of measurements ± 10	Consistend assumption.

Method	Bandwidth	Reference/Source
or Good conditions (Measurement)	km/h	
On-site weather station (Assumption) or Optimal conditions (Measurement)	Temp: Estimated temperature / mean value of measurements ± 3 °C Wind: Estimated wind speed / mean value of measurements ± 5 km/h	Consistend assumption.

7.3 Compaction

Table 17. The effect of different compaction quality control methods on variability of void content.

Method	Bandwidth	Reference/Source
Standard Roller	● best achievable compaction; target void content / mean value of measurements ± 1.0% ● standard compaction; target void content / mean value of measurements ± 2.0% ● non uniform compaction; target void content / mean value of measurements ± 3.5% ● very non uniform compaction; target void content / mean value of measurements ± 4.5%	Questionnaire results in Deliverable D1.1 suggest that the void content is in the range of 1 - 8% for HRA.
Roller with GPS	● best achievable compaction; target void content / mean value of measurements ± 1.5% ● standard compaction; target void content / mean value of measurements ± 2.5% ● non uniform compaction; target void content / mean value of measurements ± 3.5%	Consistend assumption.
Roller with IR sensor and GPS	● max achievable compaction; target void content / mean value of measurements ± 1.0% ● standard compaction (minus); target void content / mean	Consistend assumption.

Method	Bandwidth	Reference/Source
	value of measurements ± 1.5% ● standard compaction (plus); target void content / mean value of measurements ± 2.0% ● non uniform compaction; target void content / mean value of measurements ± 3.5%	

Table 18. The effect of different compaction quality control methods on variability of roller passes.

Method	Bandwidth	Reference/Source
Standard roller	Standard deviation = 4 roller passes	Standard deviation of 2-3 roller passes is measured by Bijleveld (2015). This give a standard deviation of 2.5 roller passes which corresponds to a bandwidth of 4.1 roller passes.
Roller with GPS	● max achievable / best practice; target value / mean value of measurements ± 0 roller passes ● standard; target value / mean value of measurements ± 1 roller passes ● min achievable / poor practice; target value / mean value of measurements ± 4 roller passes	Consistend assumption.

7.4 Equipment

For the methods concerning the ‘equipment’ construction parameter, the variability is related to the percentage of all equipment used. Information on the use of the different methods is required to select the most used method. The use of this most used method can be expressed as a percentage of the total use of equipment.

With these pre-defined descriptions of methods and their bandwidth, the methods are represented by numbers. The optimal method is represented by ‘1’ and the least favourable method is represented by ‘3’. The bandwidths are chosen relative to the delta between these values (a value of 1).

Table 19. The variability in lifespan associated with different equipment considered.

Transport		
Method	**Bandwidth**	**Reference/Source**
Truck without insulation / Thermal insulation/ Temperature conditioned	In the model developed in D2.1, the three methods are represented by numbers (1 = truck without insulation; 2 = thermal insulation; 3 = temperature conditioned). The variability is related to the percentage of all equipment used that meets this method. The variability is expressed as a number, relative to the numbering of the methods.	Consistend assumption.
Laying		
Method	**Bandwidth**	**Reference/Source**
Normal paver / Paver with IR and GPS: Full stops of more than 60 minutes/ Paver with IR and GPS: Full stops of more than 30 minutes/ Paver with IR and GPS: Full stops of more than 15 minutes/ Paver with IR and GPS: Full stops of more than 5 minutes/ Paver with IR and GPS: Full stops of more than 2 minutes	In the model developed in D2.1, the three methods are represented by numbers (0 = no vibratory screed; 1 = normal paver or data on paver stops or paver with IR and GPS, no full stops of more than 60 minutes; 2 = or paver with IR and GPS, no full stops of more than 30 minutes; 3 = or paver with IR and GPS, no full stops of more than 15 minutes; 4 = or paver with IR and GPS, no full stops of more than 5 minutes; 5 = or paver with IR and GPS, no full stops of more than 2 minutes). The variability is related to the percentage of all equipment used that meets this method. The variability is expressed as a number, relative to the numbering of the methods.	Consistend assumption.
Compaction		
Method	**Bandwidth**	**Reference/Source**
Lightweight roller or inappropriate	In the model developed in D2.1, the three methods are represented by numbers (1 =	Consistend assumption.

compaction/ Commonly used roller and OK compaction/ Roller IR and GPS and OK compaction	lightweight roller; 2 = commonly used roller and OK compaction; 3 = roller IR and GPS and OK compaction). The variability is related to the percentage of all equipment used that meets this method. The variability is expressed as a number, relative to the numbering of the methods.	

7.5 Workmanship

For the methods concerning the construction parameter 'workmanship', the variability is related to the percentage of all workers involved that meet the selected method (comparable to 'equipment'). For example, if all workers involved during compaction are experienced, the user of the tool developed in D2.1 will select 'experienced workers' and indicate that 100% off all workers are experienced. This results in a variability of 0.1 (which is a number).

Table 20. The variability in lifespan associated with different levels of workmanship.

Transport		
Method	**Bandwidth**	**Reference/Source**
n/a	n/a	Consistend assumption that workmanship during transport has no effect on lifespan of the material.
Laying and Compaction		
Method	**Bandwidth**	**Reference/Source**
Inexperienced workers/ Trained workers/ Experienced workers	In the model developed in D2.1, the three methods are represented by numbers (1 = inexperienced workers; 2 = trained workers; 3 = experienced workers). The variability is related to the percentage of all workers involved during transport/laying or compaction that meet this method. The variability is expressed as a number, relative to the numbering of the methods.	Consistend assumption.

7.6 Travel time and delays

Table 21. The effect of different methods on delays.

Transport		
Method	**Bandwidth**	**Reference/Source**
Standard procedures	● max achievable / standard; target travel time / mean value of travel time ± 50% ● min achievable; target travel time / mean value of travel time ± 100%	Consistend assumption.
ALIS - or similar GPS type tracking and management	● max achievable; target travel time / mean value of travel time ± 25% of expected travel time. ● standard; target travel time /mean value of travel time ± 50% ● min achievable; target travel time / mean value of travel time ± 100%	Consistend assumption.
Laying		
Method	**Bandwidth**	**Reference/Source**
Standard procedures	● max achievable / standard; target laying time / mean value of laying time ± 50% ● min achievable; target laying time / mean value of laying time ± 100%	Consistend assumption.
ALIS - or similar GPS type tracking and management	● max achievable; target laying time / mean value of laying time s ± 10% ● standard; target laying time / mean value of laying time ± 30% ● min achievable; target laying time / mean value of laying time ± 100%	Consistend assumption.
Compaction		
Method	**Bandwidth**	**Reference/Source**
Standard procedures	● max achievable / standard; target compaction time / mean value of laying time ± 50% ● min achievable; target compaction time / mean value of laying time ±100%	Consistend assumption.
Shuttle buggy	● max achievable; target compaction time / mean value of laying time ± 10% ● standard; target compaction time /	Consistend assumption.

	mean value of laying time ± 30% ● min achievable; target compaction time / mean value of laying time ± 100%	
ALIS - or similar GPS type tracking and management	● max achievable; target compaction time / mean value of laying time ± 5% ● standard; target compaction time / mean value of laying time ± 20% ● min achievable; target compaction time / mean value of laying time ± 100%	Consistend assumption.

7.7 Joints

For the methods concerning the construction parameter 'joints', the variability is related to the percentage of all joints that meet the selected method (comparable to 'equipment'). For example, if all joint are made using echelon paving, the user of the tool developed in D2.1 will select 'echelon paving' and indicate that 100% off all joints are made using echelon paving. This results in a variability of 0.1 (which is a number).

Table 22. The variability in lifespan associated with different types of joint construction.

Method	Bandwidth	Reference/Source
Cold and unpainted / Cold trimmed and painted / Echelon paving	In the model developed in D2.1, the three methods are represented by numbers (1 = cold and unpainted; 2 = cold trimmed and painted; 3 = echelon paving). The variability is related to the percentage of all joints that meet this method. The variability is expressed as a number, relative to the numbering of the methods.	Consistend assumption.

Table 23. The variability in lifespan associated with different numbers of longitudinal joints.

Method	Bandwidth	Reference/Source
0/ 1/ 2	In the model developed in D2.1, the three methods are represented by numbers (1 = two joints; 2 = one joint; 3 = zero joints). The variability is related to the percentage of all joints that meet this method. The variability is	Consistend assumption.

Method	Bandwidth	Reference/Source
	expressed as a number, relative to the numbering of the methods.	

7.8 Interlayer bond

Table 24. The effect of bond coat quality control on the interlayer bond.

Method	Bandwidth	Reference/Source
No quality control	Target rate of application ± 50%	Consistend assumption.
Test rate of application	● max achievable / best practice; target rate of application/ mean value of measured rate ± 10% ● standard; target rate of application/ mean value of measured rate ± 20% ● min achievable / unclean surface; target rate of application / mean value of measured rate ± 50%	Consistend assumption.

8 Conclusions

This report identifies ready to use quality control methods which can be used in the construction of asphalt surface course. The information on the effect of quality control methods on the construction parameters will be used in CONSISTEND Deliverable D2.1 as input to the model which will estimate the service life of the pavement.

Methods that can be used during the transport, laying and compaction of the material are discussed. Each method is examined in terms of energy, cost, applicability in practice, and reduction in the variability of the construction parameters. A literature review as well as consultation with NRAs and industry experts was used to find the required information. The ASPARi project, and in particular the project results presented in a PhD Thesis by Bijleveld (2015), was a very useful source of information. The research conducted by Chang et al. (2015; 2011) was also a valuable source of information on intelligent compaction. In many cases, however, the required information on the influence, applicability, cost, etc. was not available. This is particularly understandable in the case of the influence of the method on the construction parameters as it is difficult to quantify the affect of a method on these parameters especially for measurement methods which do not directly influence the construction parameters. In this case, there may be indirect effects but they are particularly difficult to quantify.

It was found that two types of quality control systems exist. The first group measures the construction parameters (temperature, compaction, location, etc) but does not directly influence any of the parameters. These methods generally aim to provide extensive real time information to equipment operators while also allowing a permanent record of the construction parameters to be kept. These measuring methods require further action to be taken based on the measurements in order to influence the quality and hence the service life of the pavement. As a result, it is difficult to quantify how these methods are influencing the construction parameters. However, the service life model (Deliverable D2.1) requires the construction parameters to be inputted and these measurement methods do provide increased confidence that the values inputted are correct.

The second group of methods directly physically influences the construction parameters (temperature, joints, etc.). The effect of these methods on the construction parameters, and hence the service life, is easier to quantify and more information is available.

It is found that the temperature is the focus of many of the quality control methods. The aim is to ensure that the material stays in the appropriate temperature range throughout the transport, laying and compaction phases. Compacting the material in the appropriate temperature range increases the likelihood of the material being compacted correctly and increases the service life of the pavement.

The information gathered in this deliverable is used to demonstrate an example of how it might be used as input for the quality assessment tool (Deliverable D2.1). The final inputs for the tool cannot be provided yet as work is still underway on Deliverable D2.1. The agreed final parameters will be presented in that deliverable.

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