Towards Intelligent Compaction

Matthias Limbach (MOBA Mobile Automation AG)

Intelligent compaction is one of the new buzzwords in the construction industry lately and a number of new intelligent compaction systems have entered the market. This article highlights and reviews the common technologies (pass counting, temperature measurement and stiffness measurement) used in these systems. Potential improvements are indicated, followed by an outlook towards roller-to-roller communication as a likely new feature for intelligent compaction systems. If error preventing mechanisms, as in quality assurance systems, provide a measure for intelligence, it is concluded that the currently available systems are not considered intelligent yet but they moving towards it.

Introduction

Europe currently has a road network length of around 5,000,000 km. On average a road needs to be repaired every 10 years, which sums up to 500,000 km each year. If quality measures within road construction would prolong this period for just one year, the average kilometers to repair each year would reduce to around 454,000 km. Based on the minimum costs to repair a road of 100,000 €/km, this means a potential saving of 4.5 Bill € per year [1]. Understandably this might be one of the reasons why in times of tight public budgets road agency are focusing on quality improving systems for road constructions. For example, the U.S. Federal Highway Administration (FHWA) launched an initiative *Every Day Counts* in 2012, which promotes quality improvements for road construction [2] and the European Union funded the ASPHALT[1] research project, which analyzed the complete supply chain for the road build-in process [3].

As part of the road construction process the compaction work of rollers has kindled research interest in the last decade (e.g. [4]–[6]). However there has been research as early as 1967 indicating that an improvement in compaction practice is necessary to increase road quality [7]. The emergence of powerful computers on construction machines made companies revisit these processes and research, for example [8], [9]. These systems are summarized under the term *intelligent compaction systems* (IC systems). At this stage this term summaries a number of different systems with different aims and different technologies. Within the area of hot mix asphalt (HMA) all systems aim to help the roller operator to compact the asphalt optimally.

There are several ways to express optimal compaction, however, a common expression is that the asphalt is compacted in such a way that 4% to 8% air voids remain within the asphalt [1].

Most IC systems in the market now use some or all of the following devices [9]–[13]:

- A global navigation satellite system (GNSS) receiver for position tracking;
- one or more temperature sensors;
- an accelerometer for “stiffness” measurement;
- an onboard computer to show current compaction values to the operator as well as storing and transferring collected data about the compaction process; and
- automatic control of the drum based on compaction values.

The onboard computers often use some form of operating system like Windows or Linux. Even though the user interfaces differ quite significantly, the computers themselves are quite similar. The methods for transferring the collected data from the

[1] Advanced galileo navigation System for asPHALt fleeT machines

jobsite are also similar and use standard technologies and protocols (often done via USB memory stick or wireless onto the Internet).
Therefore this report will focus on the input devices of IC systems and review them towards the goal of intelligent compaction. Then, the emerging technology of machine-to-machine communication is touched. Finally a brief attempt is made to evaluate how intelligent current IC systems are.

Current Technologies

Based on research findings the usage of the three currently used input devices for IC systems are described and the positive impact on the compaction process is highlighted.

GNSS receiver
Construction specifications often require that rollers roll a specified number of passes over every area of the asphalt mat. After these passes the compaction is considered done [14]. This is based on good compaction practice to get a consistent compaction on the asphalt mat [8]. However, Kilpatrick and Mcquate showed that a roller operator tends to drive more often in the middle of the area, which needs to be compacted (Figure 1) [7].

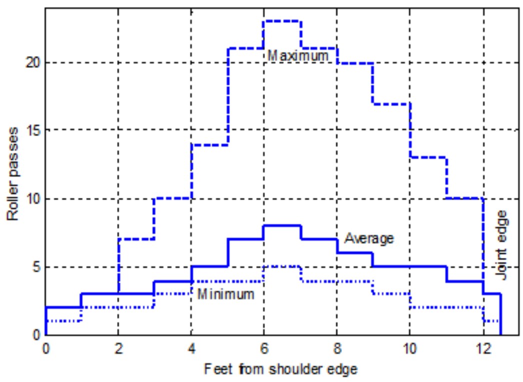

Figure 1: Pass distribution for a roller based on 23 observations on 2 mile stretch [7].

With a GNSS receiver it is now possible to track the position of the roller and provide a map to the operator indicating, where he has been already (**Figure 2**). This is often referred to as a pass counting or pass counter map [14], [15].

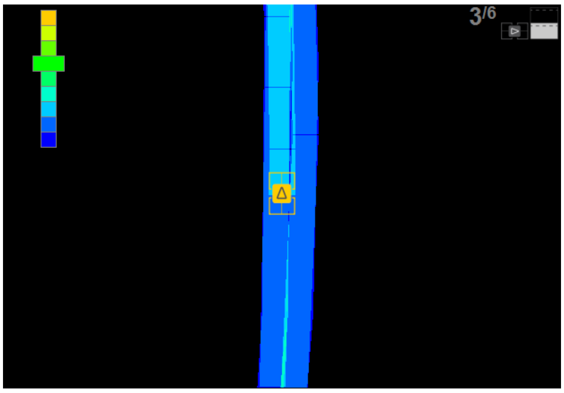

Figure 2: Pass counting map, showing the roller operator where he has been already. The map centers on the roller (yellow icon), it is currently the 3rd pass. The first pass is shown in blue, changing gradually to green, when the target value (in this case 6 passes) is reached.

This should reduce the observed tendency to over-compact the middle area and under-compact the edges. Horan et al. showed that after the installation of an IC system the rolling pattern has become much more consistent (Figure 3) [16].

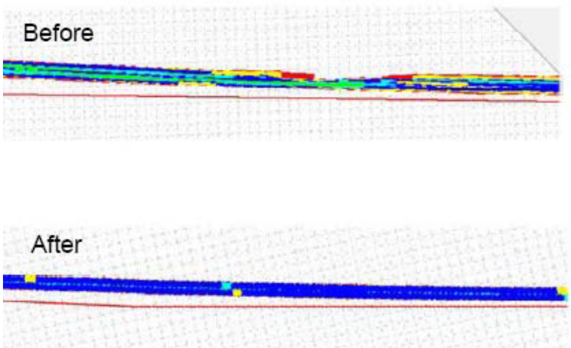

Figure 3: Top: Inconsistent rolling pattern before the use of an IC system. Bottom: Much improvement on the consistency with the use of an IC system. The 1st pass is colored red, 2nd yellow, 3rd blue, 4th light blue and all following passes green. Adapted from [16].

Temperature sensors
HMA has to be compacted in a specific temperature range (e.g. [8], [14], and [17]). Usual temperature ranges are around

100°C to 180°C [17]. If the temperature of the asphalt is too hot for compaction, asphalt might scuffs in front of a drum, might stick on the drum, might camber alongside the drum or even cracks in the asphalt (alongside the driving direction) might occur. On the other end, if the asphalt is too cold, the bigger components within the asphalt (usually pebbles) get destroyed. This reduces the quality of the asphalt [4], [8]. Figure 4 shows an idealized cooling curve for HMA. Obviously the cooling curve of asphalt is influenced by several environmental factors. If the factors are kept constant, the only other influence is layer thickness. So for example roller operators have up to 36min to compact a 7.5cm thick asphalt layer [17].

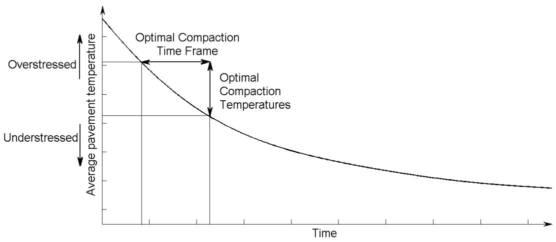

Figure 4: Idealized cooling curve for hot mix asphalt, assuming all other environmental influences are held constant [6].

In most of the available systems, infrared sensors measure the current surface temperature and display them to the operator. Often two sensors installed (in the front and in the back of the roller) so that the temperature in front of the current driving direction is shown.
Besides the information that the asphalt might be too cold or hot for compaction, an experienced operator might use this information to assess how much time is left before the asphalt get too cold for compaction.

Acceleration sensor
An acceleration sensor is usually mounted at the drum of a roller (Figure 5). It measures the frequency of the rebound of the drum or in other words the stiffness of the underground [10].

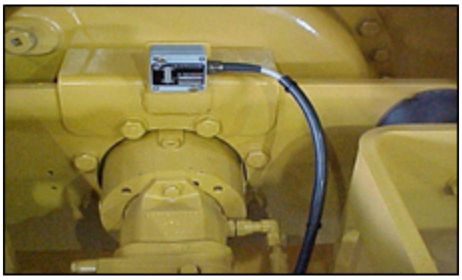

Figure 5: Usual mounting of an acceleration sensor on a roller [9].

As the asphalt gets more compacted or denser, the rebound of the drum gets more irregular. Figure 6 shows a very regular (sine) response for the 1st pass of a roller, while the response at the 13th pass of the same area becomes very irregular (Figure 7).

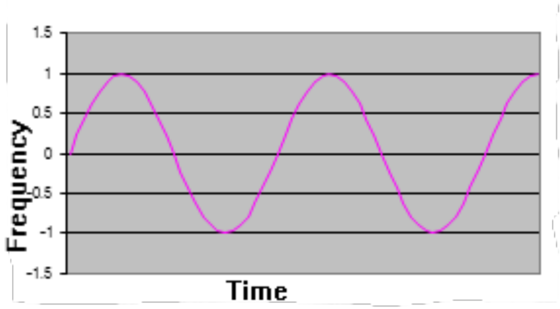

Figure 6: Measured drum rebound (frequency) at 1st pass. Adapted from [18].

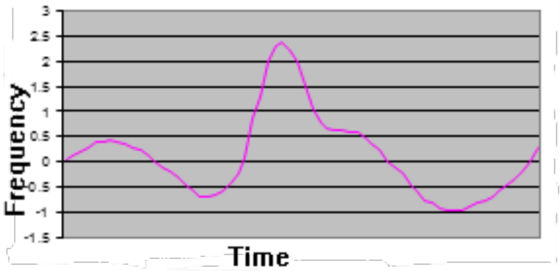

Figure 7: Measured drum rebound (frequency) at 13th pass. Adapted from [18].

Several IC systems provider show a stiffness value to the roller operator. Most values are without any unit, except one provider, which shows Meganewtons per square meter [8]. If the value stops changing, the compaction with this roller is finished [14]. However, stiffness and asphalt density are not highly correlated [10], [15], which is part of the discussion in the next section.

Review of the current Technologies

The shown measurement and analysis methods are certainly very important to increase compaction quality. A decade ago (and in a lot of cases still today) the experience of the roller operator mainly determined the compaction quality of the asphalt mat. The technologies used today help to solve identified shortcomings in the process. However, there is still a potential to increase these technologies.

GNSS Accuracy

The use of a GNSS receiver for IC systems is undisputed; it actually builds the basis for most available systems. However, systems provide different levels of position accuracy. Table 1 provides an overview of used position types for IC systems (GNSS only positions included for reference).

The higher the accuracy the higher the price is. The price for a complete RTK receiver system can easily be around $20,000 [19].

Table 1: Selected GNSS horizontal accuracies for Novatel GNSS receivers, assuming ideal open sky environment. Adapted from [20].

Position Type	Horizontal 1σ RMS Accuracy (m)
GNSS only	1.2
GNSS + SBAS[2]	0.6
OmniStar XP	0.15
OmniStar HP	0.1
RTK[3]	0.01

The FHWA currently requires an RTK based GNSS Receiver for an approved IC system [2]. An IC system in such a case can make up to a quarter of original roller list price[4]. In contrast, the ASPAHLT research project defined a medium GNSS accuracy (around 0.2m – 0.4m) necessary for an IC system [22]. This reduces the cost dramatically (IC system price around $10,000). With this lower accuracy it might be difficult to fulfill the requirements of a pass counter, to document that a roller has rolled a specified number of passes over every area of the asphalt mat with 100% certainty.

Even though this might look like a sales or marketing problem, there could be technical solutions to reduce costs for the GNSS receiver while providing high enough accuracy. A good example for this is the GL1DE filter from Novatel, which aims to smoothen the position so that the pass to pass accuracy is very high [23]. However this has the drawback that only the relative accuracy is high. If the roller operator restarted the system in between rolling over the same area, there might be an offset in positions (Figure 8).

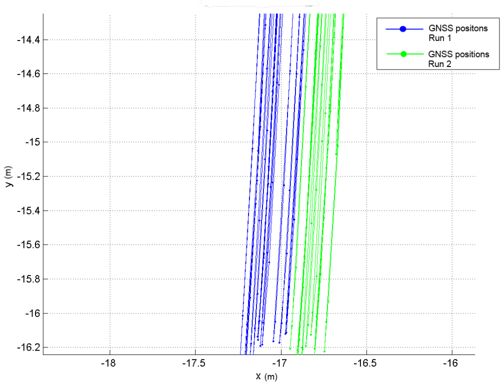

Figure 8: Position trace from one GNSS receiver with smoothing pass to pass filter. Green indicates the trace before a restart, blue the later ones.

In general terms, most likely a Kalman filter is the best choice to enhance a GNSS position [24]. If possible other sensor inputs, like steering angle and stop information, could be used as an input for the Kalman filter to enhance the position even further.

Surface vs. Core Temperature

As highlighted, most of the available systems measure the surface temperature. Even though this is valuable information, other environmental factors influence the asphalt mat as well (Figure 9).

[2] Satellite-based augmenting system
[3] Real-Time Kinematic
[4] Based on an estimated IC system price of around $30,000 and a roller price around $120,000 [21]

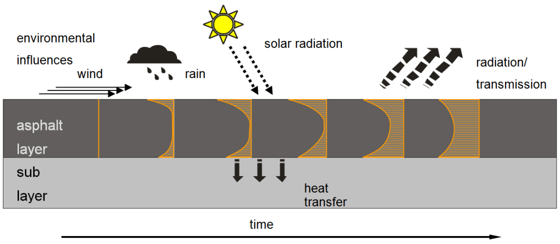

Figure 9: Environmental influences on an asphalt layer in regards to the temperature of the asphalt layer [22].

Therefore the core temperature of the asphalt map is likely to be more reliable information for the roller operator. Currently there is no way to measure the core temperature directly, so an estimation of this temperature is necessary. Research has developed different cooling models (most recently [6], [4]), which could improve the information about the asphalt temperature and ultimately be used to give an indication about the remaining time for compaction.

Stiffness and density

Acceleration sensors measure the stiffness of the underground. In soil compaction applications, there is a high correlation between the stiffness and density of the underground. However, this correlation is not found for HMA [10], [15]. One of the issues is that acceleration sensors measure the stiffness in 0.6 m to 1.5 m depth. Even though one manufacturer tries to sell this as an advantage, it is actually problematic, as the density of the currently build-in asphalt mat is of interest [10].
The FHWA launched a research project in 2012 to further investigate the correlation between the measured stiffness and the resulting density of the asphalt. It is worth mentioning that there also other calculation methods available, which build a running average on the measured stiffness values as a reference point. If the roller cannot reach a higher stiffness value compared to the reference value, the compaction is considered done [14].

Emerging Technologies

Besides these widely used technologies, machine-to-machine (M2M) or roller-to-roller communication has come into focus. So far, only one system supports M2M communication [12]. Usually more than one roller is in use at a construction side, which suggests that communication might be highly useful.
If the rollers exchange information about their positions, measured surface temperatures, and stiffness values, it is likely that over- and under-compaction can be further reduced. Three use cases can easily be identified. (a) The successional roller knows how often the roller in front has already rolled over a particular area. (b) Possible overlapping areas between rollers can be identified. (c) If a roller needs to interrupt its compaction work (e.g. engine problems), the other rollers can take over easily.
Research has highlighted that M2M communication should also include the paver [5], [22]. Figure 10 shows the principle set-up. For example, this would allow a better estimation of the core temperature [3].

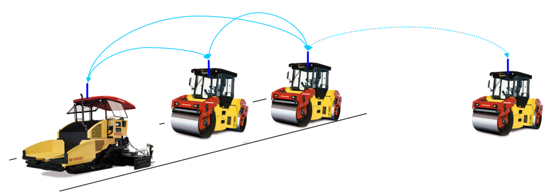

Figure 10: Principle idea about the machine to machine communication including rollers and pavers. Adapted from [22].

So far Wi-Fi seems to be the preferred technology to enable communication [12], [22]. The network structure will be an interesting point for the M2M communication. The network is likely to have the following characteristics.

- The network (all IC systems and optional the paver) has to tolerate failures (e.g. rollers might leave the communication range).
- The system structure is unknown in advance (e.g. the number of

rollers and in which order they compact is unknown).
- Each IC system has only an incomplete view of the complete compaction work.

Following Rechenberg and Pomberger [25], this network fulfills all major characteristics of a distributed system. If distributed systems are implemented, a complete new class of algorithmic problems will have to be solved. For common algorithmic problems in distributed systems, see for example [25].

Conclusion

Currently three major technologies are used to support the roller operator in achieving a high quality compacted asphalt mat. This is a major improvement compared to the last decade, when quality was mainly determined by operator's experience. However, all three technologies provide room for improvement to make the systems either more affordable or more importantly improve their functionality. Additionally M2M will likely become an important new feature promising even better compaction.

However one might ask whether the current systems can be considered intelligent after all. Even though there is no global valid definition, what makes an intelligent compaction system intelligent, maybe the error preventing mechanisms in quality assurance systems could be a measure for intelligence.
So far, the available systems mainly collect data, which is probably comparable to a quality control system. The operator can spot potential problems in real-time and in a post-processing step, problems can be identified and analyzed to improve quality for the future. However, none of the available systems provide error prevention mechanisms. Even the highlighted improvements for the established technologies might not lead to error prevention. Maybe the communication between machines on a jobsite might provide additional measures to come closer towards this goal, as they allow IC systems a more complete view as they can collect and process much more information about more build-in process parameters.
In summary recent developments have improved the compaction systems largely, however, the current systems might not be considered intelligent yet.

Matthias Limbach
MOBA Mobile Automation AG
Kapellenstr. 15
65555 Limburg
Germany
Phone: +64 21 55 66 85
Fax: +64 9 963 2745
mlimbach@moba.de
www.moba.de

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