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# Geostatistical analysis of intelligent compaction measurements for asphalt pavement compaction

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A B S T R A C T

Although unable to address the issue of spatial uniformity, univariate statistics are commonly used to evaluate the compaction uniformity of asphalt layers nowadays. Intelligent compaction (IC) technology can provide the spatial IC measurement values (ICMV) with 100% coverage during compaction and offers an opportunity to perform the geostatistical analysis on the compacted asphalt layers. In this study, the construction quality of two typical asphalt pavement projects, including one new pavement construction project and one resurfacing construction project, were evaluated by performing geostatistical analysis for ICMV. Some critical issues regarding the use of geostatistical method for the evaluation of construction quality were also addressed by the case studies. The results from the geostatistical analyses show that IC technology can offer detailed information about spatial compaction uniformity. Upon comparison of the spatial uniformity between different layers, the semivariogram after the normal score transformation was suggested due to the measuring depths of the IC roller. The spatial statistics of ICMV could be adopted to monitor the changes in spatial uniformity during compaction. The factors affecting ICMV and geostatistical analysis were further discussed.

## 1. Introduction

A widely-recognized criterion for pavement compaction is to achieve a uniform and desirable density. Nowadays, univariate statistics are typically used to describe the uniformity of compacted asphalt. However, univariate statistics are incapable of addressing the issue of spatial uniformity [1, 2]. Two datasets with identical mean and variance values can have distinct spatial characteristics, therefore, it is necessary to combine the method of geostatistical analysis to better quantify spatial uniformity, improve process control, and identify the poorly compacted locations during asphalt compaction.

A fundamental assumption of geostatistics is the existence of spatial autocorrelation [3], which can be simply described as the phenomenon that in the vicinity of large values there are other large values, while small values may close to other small values. Although constant material inputs are generally used in pavement design, the engineering properties of asphalt mixtures can vary significantly in the spatial direction. Geostatistical analysis tools including the semivariogram model are useful for evaluating the spatial variation and the performance of asphalt layers [1]. An increasing number of studies have been conducted to understand the effect of spatial variability on the actual performance of pavement structures [4, 5]. However, detailed information with accurate location identification is essential for geostatistical analysis, and the conventional point-wise measurements for asphalt compaction are difficult to meet the requirements [6].

Intelligent compaction (IC) technology was applied to soil compaction initially in the 1970's [7], it was then further utilized for asphalt compaction. IC roller is usually equipped with Global Positioning System (GPS), accelerometers, infrared thermometers, and an onboard computer [8]. IC can provide real-time spatially referenced compaction measurements with 100% coverage, which is a radical change from the conventional spot density measurements of the asphalt layer [9]. The machine-ground interactions are evaluated by sensors such as accelerometers or torque sensors, and recorded as the IC measurement values (ICMV) with a default data mesh size around $1.0\,\mathrm{m} * 0.15\,\mathrm{m}$ [10]. The spatially referenced ICMV data offer an opportunity to perform geostatistical analysis on the asphalt layer. Some researchers have performed geostatistical analysis to evaluate the compaction uniformity using IC technology [4, 5, 7, 10–14]. However, these studies either focused on the application of soil compaction or introduced it briefly as a function of IC technology. Therefore, the utilization of the ICMV for asphalt layer compaction remains a challenge due to many factors

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including the measuring depth of IC rollers, and asphalt temperature changing. With suitable geostatistical models, the benefit of ICMV should be utilized and new insights into the spatial uniformity of asphalt layers should be developed.

The objective of this paper was to examine whether geostatistical procedures are suitable for analyzing the uniformity of asphalt layers during compaction. Utilizing the semivariogram model, the spatial variability of asphalt layers from two projects in Tennessee were analyzed using both ICMV data and conventional point-wise measurements. The results of the spatial statistics and univariate statistics were compared to identify the model's capacity in characterizing spatial uniformity, and challenges involved in performing the geostatistical analysis for the asphalt compaction using the IC technology were also identified.

## 2. Background

### 2.1. Compaction Meter Value (CMV) and Resonant Meter Value (RMV)

In the two asphalt projects, the vibratory-based Compaction Meter Value (CMV) was used as the ICMV, which is a dimensionless compaction parameter that depends on roller dimensions and roller operation parameters. The drum of a vibrating roller provides periodic impacts to the pavement similar to a load test on the pavement. It was found that the compaction level had a significant relationship with the ratio between the first harmonic frequency's amplitude and the fundamental frequency's amplitude [15]. CMV is determined using the dynamic roller response and calculated as follows [16]:

$$\mathrm{CMV} = \mathrm{C} \times \frac{\mathrm{A}_{2\Omega}}{\mathrm{A}_{\Omega}} \tag{1}$$

where

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

$A_{\Omega}$ = acceleration amplitude of the fundamental component of the vibration.

C = constant.

Previous studies revealed that a standardized roller or vibratory compactor keeping a constant setting can be used to evaluate the stiffness of the compaction layer with 100% coverage [17]. The resonant meter value (RMV) is also measured by the roller to indicate the changes in drum behavior as follows:

$$\mathrm{RMV} = \mathrm{C} \times \frac{\mathrm{A}_{0.5\Omega}}{\mathrm{A}_{\Omega}} \tag{2}$$

where $A_{0.5\Omega}$ = subharmonic acceleration amplitude. RMV close to zero indicates that the drum is in a continuous contact. If the RMV is far great than zero, the drum may enter a rocking or chaotic mode, resulting in an inconsistency in CMV value. Several previous studies have demonstrated that the CMV measurements are affected by drum behaviors [18, 19]. Therefore, the RMV measurements should be checked when interpreting the CMV measurements.

### 2.2. Geostatistical model

Unlike univariate statistics, geostatistics focuses on spatial datasets with the semivariogram as a common tool to describe spatial relationships in many earth science applications. The semivariogram is defined as one-half of the average squared differences between data values with a certain distance [20]. If this value is calculated repeatedly for different distance, a semivariogram plot can be obtained as shown in Fig. 1 [4]. The experimental semivariogram $\gamma(h)$ is calculated as follows:

$$\gamma(h) = \frac{1}{2n(h)} \sum_{i=1}^{n(h)} [z(x_i + h) - z(x_i)]^2 \tag{3}$$

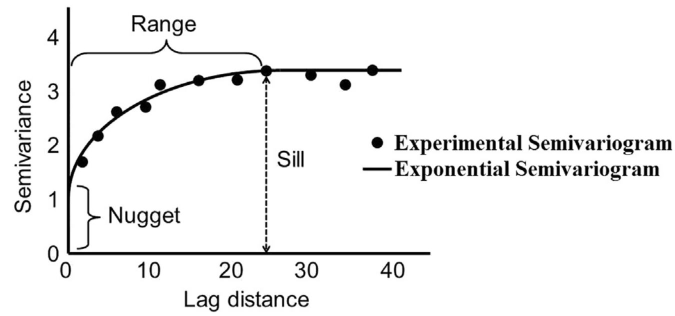


**Fig. 1.** Typical sample semivariogram.

where $h$ = lag distance; $z(x_i)$ = measurement taken at location $x_i$; $n(h)$ = number of data pairs for lag distance $h$ of a specific lag area [3].

Three main parameters of a semivariogram plot are *Range*, *Sill* and *Nugget*, as shown in Fig. 1. The distance for the semivariogram reaching the plateau is called the *Range*. Sample locations separated by distances greater than the *Range* are not spatially autocorrelated, whereas locations closer than the *Range* are autocorrelated; therefore, longer range values indicate better spatial continuity. Furthermore, the *Sill* is defined as the plateau that the semivariogram reaches at the range. The sill for a semivariogram is approximately equal to the variance of the data, measuring how far a set of data are spread out from its mean. Theoretically, the value of semivariogram is equal to zero at $h = 0$; however, variability in very short scale may result in a significant dissimilarity between sample values separated by extremely short distances. Lastly, the *Nugget* is applied to describe a discontinuity at the origin of the semivariogram caused by this phenomenon.

To give an algebraic formula for the relationship between semivariogram values at specified distance, a theoretical model (the exponential semivariogram curve in Fig. 1) is usually fitted to the experimental values. Some commonly models to fit an experimental semivariogram include linear, spherical, exponential and Gaussian models. For IC technology, the exponential model fits well with most of the experimental semivariograms, and practically no other theoretical models have been adopted in previous studies [4, 13, 14]. In this study, the exponential model is utilized to fit the experimental semivariograms of the two projects.

If the data values are not stationary and show a systematic trend, the trend needs to be removed prior to modeling a semivariogram [4]. To increase the data's univariate normality which be required by many interpolation and simulation methods, the data can be converted to normal scores [3]. After the transformation, the data will have a normal distribution with a mean of zero and a variance of one. However, this operation is optional, and the meaning of the semivariogram parameters may be difficult to interpret after the transformation. In this study, both the semivariograms before and after the transformation were analyzed and compared to find a preferable model to evaluate the asphalt compaction.

Geostatistics can also be used to predict a value at unsampled locations based on values at sampled locations. Kriging is a stochastic interpolation procedure that creates "smoothed" contour maps of CMV or other IC measurements, which can be used to analyze nonuniformity and compare the maps [21]. Results from Kriging are demonstrated later in this paper.

## 3. Case studies

CMV obtained from two case studies were analyzed using geostatistical models in the ArcGIS software, and other IC recordings such as RMV and vibration amplitude were also checked to clarify their influences on the CMV value. The trend of the data was checked using the trend analysis tool in ArcGIS, and no obvious trend was found. Two projects in this study demonstrate two typical scenarios for the asphalt