Measurement 123 (2018) 246–253

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Critical assessment of the impact of vehicle wandering on rut depth measurement accuracy using 13-point based lasers

Bing Hui[a], Yichang (James) Tsai[b], Mu Guo[a,*], Xiaofang Liu[a]

[a] School of Highway, Chang'an University, Middle Section of Nan Erhuan Road, Xi'an City, Shaanxi Province 710064, China
[b] School of Civil and Environmental Engineering, Georgia Institute of Technology, 790 Atlantic Dr., Atlanta, GA 30332, United States

ARTICLE INFO

Keywords:
Road engineering
Asphalt pavement
13-Points laser detection
Rut shape
Vehicle lateral offset

ABSTRACT

Accurate rut depth measurements have a substantial impact on the reliability of pavement performance evaluation, maintenance and rehabilitation (M&R) determination, and M&R funding allocation. To measure pavement rutting, China commonly uses 13-point based lasers. However, based on the 13-point lasers configuration, errors in rut depth measurement are inevitable if the vehicle on which the lasers are mounted wanders. Existing studies have not considered the impact of vehicle wandering on rut depth measurement accuracy and the relationship between rut shape and offset error. In this paper, 10 representative transverse profiles, including both symmetrical and non-symmetrical rut shapes with low and high severity levels of rut depths, were selected from 1100 actual transverse profiles (a 220-m rutting section from a 1.2 km roadway) that were acquired using a 13-point laser bar to simulate the impact of 5 different degrees of vehicle wandering on rut depth measurement accuracy. Results show that vehicle wandering could result in rut depth measurements error of the absolute and relative by as much as 6.4 mm and 29%, respectively. In-depth analyses show that the degree of rut depth measurement error is impacted substantially by the rut shape characteristics, including the position, slope, depth, and pattern of rut shapes (symmetrical and non-symmetrical), and the corresponding direction (right or left) of a vehicle's wandering. For example, a vehicle wandering in the direction opposite to the dominating/severe rut depth will result in a large rut depth measurement error. The contributions of this paper include quantifying the impact of vehicle wandering on rut depth measurement accuracy and identifying the factors, including the rut shape characteristics and characteristics of vehicle wandering, that might reduce rut depth measurement accuracy.

1. Introduction

Rutting, which is a permanent deformation a pavement's wheel path when the pavement is stressed by repeated traffic loading [1–3], is one of the most important distresses of asphalt pavement [4–6]. Rutting affects the quality of roadway roughness, decreases driving comfort, indirectly reduces pavement skid resistance on rainy days, and likely leads to hydroplaning. It needs to be identified for timely maintenance and rehabilitation [7–10]. Therefore, the accuracy of rut depth measurement substantially impacts the reliability of performance evaluation, maintenance and rehabilitation (M&R) determination, and M&R funding allocation.

Because it is inefficient and dangerous, the traditional manual straightedge measurement method has been replaced by rut detection equipment with non-contact and automatic multi-point lasers mounted on survey vehicles [11–19]. The 13-point based laser bar is commonly used in China for rut depth measurement [20]. Under ideal conditions, the survey vehicle can be drived along the centerline of the road to ensure the laser obtaining a complete rut profile, then the measurement results can be used to calculate the maximum rut depth. However, Because of many factors, including road alignment, environmental conditions, physical condition of vehicle drivers (that is, they might be tired, distracted, or responding to the driving conditions of the pavement/driving environment) can cause the survey vehicle to wander over a lane [21,22], and this vehicle wandering is inevitable. Furthermore, the typical laser bar is not as wide as the typical lane, so rut depth measurements might not be complete and may be erratic. This situation is illustrated in Fig. 1. Consequently, because a survey vehicle might not stay straight on the center line of a pavement, errors in measuring the rut depth could occur because the laser bar does not cover the entire lane. This means the entire and real morphological characteristics of a rut's cross section may not be captured [23]. The survey vehicle wandering have a significant impact on the validity of the rut depth measurements, particularly when trying to monitor rut depth between

* Corresponding author.
E-mail addresses: 82628532@qq.com (B. Hui), jame.tsai@ce.gatech.edu (Y.J. Tsai), 1927834917@qq.com (M. Guo), 871725631@qq.com (X. Liu).

https://doi.org/10.1016/j.measurement.2018.03.069
Received 22 December 2016; Received in revised form 21 April 2017; Accepted 29 March 2018
Available online 30 March 2018
0263-2241/

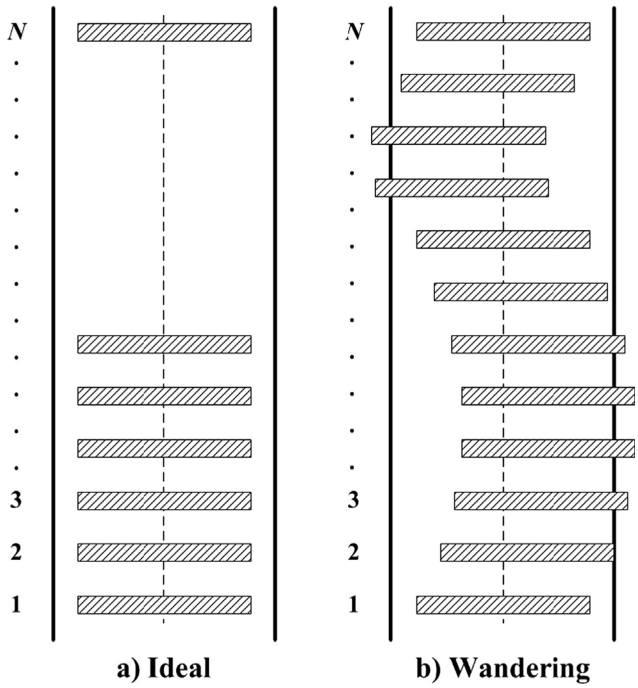

Fig. 1. Illustration of lateral vehicle wandering to the pavement marking.

years. (The terms "vehicle wandering" and the "offset to the right/left" are used interchangeably in this paper. Fig. 1(a) and (b) shows this potential problem.)

In order to analyze the impact of the lateral offset on rut depth measurement, Simpson utilized 3- and 5-point laser rut detection equipment and used the simulation method to hypothesize that the offset would randomly occur on both sides of a pavement and that the offset distance would be between ± 50 ~ ± 250 mm [24,25]. The lateral offset would cause rut depth measurement errors. Instead of 3–5 laser points, Tsai has used emerging 3D laser technology with more than 4000 laser points in transverse direction to measure the near ground truth rut shape [26]. Results show the more laser points there were, the smaller the error would be.

Bennett used the real rut's cross section and conducted a field test to study the errors in rut depth after a 30-point based laser was offset to the right by 50, 100, and 150 mm [27]. He discovered that over-estimation and underestimation for the errors caused by different offset distances existed simultaneously, and the cross section of a rut shape could also influence the measurement. He pointed out that the actual maximum lateral offset distance could be 500 mm, although he did not actually analyze the offset of 500 mm. Mallela found that with the increase of lateral offset, there was a decrease in rut depth measurement accuracy [28]. In China, Ma Ronggui simulated the symmetric W-shape rut obtained by n sensors with d distribution of equal space and found that the maximum rut measurement error when shifting to the right occurred in the place of $d/2$ where the sampling points were offset [29]. As shown above, the existing studies did not consider the rut depth measurement errors caused by various rut shapes under different severities, and the relationship of rut shape and offset error has not been discussed. The maximum offset was not large enough (only up to 250 mm) in the previous studies (which need to be expanded).

Therefore, the objectives of this paper are to analyze the symmetrical and non-symmetrical rut shapes in two severities (low and high), taking into account different lateral offset distances (up to 500 mm) in the left and right directions and, also, to analyze the factors (from rut characteristics) influencing the accuracy of rut depth computation.

This paper is organized as follows. In section one, the research background and objectives are introduced. In section two, the 13-point based laser bar widely used in China is introduced along with the raw data collected by use of a 13-point laser bar and the method of rut depth computation. In section three, the data selection, the analytical method of lateral offset and the computation of rut depth error are introduced. Then, the simulation of different lateral offsets is carried out to analyze the impact of a vehicle's wandering on the accuracy of the rut depth measurement. The errors caused by rut shape characteristics (position, slope, depth, and patterns of rut shapes) are also discussed. Finally, conclusions and recommendations are presented.

2. Rut depth measurement and computation using 13-point laser bar in China

The 13-point based laser bar is commonly used in China for rut depth measurement, and it is also a standard practice used for national highway pavement evaluation. The raw data collected using a 13-point laser bar and the rut depth computation methods that are required by the Chinese Standard are also presented in this section [30].

2.1. 13-point-based laser bar

Fig. 2 shows a photo of the 13-point laser bar ("The Rapid Detection System of Road Condition") developed by the Research Institute of Highway Ministry of Transport China [31]. This piece of equipment is based on the principle of height measurement for discrete points, which, for the width of a laser bar, is 2300 mm; the installation height is about 300 mm to the ground. Meanwhile, there are nine vertical laser sensors that are unevenly laid out along the direction of the bar, close in the wheel path and sparse in the non-wheel path. Furthermore, two oblique laser sensors are set in both left and right ends of the laser bar so that a valid detection width of 3600 mm can be reached. The detailed layout and laser spacing are shown in Fig. 3.

2.2. Raw data of 13 point-based laser bar

Table 1 shows the representative raw data of a rut cross-section collected by the 13- point-based laser bar. Every rut cross-section consists of three rows of data. In the first row, the letter "G" represents the National Road, "40" shows the identification number of the roadway, and "A" represents the upper line. In addition, 104 represents the stake mark, which has 111 and 147 represent as the rut depths for left and right with the unit of 0.1 mm. The rut is located in K0 + 1.04 m, and the left and right rut depths are 11.1 mm and 14.7 mm. In the second row, each point shows the altitude data of the pavement measured by the 13 laser displacement sensors in units of 0.1 mm in the z direction. The third row is the coordinate of the 13 laser points in a horizontal position in units of 1 mm. The difference of the horizontal coordinates between the first point and the last point is the width of measurement for the rut detection equipment.

Fig. 2. The vehicle with 13-point laser bar [31].