Illinois Asphalt Pavement Association

Final Report:

A Literature Review on Wheel Wander

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January 31, 2018

1 Introduction

Realistically predicting pavement performance over its service life is instrumental to design optimal and feasible pavements. There are many different pavement design methods and guidelines suggested in the literature. Although the methodology of the developed pavement guidelines significantly vary across the countries (even across the states), they all start with the same first step: collecting the traffic (e.g., axle load, daily truck number) and environmental inputs (e.g., temperature, moisture). Therefore, characterizing and understanding of these inputs are instrumental for all of the guidelines to realistically predict pavement performance over its service life.

One of the most important traffic-related inputs is the lateral position of a wheel load on a lane. It is a well-known fact that the vehicles seldom follow a straight path. On the contrary, their lateral position deviates significantly as they travel. This lateral movement of a vehicle is called "wheel wander". Wheel wander is considered as a random phenomenon due to its contributing factors such as individual driving habits, wind effect, mechanical alignment [1].

The importance of the wheel wander for pavement design and analysis has been clearly recognized by many studies. This report presents a literature review that attempts to summarize the research effort made so far that models, measures and evaluates the wheel wander from pavement design and analysis point of view.

This report is organized as follows. The next chapter introduces the studies that developed probabilistic models to account for the wheel wander in pavement design and analysis. Afterwards, the third chapter presents the studies that measured the wheel wander distribution in traffic. Later, the fourth chapter summarizes the studies that evaluated the impact of the wheel wander on pavement behavior and performance. Finally, the last chapter concludes the report.

2 Wheel Wander Definition

Wheel wander can be interpreted as the uncertainty of lateral position of wheel loads on a lane. Mathematical representation of the wheel wander can be built by defining a variable (d_w) as the distance between the edge of the tire and road. This distance is not a deterministic value i.e., its value changes in a random fashion. Therefore, it should be modeled using probabilistic approaches while designing and analyzing pavements. Figure 1 illustrates the wheel wander on a standard lane layout. This figure assumes that the lane width and axle width as 365.8 cm (12 ft) and 259.1 cm (8.5 ft), respectively.

The probabilistic modeling of wheel wander starts with a conventional assumption that the vehicles are inclined to be centered on the lane with an uncertainty i.e., their position deviate from its mean location (from the center of the lane) with some probability. Traditionally, this assumption is modelled using a zero-mean normal distribution with a known standard deviation (Equation 1). MEPDG [2] recommends 10 in as the default value for the standard deviation. There are a couple of studies in the literature that recommend different standard deviations. These studies are summarized in the next chapter.

$$f(d_w) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(d_w-\mu)^2}{2\sigma^2}} \quad where\ \mu\ =\ 0\ and\ \sigma\ =\ standard\ deviation \tag{1}$$

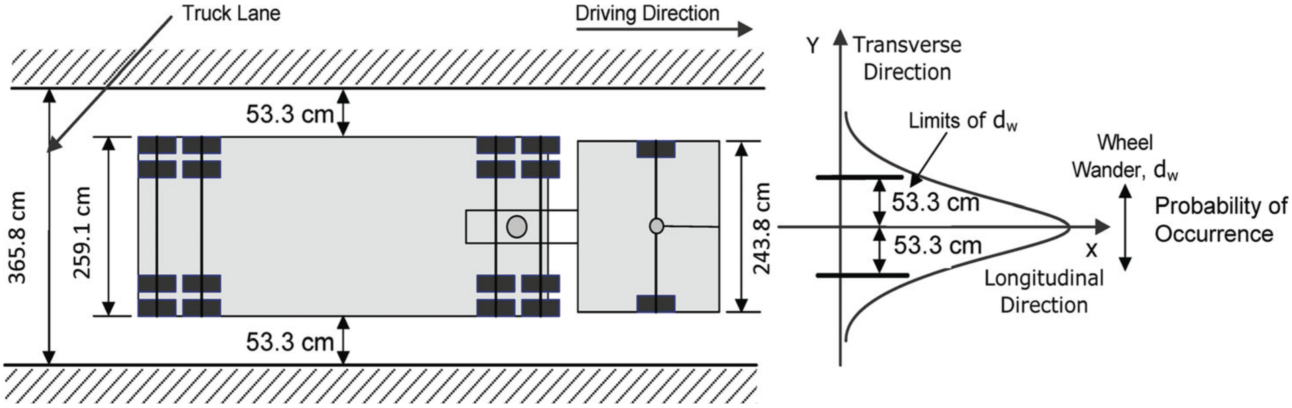


Figure 1: The demonstration of wheel wander (reprinted from [3])

3 Wheel Wander in Pavement Design

It is important to incorporate the impact of wheel wander while designing the pavements. There are two studies in the literature that developed analytical approaches to consider the wheel wander in pavement design based on its definition given in the previous chapter.

The first approach was developed by MEPDG [2] and is illustrated in Figure 2. In this figure, row B shows the damage accumulation profile whose maximum would be used to compute the pavement service life if there was no wander. Instead, MEPDG computes the average of damage predicted at 11 different locations (the figure just shows five points for the sake of brevity) and use it as the final damage (Equation 2). The discrete points are selected by moving -1.28155*σ (Equation 1) from the center for five times. Each jump is assumed to represent 20% of the traffic. It is important to note that this approach could only be used for fatigue cracks prediction. In MEPDG [2], it is stated that “for rutting, the guide software modifies the actual pavement responses for the effects of wander and uses this modified response for the calculation of the incremental permanent deformation within each layer”. However, there is no explanation provided in the guide as to how the responses get modified.

$$D = 0.2D_1 + 0.2D_2 + 0.2D_3 + 0.2D_4 + 0.2D_5 = \sum_{i=1}^{5} 0.2D_i \quad (2)$$

The second approach was developed by Siddharthan et al. [3]. This approach modifies the pavement structural responses computed by 3-D Move software to account for the wheel wander. The modification is performed based on Monte Carlo simulation. Later, the modified responses are injected to the empirical functions also used by [2] to predict the damage within in the pavement structure. The important steps of the developed approach are listed below.

1. Draw a sample from the distribution given in Equation 1
2. Accept the sample if it is not outside of the boundaries (Figure 1).
3. Calculate all critical pavement responses at the accepted sample
4. Repeat steps 1 to 3 for 10,000 times
5. Generate cumulative distribution function for each critical pavement response
6. Discretize the cumulative distribution on specific probabilities (e.g., 0%, 20%, 40%, 60%, 80%, 100%)
7. Extract the responses at the selected probabilities and average them
8. Use averaged responses in the empirical equations and compute the damage

4 Wheel Wander Measurements Methods

The previous chapter presented the approaches that probabilistically simulate the impact of wheel wander in pavement design and analysis. The approaches were based on the assumption that the wheel wander follows a zero-mean normal distribution with a known standard deviation (Equation 1). In order to validate this assumption and have a better understanding of the wheel wander distribution, there has been many studies conducted to measure the lateral position of the vehicles in the field. Based on measurement methods, these studies can be grouped into three categories [4].

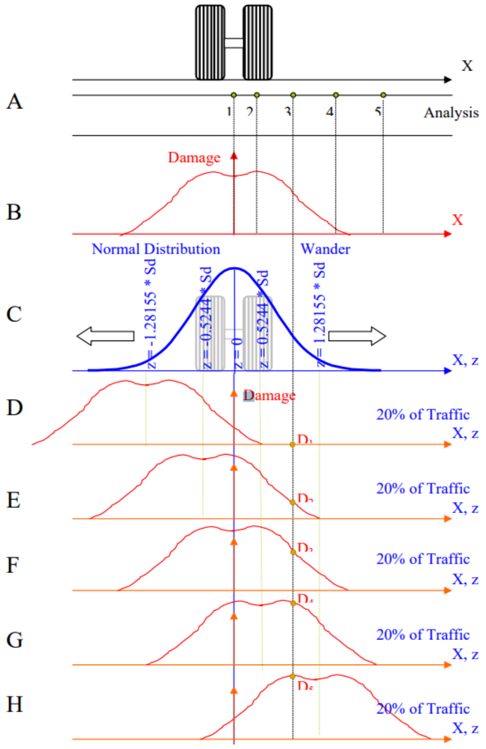


Figure 2: MEPDG analytical approach for wheel wander consideration (reprinted from [2])

4.1 Manual Survey

This method was used when there was no existing camera or sensor technology ([5], [6]). In this method, a reference line is placed on the road and an observer records the distance between the right rear wheel of the vehicles and the reference line. Although this method gave an idea to pavement researchers about the wheel wander distribution, it was later abandoned due to accuracy and subjectivity concerns.

4.2 Video Processing

This method involves processing the videos that are collected by cameras to extract the lateral position of vehicles. The studies that utilized video processing for wheel wander measurement can be classified into two groups depending on the place where the camera is mounted.

The studies in the first group mounted a camera to the vehicle (also called the research vehicle) that tailed other vehicles in the traffic and recorded their lateral movements as they traveled. Shankar and Lee [7] placed a camera on a van that followed 50 trucks and collected 6 hours of video. Trucks to be recorded were selected in a way that percentage of the truck types in the database represented the actual truck traffic. The distance between the right edge of truck tire and the left side of the pavement were extracted from the videos by placing a grid on a computer screen. The grid sizes were scaled based on the lane width. Triggs [8] followed a similar methodology to better understand the effect of approaching vehicles on the lateral position of cars traveling on a two-lane rural road. The total of 170 randomly selected cars were recorded by a camera mounted on the research car for 75 m in average. Lennie and Bunker [9] measured the lateral position of three multi-combination vehicles (MCVs) to “understand how lane width requirements are influenced by the sideways movement of the trailers and the lateral position of the prime mover.” The MCVs were monitored in an urban arterial and highway to study the effect of the behavioral characteristics of the drivers of surrounding vehicles. The purpose of the study was to investigate if the lanes were wide enough to accommodate MCVs considering their lateral movements which were extracted from the videos (Figure 3).

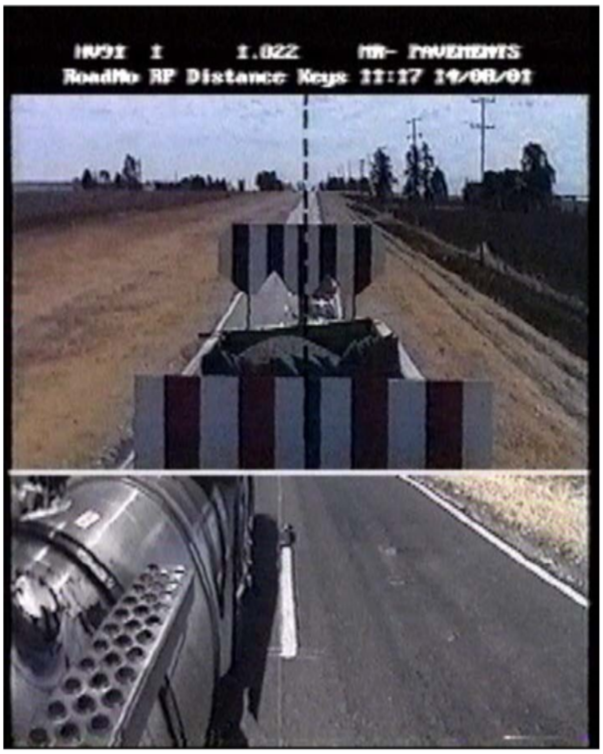
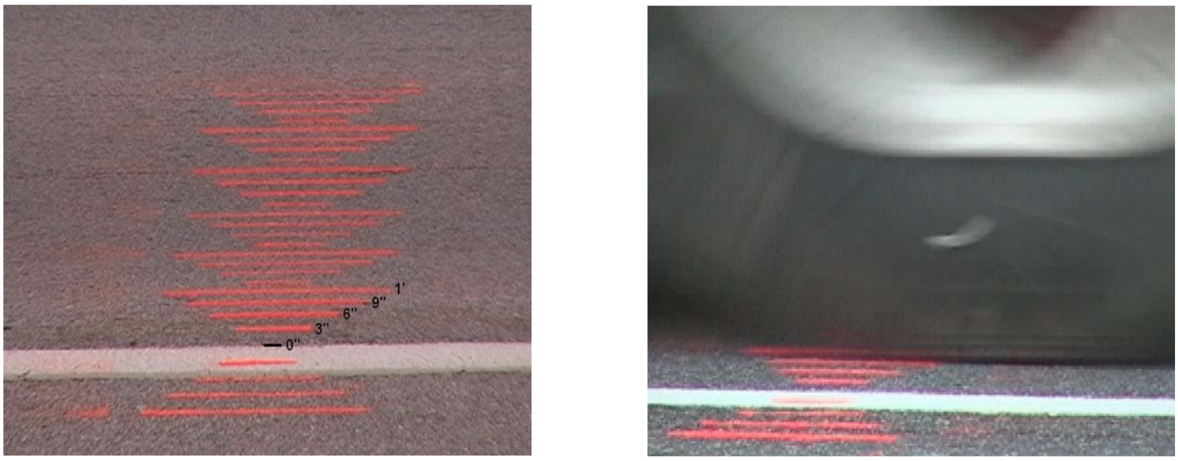


Figure 3: A snapshot from video recordings (reprinted from [9])

The studies in the second group mounted a camera to an infrastructure (e.g., bridge or shoulder) instead of a vehicle to record the lateral position of the vehicles in the traffic. Stempihar et al. [10] placed a camera to a shoulder to monitor the lateral movement of the vehicles. Additionally, reference lines were marked on the road in traffic direction with 3 in intervals (Figure 4a). Thereby, the distance between the edge of the tire and the lane marking could be computed (Figure 4b).

Lennie and Bunker [11] conducted a study that shares the same motivation as their previous paper [9]: evaluating the impact of MCVs on behavioral characteristics of car drivers. However,



(a) The references lines (b) Measurement of the lateral distance

Figure 4: Data collection system developed by [10]

the methodology was different. While the camera was mounted on the research car in [9], an overpass was used to position a camera in [11]. The lateral position of vehicles were measured by overlaying a transparent sheet with a horizontal scale on the computer screen. The total of four hours of footage was collected. However, the data size was later reduced due to high manual processing time. Luo and Wang [4] followed similar methodology where the camera was mounted on an overpass to measure lateral position of the vehicles under different conditions: low/heavy traffic, during day time and nighttime, in sunny, rainy, and windy weather, and at five different locations on an interstate highway (Figure 5). The purpose of the study was to develop a new wheel path definition based on the collected data. Luo and Wang placed reference lines on the road to extract the lateral position of the truck from the videos as opposed to overlaying a scaled paper on a computer screen [11].

(a) Marked references lines (b) Measurement of the lateral distance

Figure 5: Data collection system developed by [4]

4.3 Road Instrumentation

In this approach, the lateral position of the vehicles are determined through sensors instrumented on a road surface. The studies using this approach can be grouped into two categories: placing instrumented mat on road surfaces (i) or embedding the sensors in road surfaces (ii).

Buiter et al. [1] placed 120 switch elements side by side with 20 mm intervals on a mat. Later, this mat was attached to a road surface using a double-sided adhesive tape. The switch elements are sensitive to pressure i.e., they get activated when a wheel passes over them. Therefore, the lateral position of a wheel along with tire footprint can be extracted by registering which sensors are activated along the mat after each pass. Additionally, this system allowed identifying the tire type as singe, double or wide-base tire. Blab and Litzka [12] developed a similar system in collaboration with [1]. They called this system “Lateral Displacement System (LDS)” which is demonstrated in Figure 6. The switches in LDS have 15 mm of width and placed with 30 mm of spacing. Because of its high flexibility, it can adapt itself to any kind of deformed surfaces. Two additional tape switches were attached to LDS to measure the velocity of vehicles. Developed system were installed in 27 different road segments to collect data under varying traffic conditions. This study performed regression analysis on collected data to investigate the relations between the wheel wander and lane width, speed and rutting.

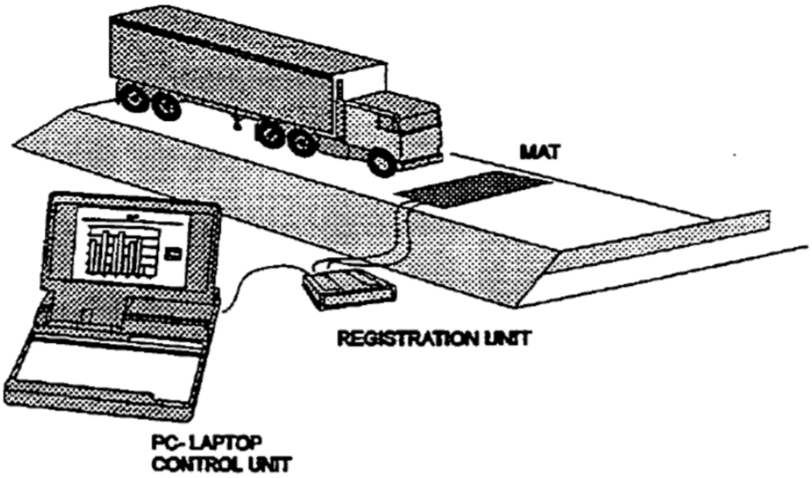


Figure 6: Lateral Displacement System (LDS) developed by [12]

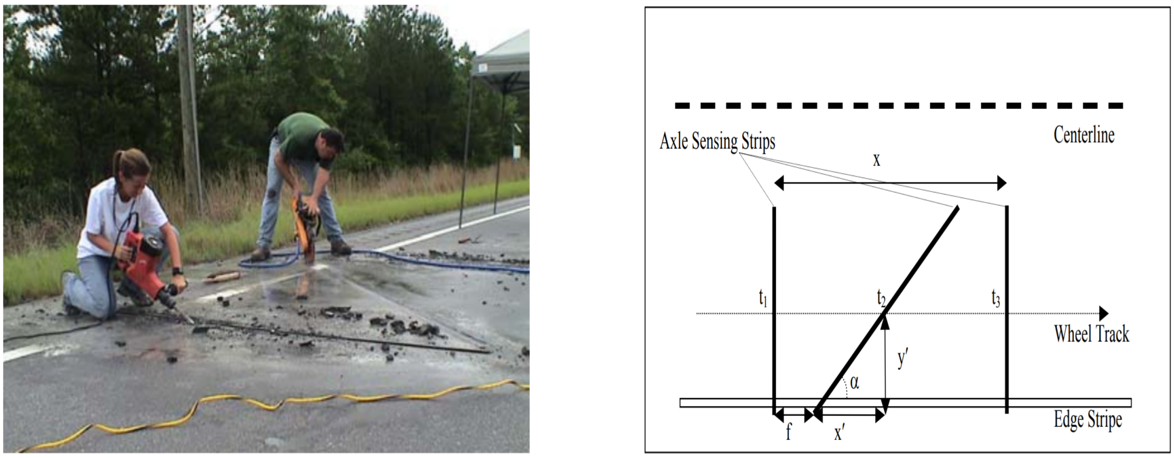
Timm and Priest [13] embedded three axle sensing strips in road segments in National Center for Asphalt Technology Test Track (Figure 7a). The stripes were placed with a specific layout, two vertical and one diagonal stripes (Figure 7b). The stripes had a cross section of 1 square in. While the length of vertically placed stripes were 88 in and the diagonal strip had the length of 120 in. The time steps recorded from the strips were injected to Equation 3. Afterwards, the lateral distance of a wheel ($y^{'}$) could be computed using the trigonometric relation given in Equation 4. The data collection system was calibrated by using field measurements which was obtained using line of fine sand.

$$x^{'} = \frac{x}{t_3 - t_1}(t_2 - t_1) - f \tag{3}$$

where
t_i = Time stamps recorded by i^{th} strip
x = Distance between the first and third strip
f = Distance between the first and second strip

$$y^{'} = x^{'} tan\alpha \tag{4}$$

where
α = The angle of diagonal strip (Figure 7a)



(a) Instrumentation of strips (b) Strip layout

Figure 7: Sensor layout and instrumentation [13]

5 Quantification of Impact of Wheel Wander Through Pavement Testing

The previous two chapters introduced the stochastic modeling of wheel wander in pavement design and field measurement of wheel wander, respectively. This chapter summarizes the studies that assess the impact of wheel wander on pavement structure using pavement testing.

Al-Qadi et al. [14] instrumented more than 500 sensors to 12 pavement sections with varying layer properties (e.g., thickness and material properties) in a facility called “Virginia

Smart Road". The length of each section was approximately 100 m. The purpose of the project was to monitor the pavement responses to have better understanding of the factors affecting pavement behavior. One such factor studied in this project was wheel wander whose impact was assessed by developing a shift factor [15]. The shift factor was developed by distributing the load over 1 m wider strip around the wheel path to obtain the pavement response distribution with respect to the central point. A similar methodology was also followed by Timm et al. [13]. In this study, regression equations (Figure 8) that input the lateral position of a wheel and output a pavement response (e.g., strain at the bottom of AC) were developed. The last study that tries to quantify the impact of wheel wander on pavement responses was conducted by Shafiee et al. [16]. In 2012, around 20 sensors including strain gauges and pressure cells were installed to two pavement sections at the University of Alberta's Integrated Road Research Facility (IRRF). Pre-loaded single and multi units trucks were used to measure the pavement responses at different offsets changing between -600 mm and 600 mm. Later, the responses were linked to Mechanistic-Empirical Pavement Design Guide to perform a sensitivity analysis based on predicted damage.

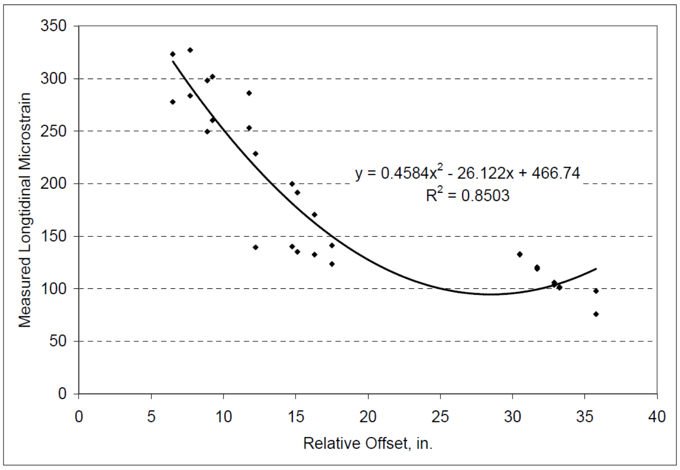


Figure 8: Offset-Strain Regression Equation [13]

Wu and Harvey [17] used the heavy vehicle simulator at the University of California Pavement Research Center to understand how the wheel wander affects rutting development within pavement structure. In order to accomplish this goal, two identical pavement sections that that has 100 mm of AC and 300 mm of base were built. While one of the sections were exposed to channelized load application (i.e., without wander), the wheel wander was simulated on the other one so that the results can be compared to quantify the impact of wheel wander. The wheel wander was simulated in a sweeping pattern i.e., the wheel path was moved by 50 mm after each load application. The width of the section and the wheel (dual tire assembly) were 1000 mm and 600 mm, respectively. Therefore, the position of wheel load in a full cycle was 0, 50, 100, ... 350, 400, 350, 300, ..., 50 , 0 mm. Figure 9 shows measured rutting profile after 3000 repetitions. There are two important observations that can be made from this figure. The first one is that the wheel wander decreased the maximum rutting by around 25%. The second one is that the location of maximum rutting changed. For the case without wander, the maximum rutting was observed right under one of the tires whereas it shifted towards the center of the tires for the case with the wheel wander. Therefore, the wheel wander not only decreased the magnitude but also changed the shape of rutting profile. This study also developed an analytic model for rutting simulation and calibrated it with the measurements.

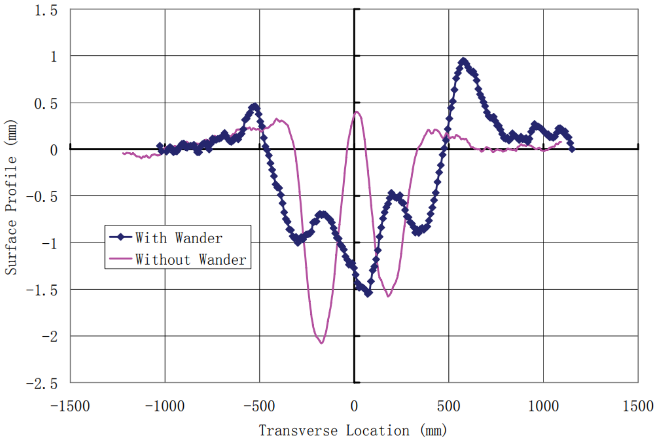


Figure 9: Rutting profile after 3000 load repetitions [17]

6 Summary

The lateral position of wheel load is one of the most important variables for pavement design and analysis. However, it is not a deterministic variable i.e., its value changes in a random fashion. Therefore, this variable is commonly referred as the wheel "wander" and should be modeled using probabilistic approaches.

This report starts with introducing probabilistic models that simulate the wheel wander in pavement design and analysis. Although the methodology of the models varied, they all started with the assumption that the wheel wander follows a zero-mean normal distribution with a known standard deviation. Later, the studies that conducted field experiments to measure the lateral distribution of the wheel load were presented. These studies could be grouped into three based on the measurement techniques: manual measurement, video-based measurement and sensor-based measurement. Finally, the studies that quantify the impact of wheel wander on pavement behavior were summarized. These studies highlighted the importance of wheel wander through full scale testing.

7 Acknowledgment

I would like to express my sincere gratitude to the Illinois Asphalt Pavement Association (IAPA) for selecting me as a recipient of the IAPA scholarship. I am so honored to have been chosen for this scholarship and look forward to collaborating with the association and its associates in the near future.

Also, I would like to express my gratitude to Professor Imad Al-Qadi for his support and guidance during this process of study.

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