Assessment of Splash and Spray Potential of Experimental Quiet Pavement Surfaces

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**Abstract**
The effects of vehicle splash and spray are well known to motorists who have undertaken journeys in wet weather conditions. Research suggests that splash and spray contributes to a small, but measureable, proportion of road traffic accidents and provides considerable nuisance to motorists. Furthermore, splash and spray from highway pavements can carry a number of pollutants and contaminants that can be poisonous to plant life and cause the accelerated corrosion of street furniture.

Vehicle and highway engineers are working on several types of solutions to reduce splash and spray, examples of which include splash and spray reducing devices and/or a permeable surface layer on pavement. A robust splash and spray measurement device could be used to assess the effectiveness of those solutions. Furthermore, fluid mechanics computational models are used to simulate the process by which splash and spray is generated. To calibrate and validate these models, it is necessary to measure the physical properties of the droplet cloud generated, including the droplet’s size and space density.

This project proposed a methodology to measure splash and spray on in-service pavements and developed a proof-of-concept system to quantify splash and spray on in-service roads using this methodology. This effort included developing the system, which involved integrating a light source (beam laser) and a camera, preparing the image processing software, and subsequent laboratory and road tests to validate the proof-of-concept.
Field Assessment of Splash and Spray
Final Report

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ACKNOWLEDGMENTS

The authors would like to thank the Virginia Department of Transportation (VDOT) for their support in the development of the course. The project was partially funded by the U.S. Department of Transportation Mid-Atlantic University Transportation Center (MAUTC).

DISCLAIMER

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**INTRODUCTION**

The effects of vehicle splash and spray are well known to motorists who have undertaken journeys in wet weather conditions. Research suggests that splash and spray contributes to a small, but measurable, proportion of road traffic accidents[1] and provides considerable nuisance to motorists [2]. Furthermore, splash and spray from highway pavements can carry a number of pollutants and contaminants. When deposited, these contaminants can be poisonous to plant life and cause the accelerated corrosion of street furniture.

To reduce splash and spray, vehicle and highway engineers are working on several types of solutions, examples of which include splash and spray reducing devices and a permeable surface layer on pavement. A robust splash and spray measurement device could be used to assess the effectiveness of those solutions. Furthermore, fluid mechanics computational models are used to simulate the generating process of splash spray. To calibrate and validate these models, it is necessary to measure the physical properties of the droplet cloud generated, including the droplet’s size and space density.

The objective of the project was to propose a methodology to measure splash and spray on in-service pavements and develop a proof-of-concept system to quantify splash and spray on in-service roads using this methodology. The effort included the system’s development, which involved integrated a light source (beam laser) and a camera, and preparing the image processing software, along with laboratory and road tests to validate the proof-of-concept.

**BACKGROUND**

The generation of splash and spray is an extremely complex process and is dependent upon a number of independent variables. The terms “splash” and “spray” relate to two separate processes. The definitions of splash and spray are usually given as a function of the droplet sizes produced or as the process by which they are created, as presented by Pilkington in 1990 [3]:

- **Splash** is defined as, “…the mechanical action of a vehicle’s tire forcing water out of its path. Splash is generally defined as water drops greater than 1.0 mm (0.04 in.) in diameter, which follow a ballistic path away from the tire.”

- **Spray** is defined as being formed, “…when water droplets, generally less than 0.5 mm (0.02 in.) in diameter and suspended in the air, are formed after water has impacted a smooth surface and been atomized.”

Although splash and spray are separate processes, they are often referred to together because it is difficult to monitor and measure them individually. Generally, splash and spray are formed on wet roads by four well-established primary mechanisms: bow splash waves, side splash waves, tread pickup, and capillary adhesion [4]. In 2005, McCallen et al. [5] designed a tool to illustrate the spray under controlled conditions. High-speed image capture was used to examine and analyze the case of the tread pickup source and the interaction between the water and the interface of two counter rotating tires.

**Influential factors**

Though no consensus of opinion has been achieved about the relationship between water film thickness and splash/spray, it is generally concluded that the splash and spray increases with the thickness of the water film. In addition to the water film thickness, the other main factors that affect splash and spray include vehicle speed, tire geometry, vehicle aerodynamics, vehicle spray suppression devices, and wind vector.
Water film thickness is usually considered to be a major contributory factor to the generation of splash and spray. In 1978, Weir et al. [4] studied how the spray was affected by the thickness of water film, and found that the threshold was 3 mm, a thickness which determines whether tire tread grooves are filled and the spray reached the maximum strength. In 1985, Koppa [6] et al. used laser transmitters to measure the spray generated by a truck under three water depth conditions (0.5 mm, 1.3 mm, and 2.5 mm). It was found that the spray production increased with a linear relationship to the thickness of water film.

A great deal of research has been carried out to assess the effect of vehicles on the generation of splash and spray. Among all the vehicular factors, speed is the largest factor of influence. As early as 1966, Maycock [7] observed that spray density was very small at speeds below 50 km/h and increased rapidly with speed when speed was above 50 km/h. Similar results have been reported in the following studies conducted by Chatfield et al. [8] and Resendez et al.[9]. In 1997, Huebner et al. [10] developed a series of models relating water film thickness to hydroplaning speed.

Tire-road interaction is another important factor for splash and spray generation, and is affected by pavement texture and tire properties. In the work presented in 1966 by Maycock [7], a worn tire produced much more splash than a zig-zag rib and heavy duty block tread patterns. Believing that tire geometry was related to vehicle hydroplaning speed, Horne et al. [11] conducted experiments to ascertain a relationship between tire inflation pressure and footprint aspect ratio to hydroplaning speed for a given water depth. Yager [12] did a similar experiment in Texas and developed another relationship. Three distinct zones of contact were studied by simulating tire rolls or slides over a wet road surface in Gough and Moore’s works [13, 14].

Measurement Methods

Many techniques have been developed to quantify splash and spray. The collection method was developed earliest by fitting devices to the test vehicle itself or to a following vehicle. In 1966, the device Maycock [7] used involved disposable collectors consisting of several layers of absorbent paper. The difference in mass before and after testing was used to measure the generated spray. In 1990, Pilkington [3] used an absorbent screen to collect the droplets. Instead of using absorbent devices, Ritter attached a collection device to the side of the vehicle close to the wheels, and part of the spray entered the device, leaving behind a pool of water for quantification.

The spray can also be quantified by observing the change in the contrast of images during experiments. The working principle of this method is that the contrast of images will be reduced if it is viewed through a spray cloud due to the light refraction occurring within the spray particles. This method has been used by many scholars [16, 16-18]. Another measurement method with the same principle used by Knight et al. was used [18] in 2005. In this method, a black screen was fixed to the rear of the vehicle, and the video camera mounted in the following vehicle filmed the screen to capture the changes in contrast.

In addition to reducing the image contrast, the scattering light induced by a spray cloud can also reduce the strength of a light passing through the spray. This process is utilized in another measurement method, which is known as the transmittance analysis method. Ritter [16] employed this method in 1974 by using a visible-light source from an automobile headlamp. This technique was developed further by Koppa et al [6] in 1985 using low power laser light sources instead. Some years later, Manser [15] concluded that the works of Ritter and Koppa provided very similar results.

Observations, including photographs, video, or direct observation, can also evaluate some properties of the spray cloud. Although this method has a poor repeatability, it is convenient and
can be used for confirming the results gained by other means. In some previous research [3], observers were used to rate the visibility loss caused by a spray cloud, and the observed results were compared with those obtained by other methods.

In addition to the methods described above, many other techniques have been developed to measure the amount of splash and spray. The Doppler technique has been used to determine the number flux, size distribution, and the velocity of water droplets [19]. Raindrop size, fall velocity, and intensity have been measured with an optical spectro pluviometer (OSP) [20]. In addition, Pérez-Jiménez, F., et al., (2011) developed a prototype laser-based system to measure the amount of splash produced by a tire when it passes over wet pavement [21].

**Modeling**

Due to the complexity of splash and spray, it cannot be calculated accurately with of all the fundamental inputs by any of the current models. Most of the existing models are derived from aerodynamics using Computational Fluid Dynamics (CFD). Commercial software is used to calculate the air flow around a vehicle and the distribution of water droplets. McCallen [5] used this method to calculate the spray cloud generated by heavy vehicles. Paschkewitz [22] used the same method to study the spray dispersion about a simplified trailer wheel assembly. In a different approach, Resendez et al.’s work [9] presented a splash and spray model as a function of water film thickness and air/rubber ratio in the vehicle’s tires.

**Methodology and Approach**

Generation of splash and spray can be simplified as a process of droplets shooting from the tire to the air. However, given the nature of the fluid/cloud, it is very hard to distinguish one droplet from another, let alone to measure a droplet’s speed or size.

The method proposed in this report measures the droplets using a special laser, which operates at a frequency different from environmental lights, to illuminate the water droplets. Just like the small particles in the air, the human eye won’t see those particles until one beam of strong sunlight cuts into the shadow. The laser illuminates the droplets, a camera is used to capture them, and an image-processing algorithm is employed to find the requested result. The work included for the proposed method included developing the laser-camera system, mounting the system in a vehicle, and preparing the image-processing program.

**Equipment Development**

The prototype system deployed for the experiment is shown in Figure 1. The system consists of three major parts: the camera; the laser generator; and the frame, which includes two waterproof box containers for the camera and laser generator. The laser generator produces a laser curtain that lights up droplets as they cross it, and the camera takes pictures of those droplets.

The working environment for this system is shown in Figure 1 (b). As the camera is intended to catch the droplets lighted by the laser, the experiment must be performed without other sources of illumination. This situation is easy to create in the lab, but rather difficult to produce on the road. To reduce the light disturbance, the field experiment will be conducted at night. A filter that filters out other light will also be installed on the camera. Before getting on the road, laboratory tests will be conducted to preliminarily validate the idea.
Preliminary Laboratory Testing

Laboratory tests were conducted and the results analyzed. Images were collected in the laboratory and were assumed to be in ‘perfect’ condition, as there was neither vibration nor other light sources in the laboratory. The collected images were processed with MATLAB using the procedures visually summarized in Figure 2.

Figure 2 shows the droplets count procedure for the laboratory experiment image, which has a pure dark background (Figure 2 [a]). On the image, each droplet can be seen as a point spread function from the center point. The droplets were found by locating all the local peaks on the image. Figure 2 (c) prints the droplets count over the raw image (background), showing a good fit. Using this procedure, the splash and spray quantity can be estimated by counting the number of droplets on each picture in the perfect condition.
Road Testing

After being verified in the laboratory, the prototype system was tested on the road, running at three different speeds: 30 mph, 45 mph, and 60 mph. For the field experiments, it was inevitable that the results might be affected by some noise, with vehicle vibration being the most likely primary source. To address this problem, the laser and camera were installed on the same frame, and the stiffness of the frame was increased. The environmental light was another potential expected source of noise. This issue was addressed by conducting the experiment in the evening to reduce the effect of environmental lights. The beam laser and corresponding filter were also used in the field experiments. The whole test process was recorded, and one frame of the video is presented in Figure 3 as an example of the results.
Figure 3: One image taken during the road test.

As Figure 3 shows, when the experiment was moved from the laboratory to the road, the image was noisier. The vibration of the vehicle caused blurring, the light source in the direction of the camera formed large light spots, and the water deposited on the camera cover reduced the image quality. Although the noise could not be totally removed, a filter was used to reduce the strength of other light sources, and a wiper was used to clean the water from the camera.

Figure 4 shows an example of an image that has been filtered and de-blurred. The filtered image (Figure 4 [a]) looks very similar to the images obtained in lab tests. The light intensity of each pixel in the raw image is shown in colors, as illustrated in Figure 4 (b), which shows the distribution of splash and spray. However, further analysis was necessary to get more accurate results. A background filter was used to eliminate the background noise by deleting a single pixel with extraordinary brightness. The resulting the image is shown in Figure 4 (c). In this image, the number of droplets can be counted by grouping all the pixels that are close to each other with gradational light intensity into clusters, as shown in Figure 4 (d).

The image was then scanned strip by strip for the change of light intensity, and the final distribution of droplets is shown in Figure 4 (e). This image scan curve represents the distribution of light intensity in the image, which means the distribution of splash and spray in the plane. This curve could serve as the basis for quantifying splash and spray, but more data analysis is needed to interpret the curve and combine the distribution at different planes.

In addition to the blurring, other images were affected by light sources. It was difficult to analyze such images because the intensity of the light source was so strong that the data points could not be recognized. As a result, further procedures were required for processing these images, as shown in Figure 5.

When there is a light source in the frame, the raw image will be affected with a lighted cluster at the position of the light source, as shown in Figure 5 (a). In this case, if the image is not treated to eliminate the effect of the light source, the light distribution will concentrate at the position of the light source, resulting in the real valuable data points being overwhelmed, as shown in Figure 5 (b).
Figure 4: Processing of blurred images.
Figure 5: Processing of the images with surrounding light sources.
The problems associated with the light source are also evident in the image scan curve shown in Figure 5 (c). The light intensity around the light source is increased notably, so the scanned curve is dominated by the light source and the details of the actual distribution cannot be detected. In this case, two filters are used: the first eliminates the background noises as shown in Figure 5 (d), and the second reduces the effect of the light source, as shown in Figure 5 (e). In this way, the images with a light source can be processed and the droplets on the image can be recognized and counted.

RESULTS

A total of 874 images were collected in the three road tests. These included 443 images for the 30 mph test, 247 for the 45 mph test, and 184 for the 60 mph test. The number of the droplets on each image was counted and summarized as shown in Figure 6 for the runs at 30, 45, and 60 mph.

Figure 6 shows that the magnitude of the splash and spray, induced by the moving vehicle, can be compared using the number of the droplets captured in the images. The splash and spray is dynamic and complicated, affected by many uncontrollable factors. As a result, the number of droplets fluctuates significantly, as shown in all three sub-figures of Figure 6, and the splash and spray quantity changes all the time.

Since the vehicles in the road tests were driven manually, it was impossible to keep the speed exactly the same throughout the whole process. This was especially true at the beginning and the end of the tests. Acceleration and deceleration might break the balance between the tires and the water film and induce more splash and spray. Figure 6 shows that this theory can be validated, as the largest number of droplets, and therefore the largest splash and spray, can always be found at the beginning and end of the test. If we remove the beginning and the end of each test, the measurements are more uniform. Figure 6 also clearly shows that, as expected, the number of droplets increases as the speed increases. Finally, Figure 6 shows that the number of droplets is zero at many points during the road tests. This is because some raw images were too noised for droplets to be identified.
CONCLUSIONS AND RECOMMENDATIONS

This report summarized an effort to develop a system to quantify splash and spray on in-service roads. The effort included the development of a proof-of-concept system featuring the integration of a light source (beam laser) and a camera, and development of the image processing software. Laboratory and road tests were used to validate the proof-of-concept.

The testing results suggest that the system can be used to detect and count droplets both in the lab and in the field. However, more work is needed to further filter the images collected while measuring under regular road operation conditions to obtain repeatable and reliable results. It is recommended that the system be improved by acquiring a higher-speed camera and better filters, as well as by developing better image processing algorithms.
REFERENCES


