Splash and Spray and its Impact on Drivers

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ABSTRACT

Under some conditions splash and spray create a significant nuisance to road users and some evidence suggests that they contribute to a small but measureable proportion of crashes. The paper presents a model for predicting splash and spray. The model was developed to assist engineers in decisions concerning the type and priority of maintenance on the road network. Benefits of reducing splash and spay include increased user satisfaction with the network, as well as possible reductions in road crashes and detrimental pollutants being deposited on roadside assets.

The developed splash and spray model consists of three sub-modules: (1) A water film thickness model that predicts the water film thickness on pavement surfaces based on pavement surface properties and rain intensity; (2) An exposure model that estimates the amount of water that is going to be projected by the tire given the water film thickness, pavement characteristics, and vehicle speed; and (3) A splash and spray model that predicts pavement surfaces' propensity for splash and spray occurrence based on the other two models.

Field tests under controlled rainfall conditions were conducted to assess the impact of various levels of splash and spray on user comfort and perceived safety. Based on the results of these tests, a new method of measuring splash and spray, by computing an *occlusion factor*, was proposed. The models were implemented in simple prototype tools and validated through a series of additional field experiments. These experiments confirmed that the developed splash and spray assessment model is practical and can be used to support highway engineers' decisions regarding highway design and maintenance.

1 INTRODUCTION

The effects of vehicle splash and spray are well known to motorists who have driven in wet weather conditions. Splash and spray contribute to a small but measureable portion of road traffic accidents and are the source of considerable nuisance to motorists. Splash and spray from highway pavements also can carry a number of pollutants and contaminants. When deposited, these contaminants can be poisonous to plant life and accelerate the corrosion of roadway appurtenances.

The objective of this paper is to present a splash and spray assessment model developed under a project sponsored by the U.S. Federal Highway Administration (FHWA). The project started with an evaluation of prior work in the area of splash and spray mechanisms. It then followed with the development of the three sub-modules that comprise the splash and spray assessment tool: (1) A water film thickness model that predicts water film thickness on pavement surfaces based on pavement surface properties and rain intensity; (2) An exposure model for estimating the amount of water that is going to be projected by the tire given the water film thickness, pavement characteristics, and vehicle speed; and (3) A splash and spray model that predicts the likelihood of splash and spray occurrence based on the other two models.

The project also proposed a new method of measuring splash and spray, by computing an *occlusion factor*. The calculated occlusion factor measures the loss of visibility because of the splash and spray produced, and the report links it with various user perceptions. Finally, the models were implemented in simple prototype tools and validated through field experiments. These experiments showed that the developed splash and spray assessment model is practical and can be used to support highway engineers' decisions regarding highway design and maintenance.

2 LITERATURE REVIEW

A review of available literature has shown that there has been a considerable amount of research into the problem of splash and spray, but the results of this research are often inconclusive and contradictory. The mechanisms that lead to the generation of splash and spray require the consideration of several factors when modeling splash and spray (Sanders et al. 2009).

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" refer to two separate processes whose definitions are usually given as a function of the droplet sizes produced or by the process by which they are created. Pilkington (1990) defines **Splash** 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 inches) in diameter, which follow a ballistic path away from the tire." **Spray** is defined as being formed "when water droplets, generally less that 0.5 mm (0.02 inches) in diameter and suspended in the air, are formed after water has impacted a smooth surface and been atomized." Though splash and spray are separate processes, they are often referred to collectively because of the difficulty of monitoring and measuring them individually.

When traveling at high speeds on wet roads, the tires of a truck can displace many gallons of water per second by four well-established primary mechanisms: bow splash waves, side splash waves, tread pickup, and capillary adhesion (Weir et al., 1978). These mechanisms are illustrated in Figure 1.

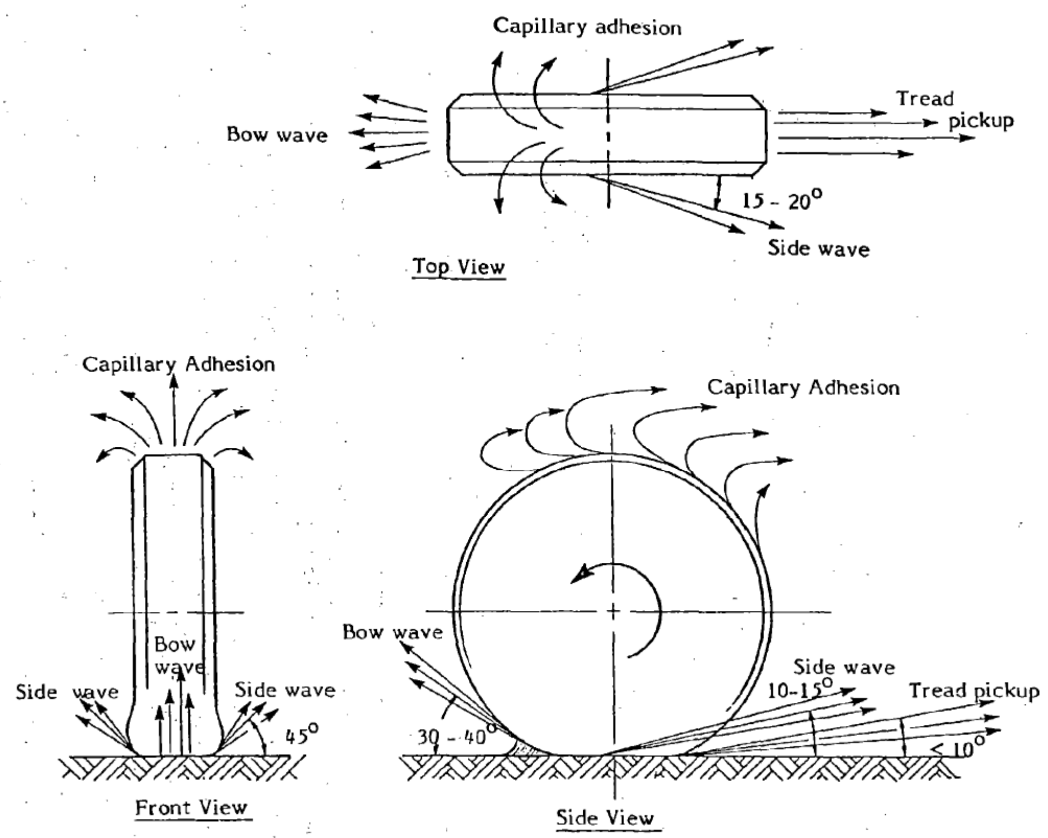

Figure 1. Diagram. Mechanisms of splash and spray (Weir et al., 1978).

The bow and side waves consist of relatively large drops (splash). Water passing through the tire tread grooves is either thrown up into the air immediately behind the wheel as tread pickup or is retained on the tire surface as a thin capillary film. Tread pickup shatters into smaller droplets (spray) through interaction with the turbulent airflow or by impacts with following tires or other parts of the vehicle structure. Water held in the capillary film creates additional spray as it is stripped off near the top of the tire by the incoming airflow.

2.1 Water Film Thickness

There are several models for the calculation of water film thickness that are based on geometric, environmental, and surface properties (Gallaway et al. 1971; Anderson 1995; Huebner et al. 1997; Roe et al. 1997). Though these models share some common features, they are not all the same. The main factors considered include drainage path length and slope of drainage (affected by cross slope and gradient), rainfall rate (or excess rainfall rate), and pavement texture depth (related to Manning's Coefficient).

2.2 Splash and Spray

The main factors affecting the generation of splash and spray are well documented. They are listed by Resendez et al. (2007) as:

- Water film thickness.
- Vehicle speed.
- Tire geometry and inflation, as well as tread design and condition.
- Vehicle aerodynamics.
- Vehicle spray suppression devices.
- Wind vector.

The first three factors impact the interaction between the tire and the pavement, which is the main focus of the project discussed in the paper. There are also limitations to the amount of splash and spray generated. For example, under certain conditions, if the water film thickness and speed are such that a layer of water completely separates the tire from the road, providing negligible skid resistance, hydroplaning may occur.

2.3 Measurement techniques

The techniques most commonly used to measure splash and spray include the following:

- **Collection** – A proportion of the generated splash and spray is collected within a container and assessed after testing to provide a representative sample of the splash and spray generated. Variations of this technique have been used by Maycock (1966) and Ritter (1974) among others.

- **Contrast change** – Images of a standardized target before and during spray are analyzed using image analysis technology, and the differences are used to estimate the amount of spray. This technique has been used by Ritter (1974) and Manser et al. (2003), among others.

- **Light attenuation** – A light source is directed through a spray cloud at a photocell a fixed distance away. The light becomes scattered through the spray, and the amount of light collected by the photocell gives an indication of the quantity of spray. This technique has been used by Ritter (1974), Koppa et al. (1985), and Manser et al. (2003).

- **Subjective observation** – Images of, or the direct observation of, spray testing has been undertaken by a number of people. Each image or test run is scored, and a subjective quantity of spray is obtained. Though this method has very poor repeatability, it can be a useful technique for confirming results gained by other means. Pilkington (1990) and Baughan and Byard (1997) used observers to rate the reduction in visibility caused by a spray cloud in conjunction with a laser transmittance technique. Good correlation was found between the two techniques, which provides extra confidence in the results and demonstrates that the nuisance caused by spray can be inferred from the transmission technique.

3 EXPERIMENTS

The experimental phase consisted of four stages:

1. Laboratory experiments to develop the water film thickness.
2. Initial field tests for assessing the impact of splash and spray on road users.
3. Computational fluid dynamic (CFD) simulations of the mechanisms of splash and spray generation to generate the model.
4. Additional field experiments to validate the splash and spray model.

3.1 Water Film Thickness Experiments

A set of laboratory experiments were conducted at the University of Nottingham to develop the water film thickness model that was used as part of the model to determine the volume of water present for splash/spray formation. The literature review revealed that most models included the following parameters: texture depth, length of the flow path (drainage length), rainfall rate (intensity), slope, and Manning's coefficient. The researchers developed a general water film thickness model based on flume experiments conducted on six types of surfaces (stone mastic asphalt, dense-graded asphaltic concrete, porous asphalt, smooth concrete, tined concrete, and Perspex). The water film thickness model developed as part of this research is presented in the next section.

3.2 Initial Controlled Condition Field Tests

A series of field tests were conducted to assess the impact of splash and spray on road users. These tests linked the experimental data, the splash and spray model, and threshold values for the classification of the model output. The tests were conducted at the Virginia Smart Road, following a full-factorial experiment that considered four within-subject independent variables—Driver Vehicle, Spray Vehicle, Maneuver, and Rain Rate—and defined five subjective user perception variables and an objective occlusion measure. The occlusion factor was defined as the ratio of the mean luminance of the black squares to the mean luminance of the white squares on a large checkerboard placed on the splash and spray-generating vehicle, as captured by a camera placed on the following vehicle and pointing toward the board. The results were used to quantify user responses (subjective ratings) to a range of different conditions under controlled conditions at the Virginia Smart Road (Flintsch et al. 2012).

3.3 Computational Fluid Dynamic Simulations

The CFD model was used to predict splash and spray generation by the four prevailing mechanisms—bow wave, side wave, tread pickup, and capillary adhesion—for different vehicle speeds and water film thicknesses. This was done by simulating, in a virtual wind tunnel, the most critical maneuver and vehicle combination identified in the field experiments. The outcomes of the various simulation runs were synthesized in a set of simple equations that model the mechanisms and combine them into a simple set of equations to model pavement splash and spray as presented in the following section. These equations were used to develop two simple prototype tools to illustrate the practicality and ease of implementation of the developed approach.

3.4 Validation Field Experiments

A second set of experiments conducted under controlled conditions at the Virginia Smart Road were used to validate the splash and spray model. The model predicted splash and spray values that approximately follow the trends observed in the field. Implementation of the model in decision support tools showed that the approach can be easily implemented using available pavement-surface data.

4 RESULTS

The main product of the study was a model that can be used to predict splash and spray based on pavement surface characteristics and climatic conditions. The model can provide useful information for supporting highway design and maintenance business processes. The following steps summarize the process that should be followed to calculate the splash and spray, according to the developed assessment tool:

1. Compute the water film thickness based on the rainfall intensity and pavement surface properties:

   $$WD = 6x10^{-4}\, T^{0.09}\, (LI)^{0.6}\, S^{-0.33}$$

   where:
   WD = water film thickness (m)
   T = texture (mm)
   L = drainage length (m)
   I = rainfall intensity (m/h), modified for considering the drainage ability if the surface is a porous layer
   S = slope (ratio)

2. Compute the maximum amount of water available for splash and spray, MR_W, based on the computed water film thickness:

   $$MR_w = V \cdot b \cdot WD \cdot \gamma_W$$

   where:
   V = truck speed (m/s)
   b = tire width (m)
   γ_w = density of water

3. Compute the contribution of each splash and spray mechanism, using the following equations in the order presented until the total amount of available water is exhausted. The tread pickup (MR_{TP}) will be activated only if there is water remaining after the capillarity adhesion (MR_{CA}), and the bow (MR_{BW}) and side waves (MR_{SW}) will be activated only if there is water remaining after the capillary adhesion and tread pickup.

   $$MR_{CA} - V \cdot b \cdot K \cdot h_{film} \cdot \gamma_W$$

   $$MR_{TP} = V \cdot b \cdot (1 - K) \cdot h_{groove} \cdot \gamma_W$$

$$MR_{BW} = \alpha \cdot \gamma_W \cdot b \cdot V \cdot \left(WD - K \cdot h_{film} - (1-K) \cdot h_{groove}\right)$$

$$MR_{SW} = (1-\alpha) \cdot \gamma_W \cdot b \cdot V \cdot \left(WD - K \cdot h_{film} - (1-K) \cdot h_{groove}\right)$$

where:
MR_i = input mass flow rate per wheel for mechanism *i* (kgs^{-1})
K = factor that indicates the proportion of the tire width that is not a groove (ratio)
h_{film} = depth of the water film (m) picked up on each rotation; assumed to be 0.0001 m (0.004 inches) or the depth of water if lower
α = proportion of water (ratio) for the wave mechanisms (MR_w - MR_{CA} - MR_{TP}) that corresponds to the bow wave
h_{groove} = depth of water (m) in the tire tread; assumed to be 0.01 m (0.4 inches) or the depth of water if lower

4. Compute the spray density corresponding to each mechanism based on the corresponding mass flow and the speed of the truck:

$$SD_{CA} = (-2.69 \cdot 10^{-5} \cdot V' + 2.43 \cdot 10^{-3})MR_{CA}$$

$$SD_{TP} = (1.16 \cdot 10^{-5} \cdot V' - 5.25 \cdot 10^{-5})MR_{TP}$$

$$SD_{BW} = (2.67 \cdot 10^{-5} \cdot V' - 4.71 \cdot 10^{-4})MR_{BW}$$

$$SD_{SW} = (1.65 \cdot 10^{-5} \cdot V' - 3.99 \cdot 10^{-4})MR_{SW}$$

where:
SD_i = total spray density for mechanism *I* (kgs^{-3})
V' = speed of the truck (mi/h).

5. Compute the total spray density:

$$SD_W = SD_{CA} + SD_{TP} + SD_{BW} + SD_{SW}$$

6. Convert the spray density level to a subjective nuisance index, for example, as presented in Figure 2.

Figure 2 was prepared to show the practicality of the splash and spray prediction model on an actual segment of road using data provided by the Florida Department of Transportation (DOT). The road segment chosen for this calculation is a state route located in Alachua County, Florida. This section of road was evaluated as part of the Florida DOT's research "Automated Cross-Slope and Drainage Path Method."

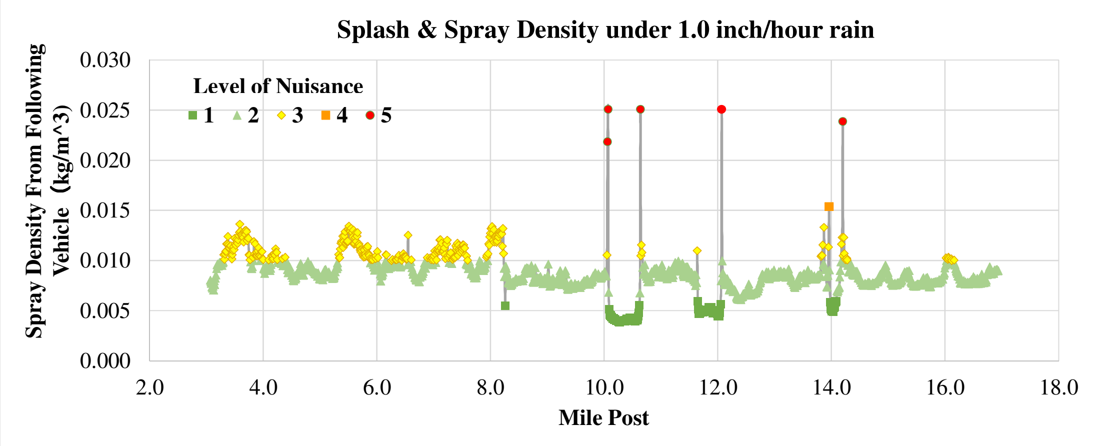

Figure 2. Splash and spray density for a 1-inch/h (25-mm/h) rain (4-hour level).

5 CONCLUSIONS

The paper summarized the development of an assessment tool to characterize the propensity of highway sections to generate splash and spray during rainfall and the impact of splash and spray on road users. The process confirmed that the development of the model is feasible and that the developed splash and spray assessment model was practical and can be used to support highway engineers' decisions regarding highway design and maintenance.

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Author Biographies

Alan Dunford

Alan manages a portfolio of projects related to measurement research and advice. The projects are generally focussed on material properties, skid resistance and monitoring of other pavement surface characteristics as well as aspects of road user safety such as splash/spray generation and asphalt durability. Alan leads a team of staff, coordinates activities in over 20 projects and provides technical input and guidance. Alan leads research into new devices such as the Wehner-Schulze polishing machine and novel techniques such as the contactless measurement of microtexture; the latter formed the basis for his part-time study for a PhD at the School of Civil Engineering at the University of Nottingham.

Helen Viner

An experienced scientist and manager, Helen joined TRL in 1997 after two years of post-doctoral academic research. In January 2013, she was appointed as Chief Scientist and Research Director for Infrastructure Division, a role that includes developing collaborative research partnerships, preparing proposals for research funding, oversight of technical quality, and communicating our activities internally and externally. She is also the UK Research Coordinator within FEHRL (the Federation of European Highway Research Laboratories). Prior to this role, Helen led Infrastructure Division's Safety and Consultancy Group, with 11 technical specialists and a portfolio of projects for Government, private sector and overseas clients. Helen has worked extensively on the surface characteristics of road pavements, being responsible for innovative research and developing associated advice and standards. Her expertise includes tyre-road interaction (friction, splash/spray, rolling resistance and noise), accident trends, condition monitoring and management performance indicators.