Splash and spray assessment tool development program
First interim report: revised synthesis report

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First Interim Report: Revised Synthesis Report

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Executive summary

The effects of vehicle splash and spray are well known to motorists who have traveled in wet weather conditions. Research suggests that splash and spray contributes to a small, but measureable, proportion of road traffic accidents and is a considerable nuisance to motorists. Furthermore, splash and spray from highway pavements can carry a number of pollutants and contaminants. When deposited onto roadsides, these contaminants can be poisonous to plant life and can cause the accelerated corrosion of roadside assets.

Splash and spray are two individually definable processes and are a product of a number of different contributory factors. Extensive effort has been made by many parties to engineer means of reducing the splash and spray created by motor vehicles, especially that from heavy vehicles, by retrofitting devices that alter the vehicle's aerodynamics. Another possible solution to the problem of splash and spray is to change the characteristics of the highway pavement. Previous research shows that pavement geometry, drainage, texture, and porosity all contribute to splash and spray generation, but the exact mechanisms are largely unknown. The development of a model capable of predicting the splash and spray propensity of pavements would be a useful tool in aiding highway engineers’ decisions regarding highway maintenance and design.

This report describes results of a literature review to assess both the state of the art and scope for future development of splash and spray modeling technology and its associated topics. Such a model requires an understanding of its various potential inputs including: water film thickness, pavement texture, road geometry and rainfall.

The literature has shown that, although a direct relationship between water depth and splash and spray has not been conclusively found, the presence of water on the pavement surface is clearly a necessary prerequisite for splash and spray generation. There already exist a large number of models that predict water depth that use combinations of input parameters such as pavement geometry, rainfall rate, pavement texture, and drainage. Although these important parameters seem common to most models, there is no consistency, and some also use more complex variables such as Manning’s roughness coefficient, pavement porosity, and angle of rainfall. The literature review has identified a number of equations, and these will be reviewed more thoroughly as part of a desk study to attempt to develop a more generic water depth model.

The literature has shown that, although splash and spray can be defined individually, in practice it is very difficult to measure them separately, and they are consequently treated as a combined factor. Without being able to measure them individually, it is likely to be very difficult to validate any model that treats them as separate phenomena, and this is one of the challenges to be faced when developing the assessment tool. There is some agreement in the literature that the factors that commonly influence splash and spray generation include water film thickness, vehicle speed, tire geometry and tread depth, and vehicle aerodynamics. A common conclusion is that speed is the most important of these. Research treating speed and the presence of water frequently investigates hydroplaning (where a film of water separates the tire and the road, leading to very low friction), and it may be necessary to account for this phenomenon in the assessment tool.

In order to carry out validation, it will be important to develop a reliable method to measure the splash and spray generated while the various influencing factors are
altered. The literature contains a number of references that reports attempts to do this, and the most commonly used techniques are as follows:

- **Collection** – water generated by splash and spray is collected in a container attached to, or following the generating vehicle, and the amount of water is measured.

- **Contrast change** – images of a standardized target are analyzed before and during spray, and the difference in contrast between the images is calculated.

- **Light attenuation** – a light source is directed through a spray cloud at a photocell located a fixed distance away. Light is scattered through the spray so the amount of light collected by the photocell gives an indication as to the quantity of spray.

- **Subjective observation** – images of, or the direct observation of spray testing, is undertaken by a number of people. Each image or test run is the scored, and a subjective quantity of spray is obtained.

The review of available literature has revealed that there are no published complete and working models for the prediction of splash and spray. Furthermore, there is a considerable amount of ambiguity over the extent of the effect from the various factors that are thought to influence splash and spray or water depth. The information documented here will be used to steer the direction of the development of the splash-spray assessment tool and to confirm the need for the proposed experimentation and rigorous validation of the model.
Abstract
This document is the first deliverable in a joint project between TRL, Nottingham University and VTTI to develop a splash and spray prediction model for road surfaces. This document summarises and analyses the prevalent literature surrounding splash and spray generation, modelling and road user impact.

1 Introduction
The effects of vehicle splash and spray are well known to motorists who have traveled in wet weather conditions. Research suggests that splash and spray contributes to a small, but measureable, proportion of road traffic accidents and is a considerable nuisance to motorists. Furthermore, splash and spray from highway pavements can carry a number of pollutants and contaminants. When deposited onto verges and road hardware, these contaminants can be poisonous to plant life and can cause the accelerated corrosion of road and street hardware. Attempts have been made to reduce the amount of splash and spray generated by vehicles, but differing results are gathered as to their effectiveness. Some researchers report a 60% improvement in visibility when using a spray suppression device, but others testing similar devices report no significant improvement.

Another possible solution to the problem of splash and spray is to change the characteristics of the highway pavement. Previous research shows that pavement geometry, drainage, texture, and porosity are all contributing factors to splash and spray. An unknown, however, is how each of these factors contributes to the splash and spray propensity of a pavement. The development of a model that is capable of predicting the splash and spray propensity of pavements would be a useful tool in aiding highway engineers’ decisions regarding highway maintenance and design. This report describes results of a synthesis to assess both the state of the art and scope for future development of splash and spray modeling technology.

1.1 Project Objective
This review has been carried out as part of a project to develop an assessment tool to characterize the propensity of highway sections to generate splash and spray during rainfall, and for this propensity to be assessed in terms of the impact on road users. The overriding objective of the project is that this tool, after being developed into an appropriate software application, will contribute to on-going efforts to improve user satisfaction with state highways.

Consequently, the final model must be robust, practical, and capable of being implemented by highway administrations throughout the U.S., considering both the variation in pavement construction, climate, traffic levels, and data collection capabilities. Furthermore, the model will be calibrated against user responses, so an appropriate level of priority is assigned when different values are obtained in the model output.

The specific objectives to be accomplished within the project are the following:

1. An evaluation of prior work in the area of splash and spray mechanisms (this work is summarized in this synthesis);
2. Development of a model to predict water film thickness and splash and spray occurrence on pavement surfaces, encompassing an appropriate range of conditions;

3. Validation and refinement of the model developed;

4. Development of recommendations as to threshold criteria to classify the impact of splash and spray on highway users; and

5. Documentation of the development efforts and preparation of technology transfer materials.

1.2 Overview of the Report

The modeling of splash and spray potential of pavements can be broken down into three components: (1) determining the water film thickness given the pavement characteristics and rainfall rate; (2) 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) determining the user exposure by predicting the likelihood of a specified amount of spray being generated given local meteorological conditions and the propensity of the pavement to generate splash and spray. In addition, the model may include threshold criteria to classify the impact of splash and spray on highway users.

Within this framework, the report is organized into six main sections. This first section presents the problem and objective of the study, as well as the organization of the report. The second section defines and discusses the splash and spray mechanisms. Sections 3-5 discuss the background for the three models mentioned in the previous paragraph. Section 3 focuses on the determination of the water film thickness as it is a key input in estimating the amount of water available to be projected by the vehicle tires as splash and spray. Section 4 discusses additional factors that affect splash and spray and the attempts that have been made to model these phenomena. Section 5 covers the use of the models to define a splash and spray exposure parameter. Section 6 summarizes the main findings and conclusions of the study.
Splash and Spray Mechanisms

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 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 in.) in diameter, which follow a ballistic path away from the tire.”

- **Spray** 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 collectively because of the difficulties that can arise when attempting to monitor and measure them individually.

When traveling at high speeds on wet roads, the tires of a truck can displace many litres 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 2-1.

![Figure 2-1 - Mechanisms of splash and spray (Weir et al., 1978)](image)
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. Some splash is also shattered into spray by similar mechanisms. Water held in the capillary film creates additional spray as it is stripped off near the top of the tire by the incoming airflow.

To better understand the mechanisms, a tool designed to create spray under controlled conditions was devised by McCallen et al. (2005). Water would be injected onto the interface of two counter rotating tires (one smooth and one with a circumferential groove). The water would then be ejected from the interface and form spray. High speed image capture was used to analyze the interaction. The study examined the case of the “tread pickup” source, and results are summarized below:

1. Just beyond the tire contact patch water completely fills the tire groove (this of course depends on the necessary amount of free water available).

2. Slightly further downstream the tires separate and are subjected to high accelerations. Some of the water remains within the tire grooves and some is ejected from the interface as a water jet.

3. Further downstream, but within the tire extremities, some water still remains in the grooves, and the ejected jet is more clearly defined. The water remaining in the tire grooves is connected to the central jet by a thin web of water.

4. As the distance between the tires increased, the connecting web continually thins until breaking point where water droplets are produced.

The amount of water thrown up depends on the presence and amount of water available on the road surface, the vehicle type and design, the tires fitted, the speed, and the nature of the road surface. These factors will be discussed in the following chapters.
3 Water Film Thickness

The greater the depth of water, the greater the amount of water there is available to be displaced by a vehicle’s tires. There is no consensus of opinion in the literature about exact relationships between water film thickness and splash/spray, but there is evidence that it is an important consideration (e.g., Koppa et al., 1985), and this will be discussed in more detail in Section 4.1. Furthermore, the literature suggests that water film thickness is heavily dependent on pavement geometry, texture, porosity, and drainage. If the splash/spray assessment tool is to be useful during the design of highways, then the effect of these factors must be taken into account.

Many models for calculating the water film thickness of road pavements currently exist, each with differing levels of complexity and, presumably, accuracy.

3.1 Pavement Geometry

Pavement geometry dictates the length and gradient of the flow path that water has to take before being removed from the pavement. The geometry is introduced into the pavement as a function of longitudinal gradient and pavement cross slope. These geometric features are an important aspect of highway design, and guidelines are published for minimum values. For example, in the UK, the Design Manual for Roads and Bridges (1999) specifies a minimum cross slope of 2.5%. In the U.S., the AASHTO “Green Book” recommends a range of cross slope between 1.5 and 2% for high-type road, but indicates that a slope of 2.5% may be needed in areas of intense rainfall. It also recommends slopes of 2 to 6% low-type surfaces (AASHTO 2004). A geometric function of longitudinal gradient, cross slope, and pavement width produces a drainage length as given in Equation (1):

\[ L_f = \frac{LS_3}{S_1} \]  
\[ S_3 = \sqrt{S_1^2 + S_2^2} \]  

where:  
\( S_1 \) = cross slope gradient  
\( S_2 \) = longitudinal gradient  
\( S_3 \) = drainage path gradient  
\( L \) = width of pavement  
\( L_f \) = length of drainage path

Anderson (1995) indicated that this is the distance that water has to travel before it leaves the pavement. One of the simplest equations relating water depth to drainage length, rainfall intensity, and the slope of the drainage length was proposed by Ross and Russam (1968):

\[ d = 0.015(L \times I)^{1/2} N^{1/3} \]  

where:  
d = water depth (cm)  
\( L \) = drainage length (m)  
\( I \) = rainfall intensity (cm/h)  
\( 1/N \) = slope of drainage length
This relationship shows that the water depth increases if the drainage length increases and decreases if the gradient of the drainage path increases.

Since that research was conducted, a number of other researchers, including Gallaway et al. (1971), Huebner et al. (1997), Roe et al. (1997), and Resendez et al. (2007), have attempted to calculate water depth from pavement geometry. However, research by Pruyost and Gothie (1998), which examined nine different models for predicting water film thickness, suggests that accurately calculating water depth may require a larger number of variables to be considered, in particular a variable for texture. The various equations postulated here and those in the following paragraphs will be analyzed together as part of a desk study in an attempt to identify common mechanisms and suggest a generic water depth model.

Furthermore, pavement deterioration, such as rutting and studded tire wear in PCC pavements may contribute to longer drainage path and higher water depths.

3.2 Pavement texture and Manning’s Coefficient

Pavement texture provides a capacity for water to be held below the surface of the pavement and provides drainage for this water between the aggregate chippings of the road surface. Moore (1970) described a device that was capable of measuring the capacity for pavement texture to aid in drainage called an “outflow meter.” A commercial version of this device is the “Hydrotimer”\(^1\). In addition to a contribution to drainage, however, the texture of the pavement is also likely to contribute to the turbulence of the flow of water on its surface.

Roe et al. (1997) and Gallaway et al. (1971) devised similar equations to calculate water depths using drainage length, slope, rainfall intensity, and pavement texture. In these models, the texture variable was subtracted from the overall water depth to give the “free water depth.” Roe et al. observed a difference between measured and predicted values when validating their model, and it was considered that this was due to the hydraulic roughness having an increased effect on the flow of the water and therefore increasing the water depth.

Anderson et al. (1998) provided details of models to predict water film thickness as part of the PAVDRN software used to predict the hydroplaning speed of highways. The models used as part of PAVDRN were based on the kinematic wave equation and include the Manning’s roughness coefficient as a variable. This equation is reproduced as Equation (4).

\[
WFT = \left( \frac{n \times L \times i}{36.1 \times S^{0.5}} \right)^{0.6} - MTD
\]

where:
- \(WFT\) = water film thickness (in)
- \(n\) = Manning’s roughness coefficient
- \(L\) = Drainage path length (in)
- \(i\) = Rainfall rate (in/h)
- \(S\) = Slope of drainage path (in/in)
- \(MTD\) = mean texture depth (in)

\(^1\) http://hydrotimer.com/ (accessed 06/09)
In this equation, the Manning’s coefficient is considered an inhibitor to water flow, which results in an increasing water film thickness. The coefficient is a measure of gravity-driven free surface flow, and it can be empirically derived from several factors, including surface roughness. Commonality of different surfacing materials means that specific equations can be written for different surfacing types. Anderson et al. (1998) describes the experimental procedure used for the calculation of the Manning’s coefficients for Portland cement concrete, dense-graded asphalt, and porous asphalt surfaces, as used in the PAVDRN software.

3.3 Pavement Porosity

In dense-graded pavement surfaces, pavement porosity is very low and can be considered negligible when calculating water film thicknesses. However, porous asphalt pavements contain a much higher percentage of air voids within the pavement structure. Because of this, porous asphalt pavements can aid in the removal of surface water by draining water through the pavement.

Researchers tend to agree that the use of porous pavements can reduce the amount of spray generated by a road surface. For example, Button et al. (2004) stated that “PA (porous asphalt) pavements are the most effective products on the market for addressing S&S (splash and spray).” Daines (1992) conducted experiments to relate the hydraulic conductivity to spray generation on porous asphalt surfaces on a highway in the UK. Daines found that the hydraulic conductivity of the pavement tested substantially reduced the water film thickness and the spray propagation of the pavement. “Measurements of spray levels on new porous asphalt show almost no spray raised at speeds up to 110 km/h (70 mph) even in heavy rainfall.” Daines developed the following equation that gave the average percentage spray reduction when compared with hot rolled asphalt (i.e., dense graded asphalt):

\[ S = 270(HC) + 25(SP) \]  

where:
- \( S \) = average percentage spray reduction when compared with hot rolled asphalt
- \( HC \) = relative hydraulic conductivity
- \( SP \) = sand-patch texture depth

The properties of porous asphalt pavements were also observed by Anderson et al. (1998), and an amendment was made to their water depth equation, Equation (4), to include these effects.

\[ WFT = \left( \frac{n \times L \times I}{36.1 \times S^{0.5}} \right)^{0.6} - MTD \]  

Where the rainfall rate, \( I \), has been replaced by:
- \( I = \) Excess rainfall rate (in/h) = rainfall rate – infiltration rate/permeability of pavement.

Pavement porosity can provide some negative effects, however. Several researchers (Anderson et al., 1998, Daines, 1992, and Button et al., 2004) have found that the high void content of these pavements means that the development of ice on the surface is more rapid than on traditional materials. There are also concerns regarding the durability of the porous mixtures. Problems such as delamination from the underlying layers, higher rates of deformation, and raveling have been reported.
3.4 Pavement Drainage

Another way to remove surface water is through the use of pavement drainage systems. Drainage has the effect of removing surface water in a controlled manner and can be used to reduce the drainage length of a pavement. Button et al. (2004) showed how the use of longitudinally installed drainage systems placed between lanes can reduce the drainage length of a pavement.

For a drainage system to be effective it must have a capacity in excess of the demand placed upon it. In the UK, the Design Manual for Roads and Bridges (2000) defines the design capacities of curb stormwater inlets and manhole covers using the following equations:

\[ \eta = 100 - G_d(Q/H) \]  
\[ \eta = 100 - \frac{36.1Q}{L_iH^{1.5}} \]

where:
\( \eta \) = flow collection efficiency (%)
\( G_d \) = grating parameter defined by the type of grating (specified in the manual)
\( Q \) = flow rate (m³/s)
\( H \) = water depth against the kerb (mm)
\( L_i \) = length of the opening in the line of the kerb provided by the inlet (m)

The manual also considers the demand placed upon a drainage system by defining the design rainfall intensity for a storm with a return period of \( N \) years. A series of equations are also given that calculate the flow rate of water that approaches a drainage system.

3.5 Measurement of Water Depth

The measurement of water depth or water film thicknesses is necessary for validating a splash and spray model. Many measurement techniques have been used by different researchers. Ross and Russam (1968) used a steel bar placed on the road surface with studs set at intervals and increasing in height from 0.15 mm to 0.05 mm increments. The water depth was manually read from this bar. Gallaway et al. (1971) used a manually operated Leupold & Stevens point-gauge to take measurements of the water depth from a datum line. This device provided measurements with an accuracy of 0.2 mm.

Kulakowski and Douglas (1990) developed a tool for measuring the water film thickness and claimed an accuracy better than 0.025 mm. The device is shown on the left of Figure 3-1, and it consisted of a motor attached to a micrometer on the end of which was attached an electric probe. When the probe is lowered, a circuit is closed when it comes into contact with water, stopping the electric motor and allowing a micrometer reading to be taken. By lowering the probe further until it strikes the pavement surface, a second reading can be taken, and the water depth can be calculated. A similar principle is deployed by a device called a limnimeter, as used by Coiret (2005) for calibration when researching spectroscopy of pavement wetting states. The device uses...
a pair of metal needles lowered automatically until the water surface closes the circuit between them (shown on the right of Figure 3-1).

More indirect methods of measurement include use of the water’s conductive or absorptive properties. Roe et al. (1997) used a twin metal wire probe developed by HR Wallingford\(^2\). After calibration (for the particular water and its impurities) the resistance measured between the two probe wires, which are at a fixed distance apart, could be used to calculate the water depth. As water depth increased, a greater amount of current is able to pass between the electrodes. Coiret (2005) investigated the specific absorption properties of water for radiation in the near-infrared. A light ray is directed onto a wet pavement and analyzed after having been altered in the liquid medium and retro-reflected by the road surfacing. It was noted that the technique was sensitive to the pavement texture at lower water film thicknesses, but it was possible to reliably measure water levels between 1 and 5 mm.

Figure 3-1 - Water film measurement device developed by Kulakowski and Douglas (1990), and the limnimeter probe used by Coiret (2005).

\(^2\) [http://www.hrwallingford.co.uk/](http://www.hrwallingford.co.uk/) (accessed 06/09)
4 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 (function of pavement porosity, geometry, drainage capability, texture, and rainfall intensity as discussed in Section 3)
- Vehicle speed
- Tire geometry
- Vehicle aerodynamics
- Vehicle spray suppression devices
- Wind vector

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), then not only will the mechanisms of splash and spray generation change, it is also less likely to be a primary concern to the driver.

4.1 Water Film Thickness

Although water film thickness must be considered a major contributory factor to the generation of splash and spray, specific relationships between it and spray generation have not been widely studied.

As a secondary study to their evaluation of splash and spray suppression devices, Koppa et al. (1985) measured spray generation by a truck traversing three different water depths at approximately 0.5 mm, 1.3 mm and 2.5 mm using laser transmitters. They found that, “Water depth on the pavement appears to have a reasonably linear relationship to spray production.” However, it was also found that, as water depth increases further, the increase in spray production may be lower, and the depths at which this may occur will be close to those necessary for hydroplaning. Conversely, in a separate study, Koppa et al. (1990) found no significant differences in spray generated from water depths of 0.5 mm and 1.3 mm.

Weir et al. (1978) discussed the effect of water depth in terms of whether it is greater than or less than 3 mm. This threshold determines whether or not tire tread grooves are filled and influences the proportion of splash versus spray.

Other studies not directly related to this subject have also found similar results. Chatfield et al. (1979) conducted research into the efficiency of several spray reduction devices. In doing this, conclusions were made about other aspects of spray production, one of which was water depth. The report states that, “The third way of reducing spray is to ensure that water rapidly drains from the road surface.” The researchers also concluded that, when very large water depths were used, no spray reduction device would be expected to produce a significant improvement in spray generation.

4.2 Vehicle Contributions

A large amount of work has been carried out to assess the effect of vehicles on the generation of splash and spray. Early research concentrated primarily on the design or assessment of retrofit splash and spray suppression devices. As this work progressed and the technology available improved, the effect of vehicle aerodynamics on splash and
spray was also analyzed. To this end, much is known about how and where spray is generated around vehicles, but none of the literature found was able to provide mathematical models linking all vehicular factors. Research has also been undertaken to assess the effect of factors influencing hydroplaning. What is universally agreed upon is that the largest vehicle-related factor that influences the generation of splash and spray is its speed.

4.2.1 Vehicle Speed

The effect of speed on spray generation was observed by Maycock (1966), who noticed that at speeds below approximately 50 km/h, spray density was very small, but above this speed, spray density increases rapidly with the following relationship:

\[ SprayDensity = Const.(Speed)^{2.8} \]  \hspace{1cm} (9)

Pilkington (1990) gave very similar limits and relationships to spray production with speed and stated “spray is generally not measurable until speed reaches 50km/h and doesn't become undesirable until the speed is 80km/h” and that “the density of spray increases at approximately three times the speed increase.” Similar results were also found by Chatfield et al. (1979): “spray density increases approximately with the cube of the speed in the range 64-96km/h.” This cube relationship between spray intensity and the vehicle speed was also reported in Resendez et al. (2007).

A different relationship between spray production and speed on dense graded asphalt surfaces was found by Daines (1992), who presented a positive linear relationship (Equation 10). However, this relationship was found as a secondary result and was not the main focus of research.

\[ Spray = 5.07 \times Speed - 54.7 \] \hspace{1cm} (10)

The research mentioned previously would suggest that the minimum speed before measureable spray is generated is in the range of 48 to 64km/h, which provides a lower speed limit for spray production. A maximum speed may also exist, should conditions for hydroplaning be met i.e. at speeds required for hydroplaning the main safety consideration is loss of vehicle control, rather than splash or spray.

The work carried out by Huebner et al. (1997) on water film thickness models produced a series of models relating water film thickness to hydroplaning speed:

\[ HPS = 26.04 \times WFT^{-0.259} \text{ for } WFT < 2.4 \text{ mm} \] \hspace{1cm} (11)

\[ HPS = \left( \frac{10.409}{WFT^{0.06}} + 3.507 \right) \text{ or} \]

\[ HPS = \left( \frac{28.952}{WFT^{0.06}} - 7.817 \right) \times MTD^{0.14} \text{ for } WFT > 2.4 \text{ mm} \] \hspace{1cm} (12)

where:

- HPS = hydroplaning speed (mile/h)
- WFT = water film thickness (in)
- MTD = mean texture depth (in)
4.2.2 Tyre Properties

The mechanisms for splash and spray generation described in Section 2 rely heavily on the presence of water in the tire tread or on the tire surface. Maycock (1966) researched the effect of tread pattern and condition on splash and spray production. Three tread patterns were tested: worn, zig-zag rib, and heavy duty block, and the findings showed that the worn tire produced a larger amount of splash than the other tire types, although no significant change in spray production was found. He also observed that the worn tires threw more water out sideways. An experiment that collected splash water behind a vehicle fitted with either patterned tires or with smooth tires showed that the distribution of water across the width of the vehicle was much more skewed to the side it was also found the smooth tires.

Many researchers believe that tire geometry (particularly footprint aspect ratio and inflation pressure) are important factors in calculating the minimum vehicle hydroplaning speed. Research conducted by Horne et al. (1986) set out to ascertain a relationship between tire inflation pressure and footprint aspect ratio (width of footprint / length of footprint) to hydroplaning speed for a given water depth. The relationship for aspect ratios between 0.4 and 1.4 was found to be:

\[ V_p = 51.8 - 17.5FAR + 0.72p \]  

where:
- \( V_p \) = hydroplaning speed (mile/h)
- FAR = footprint aspect ratio
- \( p \) = inflation pressure (lb/in\(^2\))

Similar experiments at the Texas Transportation Institute, summarised by Yager et al. (2009), concluded a relation that existed as follows:

\[ VEL = 23.3(P)^{0.21} \left( \frac{1.4}{W/l} \right)^{0.5} \]  

where:
- \( VEL \) = minimum hydroplaning speed in mph
- \( P \) = tire pressure (lb/in\(^2\))
- \( W \) = width of tire contact patch
- \( l \) = length of tire contact patch

A computational model to predict hydroplaning potential was developed by Ong and Fwa (2007). This model used an analytical method to predict hydroplaning speed. Firstly, the footprint is calculated based on inflation pressure and wheel load. The model then simulates the wheel sliding over a pavement with a given depth of water at a given speed. The speed is increased incrementally until a state is reached whereby the calculated fluid uplift is equal to or exceeds the wheel load. At this point the wheel is considered to be hydroplaning. The accuracy of this method is limited by the incremental increase in speed and is only intended to produce a rough estimate of hydroplaning speed.

4.2.3 Tyre/Road Interaction

It is the interaction between the tire and the road that generates splash and spray, and it will therefore be important to consider how the factors already encountered (e.g.
pavement texture, tire properties) also affect the interaction between the tire and the road. Although this is an extensive and complex topic, and most research in the field has investigated the affect of tire/road contact on friction (rolling and sliding) and noise generation, it must be borne in mind that, for example, the effect of changing road texture will influence more than the volume of water present on the surface.

It is thought that, when a tire rolls or slides over a wet road surface, there are three distinct zones of contact (Gough, 1974 and Moore, 1975). The tire squeezes water out in front of it, and the front part of the tire in zone 1 (Figure 4-1) floats on an unbroken, thin film of water. Further back, in zone 2, the tire is able to drape over the larger asperities and will begin to make actual contact with the smaller asperities. In zone 3, only a thin film of water may remain, and in this area the tire makes contact with the surface through the film. The relative size of these three zones depends on speed, and above a critical speed there may be no contact with the pavement, which leads to hydroplaning, as noted above.

During research to investigate the tire/road interaction and its effect on skid resistance, Parry (1999) concluded that, ignoring the influence of the tire, the geometry of the contact surface determines the level of contact and the pressure distribution between the tire and the surface. The degree of contact between a tire and the surface can be predicted from numerical models derived from pavement profile measurements, and it is possible to estimate the distribution of contact pressures in the tire.

![Figure 4-1 - Three-zone contact concept](Smith, 2008)

### 4.2.4 Vehicle Loading

Data gathered as part of an accident study conducted by Horne et al. (1986) suggests that there is a correlation between truck loading values and the ratio between wet and dry single vehicle accidents. The same paper shows that a variation in vehicle loading can change the tire footprint aspect ratio which, as described above, has an influence on the hydroplaning of the vehicle. Similar work on truck hydroplaning reported by Forrest et al. (2009) produced similar findings, stating: “It was found that empty rigs were three times more likely to be involved in losses of control than were loaded rigs.”
There is also the possibility that a change in vehicle loading could change the stress distribution across the tire footprint and that this could have an influence on hydroplaning speed. However, this is not mentioned in any of the reviewed literature.

4.2.5 Vehicle Aerodynamics

Although vehicle aerodynamics do not contribute directly to the amount of spray produced, the turbulence and areas of varying pressure produced by large vehicles allow the spray particles to be suspended within the air stream. This has an effect on the size and shape of the spray cloud produced.

A full scale comparison between two tractor units was undertaken by Manser et al. (2003). One tractor unit was a 1985 Freightliner, and the second tractor unit was a 1997 Freightliner Century Class S/T. Although not quantified, the 1997 tractor unit was deemed to possess an improved aerodynamic performance over the 1985 tractor unit. A series of tests compared the spray generated by both tractor units using a laser transmittance and video measuring technique. The results gathered showed that the 1997 tractor unit produced a 13.8% reduction in spray when compared with the 1985 tractor unit. The researchers concluded that this reduction in spray was due to the improved aerodynamic qualities of the later model tractor.

Work conducted by the Federal Highway Administration (FHWA) and cited by Pilkington (1990) suggested that the critical areas of induced aerodynamic disturbance were: the front of the tractor unit, the gap between tractor and trailer, around the driving wheels, and the rear of the trailer. If there are additional trailer units, then the gaps between the trailers also become critical areas (Figure 4-2).

![Critical areas of vehicle-induced aerodynamic effects](Figure 4-2 - Critical areas of vehicle-induced aerodynamic effects (Pilkington, 1990))

One-tenth scale wind tunnel experiments conducted by Pilkington (1990), which partially agreed with FHWA results, showed that the front of the tractor unit and the “drive tandem wakes” produced the highest turbulence. However, no mention was made of the gap between trailer and cab or the rear of the trailer.

A computational study of large vehicle aerodynamics was conducted by McCallen et al. (2005) for assessing various aerodynamic improvement devices. This study showed that areas of high aerodynamic disturbance could be found between the tractor and trailer units and behind the trailer as shown in Figure 4-3.
These findings are in agreement with those of FHWA, although they differ slightly in that the area in front of the tractor unit seems to be fairly aerodynamically efficient, but this could be due to the type of tractor unit assessed. The FHWA results were based on a European-style COE (cab over engine) tractor, which presents the airflow with a large surface area, whereas McCallen et al. considered a more aerodynamically efficient American-style CBE (cab behind engine) tractor unit. An additional aspect of this work was to assess the effect of aerodynamic improvement devices on spray cloud generation. A key finding of this study was that the aerodynamic improvements made by the particular devices tested produced a “quantitatively more concentrated” spray cloud that would have a negative effect on motorists’ visibility. The increase in spray density was attributed to a focusing effect experienced by the spray droplets.

A later study by Consano et al. (2007), again looking at drag reduction devices, confirms the critical areas in terms of aerodynamic drag as the tractor-trailer gap, the underbody, and the bluff shape of the rear of the tractor.

While the majority of vehicle aerodynamic studies concentrate on the “straight line” aerodynamics of vehicles, recent work by Hargreaves and Morvan (2008) has shown that, for a vehicle traveling into a crosswind, significant modifications in its wake are seen. In particular, the transverse extent of the wake is increased since the vehicle presents a larger cross-sectional area to the incoming flow, which is a combination of both the vehicle’s movement and the crosswind. The gap between the tractor and trailer actually channels the flow of the crosswind, producing a very distinct jet on the leeward side of the vehicle. Both the widened wake and this jet will have an effect on the transportation of any spray generated.

Another important aspect of vehicle aerodynamics is that of vehicle overtaking. Corin et al. (2008) used two-dimensional computational flow dynamics (CFD) models to look at the forces acting on both the lead and overtaking vehicles as they pass at motorway speeds. Crosswind effects were also investigated, and the conclusion was that existing quasi-static models do not capture the peak forces accurately. Again, the CFD techniques used are of relevance to the present work since overtaking is one of the critical manoeuvres when driving in splash and spray conditions.

4.2.6 Spray Suppression Devices

The topic of spray suppression is well documented and the subject of much research. This literature review discovered a number of documents pertaining to this topic so great that to review each would have been unfeasible. A summary of the most influential and
relevant papers has therefore been included. NHTSA (2000) describes the most commonly used spray suppression devices as:

- **Mud flaps** - a flat, rectangular device usually grooved or coated with durable grass-like material that is placed behind the wheels. The aim of such a device is to catch the spray generated and separate the water from air, which channels this water to the road surface.
- **Side-skirt/valance** – fitted to the vehicle body just above the wheel, this device is designed to contain any spray within the wheel well. Like mud flaps, these may be flat panels with a grass-like or grooved coating.
- **Fenders** – this is a rigid structure placed around part of the wheels. As with a side-skirt, the aim of these devices is to contain the spray within a defined area and channel it towards the road surface.

Mixed results are given as to the effectiveness of spray suppression devices. Some researchers measured no difference in spray production whereas others reported as much as a 60% improvement in visibility.

As a result of early experiments in the 1960s, Maycock (1966) found that the use of a circumferential fender spray suppression device had the effect of reducing spray density 10 m behind the vehicle at 80 km/h by a factor of between 3 and 4, and that spray between the tire and mudguard was “largely eliminated” by the use of a side valance. Pilkington (1990) also assessed the effectiveness of spray suppression devices. This work concluded that, within the trial, the most effective system to suppress spray was a combination of the “Reddaway” system (now known as clear pass) and a drag shield (details of a “drag shield” were not given although a safe assumption would be that this is some kind of aerodynamic device). Pilkington reported that this combination improved visibility by 60% and that the least effective system improved visibility by 18% when compared with an untreated vehicle.

However, evidence has been found by several researchers that seems to contradict Pilkington’s results. Chatfield et al. (1979), Koppa et al. (1985), and Manser et al. (2003) all tested the effect of a number of mudguard/fender geometries or splash and spray suppression devices. Chatfield measured a reduction in spray due to mudguard/fender geometry but saw no visual improvement. Koppa found only “trivial” reductions in spray due to suppression devices. And Manser concluded that “no significant differences were found between the amount of spray produced with the spray-reducing devices and the baseline configuration.”
4.3 The Measurement of Splash and Spray

To validate any splash and spray model, an accurate comparison must be made with empirical evidence. This requires an accurate means of measuring the splash and spray generated by heavy goods vehicles. A number of techniques have been developed to quantify the amount of splash and/or spray generated by a vehicle. The different methods used can be separated into the following categories.

4.3.1 Collection

This technique consists of fitting devices to the measured vehicle itself or to a following vehicle. A technique was used by Maycock (1966) whereby a number of disposable collectors consisting of several layers of absorbent paper would be attached to the bonnet of a following vehicle. During testing the absorbent paper would collect any spray that impacted the collectors. The collectors could then be weighed and the difference in mass before and after testing would provide a measure of the amount of spray generated.

A similar system was used by Pilkington (1990) whereby a spray cloud would be “fingerprinted” by means of capturing droplets in an absorbent screen for a specified length of time. The droplet size and frequency could then be calculated as well as a representation of the spray density.

Maycock (1966) also used a collection system for the collection of splash. A series of polythene bottles were mounted in a line, close to the rear wheels of the measured vehicle. Splash thrown up by the wheels would then be caught in the bottles, and the amount could be calculated.

Figure 4-4 shows a spray collection device developed by Ritter (1974). This device was fitted to the side of the measured vehicle close to the wheels. A proportion of the spray generated by the vehicle would enter the device when the air is separated from the water. This would leave a pool of water in the device that could be quantified and could provide an indication of the amount of spray generated.

![Figure 4-4 - Spray collector (Ritter, 1974)]
4.3.2 **Contrast Change**

The small droplets of water comprising vehicle spray have the effect of scattering light as it passes through the spray cloud. If an image is viewed through a spray cloud, the contrast of the image is reduced as a function of the light refraction occurring within the spray particles. Therefore, if a simple image, such as a black board or checkerboard, is viewed before and during spray, the difference in intensity values will provide a measure of the light scatter and the amount of spray. This technique has been used by Ritter (1974), Baughan and Hart (1988), Manser et al. (2003), and Knight et al. (2005), and it has produced results similar to that of the standard transmittance analysis method detailed below.

A continual measurement system was devised by Knight et al. (2005) using this principle. A black screen would be fixed to the rear of the measured vehicle, and a second vehicle would follow at a fixed distance. A video camera mounted in the following vehicle filmed the screen on the back of the measured vehicle. The images could then be analyzed and the changes in contrast calculated. This device was used on public roads, and it was found that this technique was very susceptible to environmental conditions such as the direction of the sun or changes in light due to cloud cover.

4.3.3 **Light Attenuation**

As mentioned previously, the presence of a spray cloud has the effect of scattering light traveling through it. In addition to reducing the image contrast, this scattering of light has the effect of reducing the strength of a light passing through the spray cloud. Many methods exist that utilize the processes of scattering light, although the most widely used is known as the “transmittance analysis method.”

Early development of the transmittance analysis method was undertaken by Ritter (1974). A 12V automobile headlamp light source was directed longitudinally down the test section at a photometer. The photometer would be linked to a recording device, and light intensity measurements were taken through the spray cloud as a vehicle traveled along the test section. This method worked well, but the use of a visible-light source meant that changes in environmental lighting conditions would affect the result.

This technique was developed further by Koppa et al. (1985), who used low power laser light sources as a replacement to the automobile headlamp. The researchers also used four laser and detector couplings placed on both sides of the test section at varying distances. This configuration allowed characterizing of the effect of wind on spray position. This improvement on the original design has served as the standard method for this technique and is recommended in the Society of Automotive Engineers (SAE) standard practice for splash and spray evaluation J2245. Manser et al. (2003) compared the laser and video-based methods and concluded that the two methods provided very similar results.

4.3.4 **Subjective Observation**

Using photographs, video, or direct observations of splash and spray testing can provide subjective evaluations of the spray cloud properties. Figure 4-5 compares spray and splash images collected by running a truck at 32 km/h and 80 km/h (Chatfield et al., 1979).
Although this method has a 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. This technique also provides an advantage in that the nuisance of splash and spray can be directly measured and contributory factors such as speed can be directly observed.

4.3.5 Other Techniques

Kalantari and Tropea (2006) used the Doppler technique and a high-speed CCD camera in order to measure the amount of splash and spray produced. The Doppler technique is used in order to determine the number flux, size distribution, and the velocity of the water droplets. The CCD camera is used to characterize the droplets and to measure the film thickness caused by the spray.

Salles and Poesen (1999) describe an “optical spectro pluviometer (OSP)”, an infrared optical device used to measure rain drop size, fall velocity, and intensity. The OSP works on the principle of measuring an optical shadow, and it enables independent measurement of drop size and drop velocity in real time. Use of the OSP seems limited to the work of Salles and Poesen but may be applied to the measurement of splash and spray, certainly in the far-field, away from the truck when the droplets have assumed near-vertical trajectories.

4.4 Modeling Splash and Spray

It appears from the literature that there is currently no model capable of displaying or calculating the splash and spray created by a vehicle based on fundamental inputs such as rainfall rate, pavement geometry, vehicle geometry, etc. This is expressed explicitly by Resendez et al. (2007). However, this report does postulate how such a model may be built. The researchers hypothesize that a splash and spray model would exist as a function of water film thickness and air/rubber ratio in the vehicle’s tires. An extract from the paper giving an example of this is provided below.

“To illustrate this it might be assumed that there are four truck tires running two-by-two in the wheel tracks (ruts) of a pavement, each being 0.82 ft (0.25 m) wide expressed as
a contact patch width. A calculation could be made about how much water is accommodated within the tread of the tires. For example, if the tread is assumed to be 0.4 in (10 mm) and the air/rubber ratio in the tread is 30%, this would correspond to an average water depth on the pavement of 0.12 in (3 mm), which is equivalent to a volume of 0.24 gallons/ft (3 litres/m) of pavement before the tread is saturated. Thus, at up to 0.12 in (3 mm) of water depth, one could assume that one may find a reasonably linear relationship between water depth and spray. Splash, on the other hand, would dominate above 0.12 in (3 mm) of water depth (for the example indicated).”

The existing models for splash and spray are derivatives of aerodynamic models, based on Computational Fluid Dynamics (CFD) systems and are not based on fundamental inputs. These models calculate the air flow around a vehicle (usually a simplified computer-generated vehicle model) using commercially available computer software that contains pre-defined fluid mechanics sub-models for fluid flow droplet breakup, fluid temperature, pressure, etc. To model splash and spray, droplets of water are injected into the model at strategic points (usually just behind the wheels). These water droplets are given an initial velocity and size, and the simulation then calculates the flow path of each droplet and changes in size from impaction. This then creates a representative model of the generated spray due to aerodynamic turbulence that can be used in comparative testing.

This technique has been used by McCallen et al. (2005) in the assessment of aerodynamic improvements on heavy goods vehicles on spray cloud generation and by Paschkewitz (2006), who studied the spray dispersion about a simplified trailer wheel assembly. Both papers showed that the use of CFD to calculate splash and spray generation was indeed technologically and financially viable. This is a fairly good technique for aerodynamic properties. However, as stated in Paschkewitz (2006), the injection locations, directions, velocities, and size distribution of the water droplets is largely unknown. This has implications for the comparison of different systems influencing splash and spray, such as wheel and pavement geometry, rainfall rates, etc. However, if a relationship between water depth (a parameter for which there are existing models) and the properties of water droplets created due to tire road contact could be found, then a CFD-based system could be used to accurately model splash and spray generation for many different inputs.

4.4.1 Modeling Rain

While not directly relevant to the modeling of splash or spray, there has been some work conducted recently on the modeling of rain using CFD, which can inform the present study. In the transport field, Abdul Ghani et al. (2001) performed wind tunnel experiments and CFD simulations of rain falling on a car. Chief among the issues of relevance to the present project is a discussion of the fate of water droplets as they impact on a solid surface, either a following vehicle or the ground. Abdul Ghani et al. also classified the size of raindrops (unfortunately without reference) according to the type of rainfall event. Best (1950) was one of the earliest workers to categorize rain by size and velocity, and some of the statistical techniques used here can be applied to the analysis of spray and the subsequent definition of a droplet diameter distribution in a CFD model.
An excellent review of wind-driven rain in the built environment by Blocken and Carmeliet (2004) contains a number of interesting points. It appears that only the smallest rain drops are influenced by high levels of turbulence in the flow, with the medium-sized droplets following streamlines and the largest droplets tending to follow inertia-dominated trajectories.

In the CFD field, Choi (1997) has led the way in the modeling of rain using CFD. He has coined the Local Effect Factor (LEF), which is the proportion of droplets launched from an area upstream of the building that actually has an impact on the building. Such a concept could be applied to a following vehicle in the present work.
5 Exposure to Splash and Spray

Splash and spray causes a significant nuisance to motorists, and, under some conditions, can cause a momentary loss of vision. Accident studies on this topic agree that there is a small but measurable increase in accident risk related to splash and spray. However, the amount of research conducted thus far does not accurately provide the number of accidents caused by splash and spray (NHTSA, 2000 and Botes, 2002). The NHTSA report concluded that, “The number of recorded splash/spray crashes is extremely small,” accounting for less than 0.02% of accidents. The Fatality Analysis Reporting System (FARS) reported that 0.0011% of accidents were caused by splash and spray. The type of vehicle, however, was unable to be determined and therefore cannot specifically be attributed to trucks. The National Automotive Sampling System (NASS) General Estimates System (GES) reported 0.0036% of crashes have been caused by splash and spray. However, these small percentages could partly be due to the fact that most records do not consider splash or spray as a possible cause in accidents, meaning many splash-and-spray-related crashes may have gone unrecorded. The same report also concluded that, “It is unlikely that there is any crash file with better data than FARS or GES. It is unlikely that any state file can provide meaningful data on the question.” These figures could therefore actually be much higher, but it is still unlikely that splash and spray causes a significant accident risk. However, improvements in splash and spray could improve comfort and reduce nuisance experienced by motorists.

5.1 Human Factors

Fuller (2005) describes how driving can be conceptualized by the comparison of the demand of the task to the capability of the driver. When task demand exceeds capability, a loss of control will occur. Task demand is determined by many factors in the driver’s environment, although some are within their control, such as speed. The gap between task demand and capability is the driver’s safety margin and momentary changes in the environment, including splash or spray, will raise task demand and reduce a driver’s safety margin significantly. While a driver could reduce their speed to increase their safety margin in such an event, this is a contradictory behavior when in the process of overtaking. It is likely, therefore, that most of the time, a driver’s safety margin when driving through splash or spray is much reduced, raising a driver’s feelings of risk and anxiety.

There have been a limited number of studies relating to the human interaction with splash and spray; however, work carried out in Baughan et al. (1983) showed that spray from heavy goods vehicles was the highest rated "problem" that heavy vehicles cause to motorists. Pilkington (1990) and NHTSA (2000) presented a series of possible consequences relating to splash and spray that have been combined and condensed in Table 5-1.

Table 5-1 shows that the sources of nuisance to motorists can be separated into three categories: gradual loss of vision, sudden loss of vision, and shock. The only work that was found pertaining to any of these topics was included in NHTSA (2000). This report contains a table showing the times that drivers divert their vision from the road when performing a number of activities such as head turns prior to lane changes or viewing mirrors. The table suggested that an acceptable limit for a loss of vision could be as high as 1.5 s. The study, however, did not assess acceptable times for an unexpected loss of vision, and when overtaking a spray producing truck, it is possible for vision to be
obscured for as much as 10 s. This shows that spray-based vision loss can persist for a considerable amount of time when compared with human tolerance limits.

### Table 5-1 - Potential consequences of splash and spray

<table>
<thead>
<tr>
<th>Category</th>
<th>Motorist affected</th>
<th>Potential problem</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Short term</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead vehicle</td>
<td>Spray obscures following vehicles</td>
<td></td>
</tr>
<tr>
<td>Following vehicle</td>
<td>Visibility – spray from lead vehicle obscures lead vehicle, signs, edge lines, other traffic at intersections, traffic signals</td>
<td>Visibility – doused during passing, lane change</td>
</tr>
<tr>
<td>Approaching vehicle</td>
<td>Visibility – spray obscures vision beyond oncoming vehicle</td>
<td>Visibility – dousing during encounter may cause sudden braking and loss of control or collision with other motorists</td>
</tr>
<tr>
<td>Motorcyclists, cyclists, pedestrians</td>
<td>Numerous visibility problems</td>
<td>Knowing they cannot be seen produces a change in behavior</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Doused when vehicle passes</td>
</tr>
<tr>
<td><strong>Long term</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead vehicle</td>
<td>Dirt deposited on windscreen, mirrors, rear window, lights, and edge lines obscures view</td>
<td></td>
</tr>
<tr>
<td>Following vehicle</td>
<td>Dirt deposited on lights obscures lead vehicle</td>
<td>Dirt deposited on lead vehicle reduces vehicle visibility</td>
</tr>
<tr>
<td>All road users</td>
<td>Dirt deposited on signage and street lighting reduces their visibility</td>
<td></td>
</tr>
</tbody>
</table>

### 5.2 Rainfall Exposure

Rainfall exposure is an important input for a splash and spray exposure model, and rainfall times should be considered because prolonged rainfall will increase the exposure time to splash and spray. Harwood et al. (1987a and b) include information that can be used for this effect. Furthermore, the Enhanced Integrated Climatic Model developed for the Mechanistic-Empirical Pavement Design Guide could be used to obtain climatic data for specific sites.

In a project for CalTrans, Huang et al. (2008) attempted to update the California Wet Percentage Time table. Wet Percent Time refers to the proportion of time during which the pavement is damp enough to cause traffic accidents, and the table defines factors that can be applied to a corresponding list of high accident risk locations in order to develop a list of high wet-accident risk locations. The Wet Percentage Time factors were last updated in 1972. Historical hourly precipitation data in California reported by rain gauges were obtained from five network data sources, and a subset for the preceding 11 years was analyzed using the following process: Reprocessing, Quality Control, and Missing data In-filling. Data handling was a significant issue, and it was found that the data was often of poor quality or incomplete.

The National Oceanographic and Atmospheric Administration(NOAA) provide precipitation frequency estimates based on a partial duration series for most weather stations in the
U.S. As an example, Table 5-2 present the frequency estimated for various durations and average recurrence intervals (ARI)

Table 5-2 - Example of Point Precipitation Frequency Estimates (mm/hr) from NOAA Atlas 14 for Blacksburg VA

<table>
<thead>
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<th>ARI* (years)</th>
<th>5 min</th>
<th>10 min</th>
<th>15 min</th>
<th>30 min</th>
<th>60 min</th>
<th>120 min</th>
<th>3 hr</th>
<th>6 hr</th>
<th>12 hr</th>
<th>24 hr</th>
<th>48 hr</th>
<th>4 day</th>
<th>...</th>
<th>60 day</th>
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<td>41</td>
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</table>

NOTES: NOAA Atlas 14 Document provides more information. Formatting forces estimates near zero to appear as zero.

5.3 Light

Knight et al. (2005) noticed an interesting phenomenon while undertaking contrast change testing of splash and spray. Their methodology was to film a checkerboard as a spray-emitting vehicle passed it. The transmittance value of light reflected from the checkerboard would then be calculated to indicate the amount of generated spray. Under certain lighting conditions it was noticed that the video image could totally “whiteout.” It was thought that, under specific lighting conditions, bright sunlight could be reflected by the spray droplets directly into the camera lens. This effect was not quantified or studied further, but it does raise another question relating to safety in that it could be possible for a motorist to become dazzled by such an occurrence.

5.4 Wind

The effect of wind can have a very strong influence on the position of a spray cloud. This was noted by Koppa et al. (1985), who developed a model to correct for wind effects on the direction of the spray cloud. This model was known as “Rule 4” and assumed that the vector of the spray cloud could be corrected by using a geometric or arithmetic mean of several sensor readings. A diagram illustrating Rule 4 is shown in Figure 5-1.

Specific research into the effect of wind on spray is described by Pendleton et al. (1988). This paper stated that assuming a linear relationship (like that of Koppa et al., 1985) is

an unreasonable assumption, and the paper therefore presented three alternatives based on empirical evidence. The model that showed the smallest mean squared error and best fit is shown below in Equation (14). This model is a piece-wise least squares regression model and was developed using empirical data gathered from a laser transmittance experimental methodology. In this setup, each of four pairs of lasers and sensors were positioned longitudinally down a straight test route and symmetrically at different distances from the center of the test route.

\[ S_i = a_0 + a_1 S_j + a_2 (S_j - a_3) S_0 \]  

(14)

where:

- \( S_i \) and \( S_j \) are paired sensor readings
- \( S_0 = 1 \) if \( S_j \leq a_3 \) and \( S_0 = 0 \) if \( S_j > a_3 \)

Figure 5-1 - Depiction of Rule 4 (dependent variable refers to the amount of spray produced) (Koppa et al., 1985)
6 Conclusions

A review of available literature has shown that there has been a considerable amount of research into the problem of splash and spray, but results are often inconclusive and contradictory. Considering the mechanisms of splash and spray generation shows that it would be important to consider a number of factors when modeling splash and spray.

On the basis that the volume of water present on the pavement surface will be critical to the model, a review of literature specifically concerned with water depth or water film thickness was carried out first. Further literature specifically treating the nuisance caused by water on the surface was found to concentrate largely on measurement methods and empirical techniques for reducing the various phenomena. Additional literature concerning the modeling of water and the estimation of factors that might affect splash and spray (rainfall, wind etc.) was also reviewed. Some of the important points are summarized below.

- **Water film thickness**
  
  There are several models for the calculation of water film thickness based on geometric, environmental, and surface properties, and although there are 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.

- **Splash and spray**
  
  The literature describes the main contributory factors to splash and/or spray as:
  
  - Water film thickness
  - Vehicle speed
  - Tire geometry
  - Tire tread depth
  - Vehicle aerodynamics
  - Vehicle spray suppression devices

- **Measurement techniques**
  
  The techniques most commonly used to measure splash and spray include:
  
  - 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.
  
  - 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.
  
  - 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 as to the quantity of spray.
- Subjective observation – images of, or the direct observation of, spray testing is undertaken by a number of people. Each image or test run is scored, and a subjective quantity of spray is obtained.

- **Limitations**
  Surprisingly, no conclusive link has been demonstrated between water film thickness and splash and spray generation, and there is little knowledge of the effect of splash and spray on motorists’ safety and comfort. These factors must be considered explicitly during experiments carried out in the remainder of this project before a useful model can be achieved.
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References


This document is the first deliverable in a joint project between TRL, Nottingham University and VTI to develop a splash and spray prediction model for road surfaces. This document summarises and analyses the prevalent literature surrounding splash and spray generation, modelling and road user impact.

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