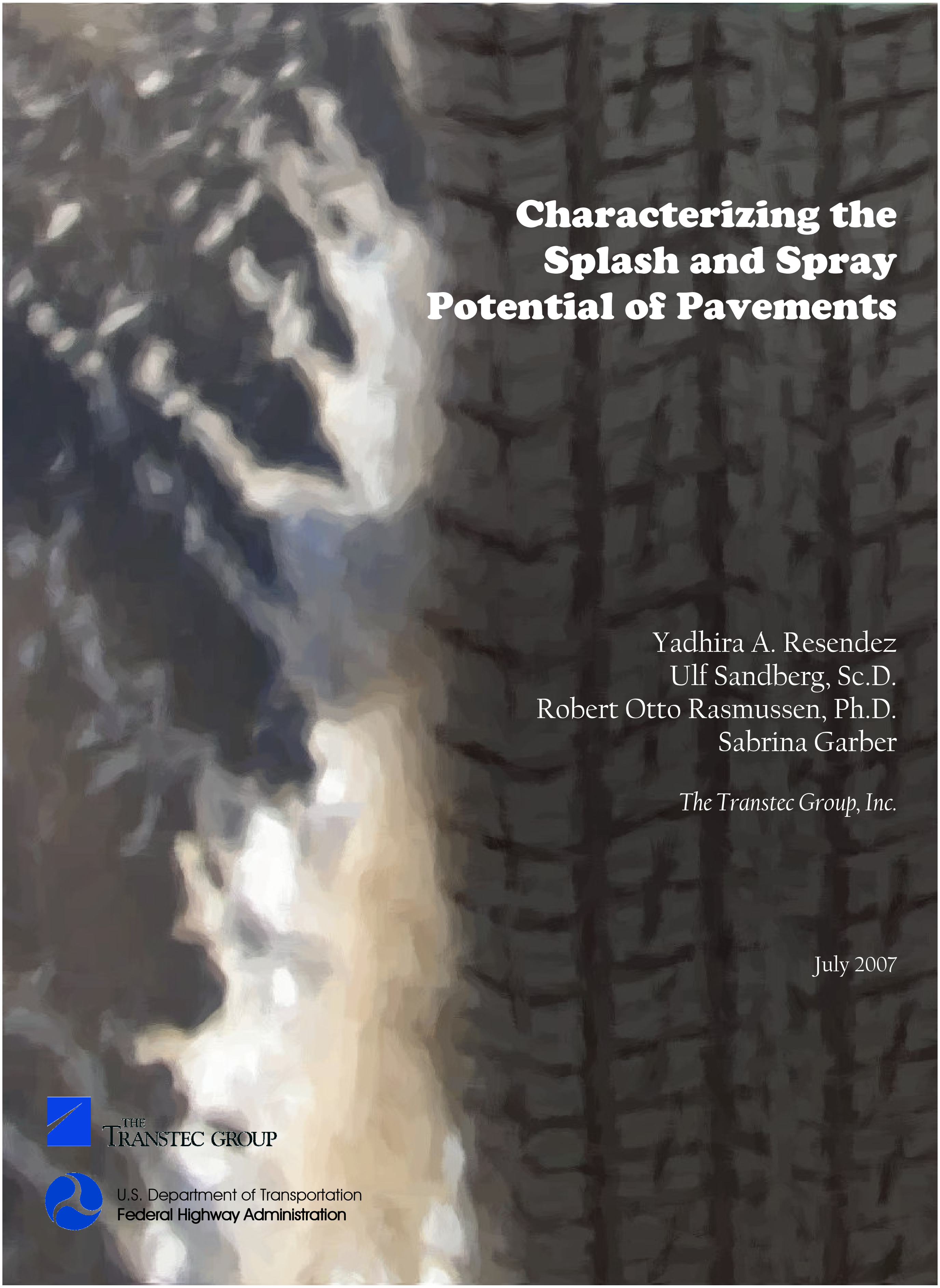

Characterizing the Splash and Spray Potential of Pavements

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1. WHAT IS SPLASH AND SPRAY?

Driving through a large puddle, through a heavy rainstorm, or over a large section of wet pavement, splash and spray is all around us. Splash and spray is, in common terms, the water that ends up on you and your car, courtesy of the drivers around you.

When vehicles travel on wet roads, water – often mixed with dirt or other debris – is thrown off from the tire tread and/or squeezed out from tire-pavement contact patch. This may form a cloud beside and behind the vehicle – termed *spray*. In some cases, a jet of water may also form to the side of the vehicle – termed *splash*. Both splash and spray obscure the view of other drivers, and can thus constitute a safety hazard. It is also a cause of pollution which may affect the vegetation beside the highway, deposit dirt on objects near the highway (such as traffic signs), and even cause corrosion.

Splash occurs when there is so much water in the contact patch or immediately in front of it, that there is not sufficient volume in the tread pattern to accommodate it. In some cases, hydroplaning can occur; more often this excess water is ejected from the contact patch and forms jets or plumes of water towards the front and the side of the vehicle. Splash plumes can form so high that oncoming vehicles will be struck, and the windshield becomes completely opaque. The resulting water film may be such that the wipers may take several cycles to clean it.

Spray is largely the product of water thrown off by centrifugal forces from the tire tread, split into small droplets which are easily caught by the wind around the vehicle. When conditions are favorable, a cloud of spray can form beside and behind a vehicle. When the spray contacts hard objects (such as "mud flaps"), it will often collect into a film that will eventually run off. However, some of the spray is caught by the air flow, and creates a cloud that can become a nuisance.

On heavy vehicles, for example, the amount of water picked up by the tires, together with the generally poor aerodynamics of the vehicle, can create a spray cloud which may be 30 ft. (10 m) wide and remain airborne for 650 ft. (200 m) behind the vehicle. Such spray clouds may obstruct the view of following vehicles, sometimes making it impossible to safely pass. For oncoming vehicles, the spray cloud can similarly obscure the view for several seconds. It may take the windshield wipers time to recover from this, during which time the driver might be blinded for a few critical seconds.

It should be noted that splash can also lead to additional spray. That part of the splash which is ejected beneath a truck can strike hard objects and be split into droplets. Some of these droplets will be light enough to be caught by the air flow and add to the spray cloud.

When driving, the amount of water picked up by tires can be rather large. For example, assume a truck runs on a smooth pavement with an average water depth of 1 mm. Based on the amount of area beneath the tires, up to 0.26 gallons (1 liter) of water can be picked up per 3.2 ft (1 m) of travel. If the truck is traveling at 55 mph (90 km/h), a volume of 6.6 gallons (25 liters) per second is displaced and possibly thrown up in the air.

Figure 1. Illustration of splash (DaimlerChrysler and SWE).

Figure 2. Illustration of spray behind and beside a truck
(Note: Rain had stopped about 15 minutes before the picture was taken).

The intent of this synthesis is to elaborate on the phenomena of splash and spray, as well as to summarize the types of measurements techniques that are available. While the primary goal of many of the existing tests was to determine the efficiency of spray protectors, the methodology can be useful to look at pavement effects.

2. THE EFFECTS OF SPLASH AND SPRAY

An increase in splash and spray can compromise traffic safety. In 1976, and OECD Road Research Group looking at these phenomena concluded that "reduced visibility is nearly as important as decreased skid resistance as a factor in accidents in rain" (OECD, 1976). However, despite the seriousness as a road accident hazard, the problem has not previously received much attention. Reduced visibility is the main safety problem which is caused in the following ways when traveling on wet highways:

- When overtaking another vehicle, the visibility is reduced during the approach and when driving beside the vehicle; in certain situations, visibility might temporarily be zero.
- A driver will get showers from vehicles traveling in the opposite direction, and the occasional spray cloud will obscure visibility ahead.
- Splash might hit other vehicles and give the driver an acoustical and vibrational shock, resulting in zero visibility for a few moments.
- During times of intense traffic, there will be spray clouds in the air along most of the highway; thus resulting in water and dirt being deposited on the windshield most of the driving time.
- Driving behind a vehicle will mean an exposure to water and dirt all the time.
- Dirty headlights decrease driver's nighttime visibility, and thus sight distances.
- Dirty headlights and taillights decrease vehicle conspicuity.
- Rear windscreen and external rear mirrors get dirty, giving reduced rear visibility.

The water in the spray cloud is often polluted with dirt and other debris, with more heavily polluted water in locations where the sand or salt might be used to increase skid resistance. Figure 3 illustrates the pollution commonly present in water spray. In locations where studs in tires are allowed, the wear effect of the studs will exacerbate the dirt generation, and the spray cloud will become even darker.

Some studies have been made of the potential effects of splash and spray on accident rates. A study in the U.K. suggested that an improvement in splash and spray conditions in the U.K. would give a potential of approximately 2000 fewer accidents per year, equivalent to 10 percent of all wet-weather accidents (Sabey, 1980). In a more recent study, it was concluded that the "elevated risk during rainfall appears to be related to visibility, since collision rates quickly return to near-normal after the rain has stopped, even if roads continue to be wet" (Andrey at el, 2001).

The mix of water, dirt, and especially salt, will also create a very corrosive environment around the highway. This affects the longevity of road signs, road barriers, and vehicles. Corrosion on cars can be particularly costly, especially considering the aggregate costs on society. In some parts of the country, vehicles in the winter are more or less constantly dirty.

Figure 3. Pollution contained in spray.
(Note: In this case, the spray is the result of condensation only, not rainfall).

Figure 4. Pollution from salt/water spray affecting the vegetation along a highway.

The spreading of polluted water to the highway environment is also a significant economic factor, due to the damage it can causes to vegetation along the highway, and to the potential pollution of groundwater (Blomqvist, 2001). The spray may propagate far away from the highway; in particular when winds prevail in a certain direction (Gustafsson & Blomqvist, 2004). The forest industry can suffer from spray hitting trees on the downwind side of the highways (see Figure 4), as shoots that are covered in pollution from the spray are often killed.

The dirt/water spray also causes a dirt cover on road signs (see Figure 5). This constitutes both a traffic safety factor (since the signs cannot be read) as well as an economic factor (due to corrosion and/or need for cleaning). Spray, especially if containing salt, may even add to corrosion on bridges, leading to an additional economic problem.

Figure 5. Illustration of dirt on road signs from spray.

3. REDUCTION METHODS

Some major ways to reduce splash and spray nuisance are:

1. **Improve pavement surface drainage.** All else being equal, using proper (higher) cross slopes for both driving lanes and shoulders will reduce water film thickness on the roadway. In turn, this reduces the water that will be displaced by the tires, and thus reduces splash & spray.
2. **Increase texture depth.** Pavement surface drainage can also be improved by using a surface with a greater texture depth, especially in the driving lanes. While heavier rainfall events will fill this texture, it will still improve splash and spray in many cases.
3. **Maintain the road in a good condition.** Minimizing the development of ruts and other depressions will reduce the potential for excess water depth on the road. Depressions can create puddles, and this affect the amount of water that is displaced by the tire. This can be particularly troublesome since intermittent deep depressions may startle the driver as vehicle behavior (esp. steering and traction) rapidly changes.
4. **Increase pavement porosity.** The use of open-graded friction courses and other types of porous surfacings allow water to channel away from the surface, reducing splash and spray as much as 100 percent for light rainfall events. This benefit will gradually diminish, however, as the pavement gradually becomes filled with water and finally reaches saturation. This benefit can also be lost if the porosity clogs over time.
5. **Decrease vehicle speed.** Spray is generally not a problem for vehicles at or below 35 mph (60 km/hr). Above this speed, the relationship between spray and speed has been shown to be approximately cubic (i.e., spray intensity $\propto$ speed^3) (Sandberg, 1980). A reduction of speed during rainy weather is therefore very effective, if it can be achieved.
6. **Improve vehicle aerodynamics.** Less turbulence around and behind a vehicle will result in less spray being picked up. What is picked up will be kept it in the air for a shorter distance. The practical reduction potential might be quite large. This factor is well beyond the control of the pavement engineer, however.
7. **Improve vehicle spray protectors.** While this too is outside of the control of pavement engineers, it is known that the practical reduction potential for spray protectors seems to be at least 30 to 50 percent, according to previous findings (Sandberg, 1980). This depends, of course, on the type of protection used as a reference.
8. **Reduce tire width.** By decreasing the width of the tire, less water is displaced and splash and spray is minimized.

4. FACTORS AFFECTING SPLASH AND SPRAY

4.1 Meteorology (rain, wind, light, etc)

Several factors related to meteorology have a profound effect on splash and spray.

Rainfall is, of course, the source of most splash and spray. Rainfall results in water collecting on – and sometimes in – the pavement. Raindrops can also hit vehicles and split into smaller droplets which are caught by the wind and contribute to the spray cloud. The intensity of the rain affects the water depth on the pavement. Saturation of the pavement will occur when rainfall reaches a certain level.

Wind intensity and direction affect how the spray cloud spreads along the highway (or away from it). A vehicle traveling in upwind conditions will face a relative wind speed higher than when traveling downwind. Even a moderate crosswind may blow a spray cloud towards the side of the road. This could result in either the spray not hitting any other vehicles (spray blowing off the road), or possibly hitting vehicles in opposing or overtaking lanes (blowing over the road). For example, a vehicle traveling at 55 mph (90 km/h) in a crosswind with a speed of 10 mph (16 km/h) would theoretically blow a 15-ft. (5-m) wide spray cloud away from the driving lane after only 80 to 160 ft. (25 to 50 m) behind the spray-emitting vehicle.

Light conditions also have a profound effect on how a spray cloud is seen. When looking into a spray cloud against the sun, light diffusion around the droplets may cause extra nuisance. This is true to some degree in other directions too. Under low light conditions, spray clouds tend to be more visible than under good light conditions. The light from another vehicle's headlights will normally be partly reflected and diffused by the droplets in a spray cloud, which make even a moderate spray cloud very difficult to see through.

Substantial condensation can form on a pavement if air temperature and humidity is ideal. The result can be water spray even when there has not been a rainfall event for several days (see Figure 3).

4.2 Driver

The driver is responsible for the speed of the spray-emitting vehicle, and speed is possibly the most influential factor of all. Empirical evidence suggests a relationship of spray intensity $\propto$ speed^3 (Sandberg, 1980). An increase of speed from 45 mph (70 km/h) to 55 mph (90 km/h) means a doubling of spray intensity. The higher the speed, the more water is pulled up from the tire-pavement interface to levels high enough to hit solid objects and to be caught by air turbulence. The turbulence itself is increased by higher speed too.

Speed also influences the amount of water that needs to be displaced from the tire-pavement interface per second. This amount (per second) increases with speed until hydroplaning occurs. Hydroplaning often occurs during fractions of a second in deep puddles.

Finally, the driver may influence the emission of splash and spray by choosing the lateral position in the driving lane. If they choose to drive in the wheel tracks, subject to more or less rutting, it is likely that more water is emitted from the tire than if trying to drive in "dryer" tracks. The driver may also have a certain possibility to avoid driving through puddles.

4.3 Vehicle

The vehicle body dramatically affects air turbulence and thus the ability to pick up water droplets and form a spray cloud. The position and material of objects behind and over the tire will affect the splitting of water drops into smaller droplets, as well as the part of the water that can be collected into running water. The deposit of such water from spray protecting or collecting devices back onto the highway may also be affected by how such water runs off the vehicle.

The design of spray protectors is essential. Traditional truck protecting devices are rubber flaps hanging down behind the tires (Figure 6), with the main purpose to protect stones being thrown from the tires towards vehicles traveling behind. It is still uncertain whether such flaps are benefiting spray. Trucks found in Europe employ more advanced spray protectors that include curved fenders and rubber flaps (see Figure 7).

Figure 6. Truck with rubber flaps behind the rear tires.

Figure 7. Typical European (Swedish) spray protector design.

Several improved designs have been tested. For example, Sandberg in 1979 tested a design made by Monsanto called ClearPass (Figure 8). This was made of artificial lawn material with the intent to dampen the impact of water droplets on the spray flap, letting the water run off towards in the bottom of the material. Several other designs were also tested during this project. The material, which was used by Monsanto, was later used to some extent in actual traffic both in the USA and Europe (Figure 9).

4.4 Tire

The primary purpose of most tire tread patterns is to drain water away from the tire-pavement interface, resulting in a firm contact between the tire rubber and the pavement texture. The air/rubber ratio in the tread pattern (ratio of non-rubber versus rubber area in the contact patch) is usually in the order of 30 percent, but may vary between 20 and 40 percent. Typical tread depths are 0.3 in. (8 mm) for new car tires and 0.6 in. (16 mm) for new truck tires. The area between the tread multiplied by the tread depth is equal to the volume that can accommodate water. While driving, part of the water volume will stick to the tire during the first milliseconds after leaving the trailing edge. This is due to water-rubber adhesion. For similar reasons, some water may also stick to the surface of the tread blocks that after they have been in contact with the pavement texture.

Figure 8. Artificial turf material used by Monsanto in a spray protection device (Sandberg, 1979).


Figure 9. Artificial turf material used on the wheel housing and flap of a Swedish truck.

The tire parameters potentially affecting water emission from the tire include:

- Tire width: the wider a tire, the more water must be displaced and can potentially be picked-up.
- Rubber compound: the adhesion between rubber in the tread and water (mixed with dirt) affects how much water that will stick to the tire and how long it may stick before thrown off.
- Shape and direction of the tread pattern: Whether the tread pattern is longitudinal or transversal or a mix of both affects the amount of water that will be picked-up and thrown off. Some tread patterns may – in the worst case – act almost like a "shovel".

4.5 Pavement

Much like it is for the tread patterns of tires, the primary purpose of pavement macrotexture is to drain water away from the tire-pavement interface, improving contact between the tire rubber and the pavement texture. The volume of air in the texture entrapped between the enveloping rubber of the tire tread and the pavement surface determines how much water may be similarly contained. Greater texture will mean more water; however, this does not mean that the rubber will be in contact with that water. Instead, the texture "holds" some water that would otherwise be forced into the tread pattern. It is therefore expected that greater macrotexture reduces the pick-up of water by the tire. To date, however, there has been no formal study exploring the relationship of macrotexture depth to the potential for splash and spray.

The cross slope of the pavement affects how fast water will run off the roadway. A higher cross slope is desirable to improve splash and spray. Megatexture and unevenness of the pavement will characterize the existence of depressions and ridges which may form puddles in rainy weather. Lane stripe and raised markers can also constitute barriers to prevent water run-off, along which water will collect.

Porous pavements containing interconnected voids (permeability) can result in a potential reservoir for water. When it first starts to rain, water will be accommodated in a porous pavement. For a pavement with 20 percent air voids and a thickness of 2 in. (50 mm), the equivalent air volume thickness is 0.4 in. (10 mm), equal to the voids multiplied by the layer thickness. This means that up to 0.4 in. (10 mm) of water may be stored in the pavement until it gets saturated. Saturation may even take a little longer time, since some of the water will run-off to the road shoulder within the pavement. Once the pavement is saturated with water, there is no additional benefit of a porous pavement, other than providing an easier escape of water from the tire-pavement interface, implying lower pressure gradients and lower pressure.

It is often assumed that porous pavements reduce spray to almost zero level. This is a misconception, at least as a general rule of thumb, even if it may be so at light rainfalls or very short rainfall that fills the porous pavement only at the bottom. However, under moderate and heavy rainfall, porous pavements may contribute to substantial spray emission. This is because the air and water become entrapped in the tire-pavement interface and form a bow wave in front of the tire, which will create pressure against the water near the leading edge of the contact area and a corresponding suction of water at the trailing edge combined with ejection of the water that is pressed down into the porosities. This creates a pumping action of the tires, which is very positive for cleaning of porous pavements, but at the cost of substantial spray.

The clogging of porous pavements, together with the rather inhomogeneous porosity in new condition, will mean that the influence of spray is very local and may vary considerably along the porous pavement. It will also vary with time, as clogging progresses, and as there will be temporary cleaning actions by traffic during rainy periods.

Finally, the material used for the pavement surface may potentially affect spray generation. For example, different materials will have different potentials for adhesion to water. As a result, the water that is picked up by the tires will likely be affected, at least when small wear particles from the pavement mix with the water. Like most pavement-related characteristics, however, no formal study of this has been identified. However, more should be learned about the fundamental mechanisms at play in this regard and, if significant, could be included as experimental variables.

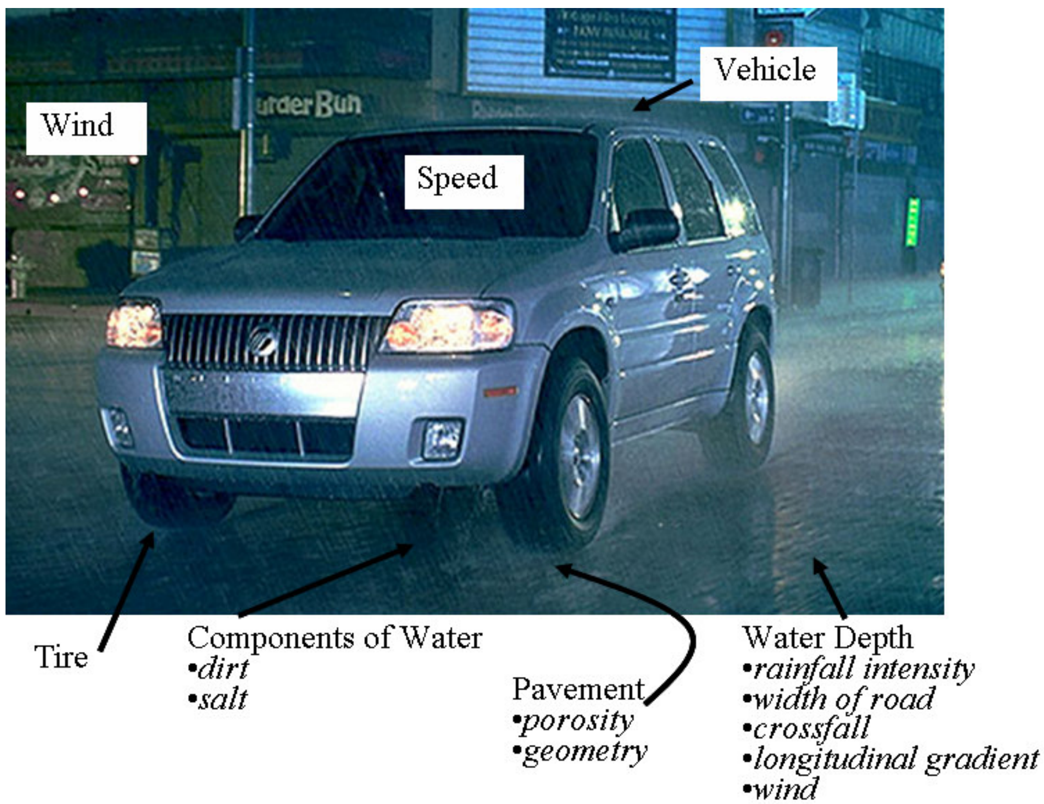


Figure 10. Overall factors affecting splash and spray.

5. MEASUREMENT METHODS

This section will summarize the types of test methods used in the past to measure splash and spray. Although the primary goal in these tests was to determine the efficiency of spray protectors, the methodology in doing so should be taken into consideration, and this information will be very useful in developing a more innovative and accurate procedure to measure splash and spray of various pavements.

5.1 Road Research Laboratory (RRL), 1966

Key Citation: Maycock, G., "The Problem of Water Thrown Up by Vehicles on Wet Roads", Road Research Laboratory, Ministry of Transport, RRL Report N0.4, 1966.

This report documents experiments conducted by the Road Research Laboratory in the U.K. to measure the amount of splash and spray by commercial vehicles. These experiments were carried out at the Laboratory's test track in Crowthorne. This paper describes the measurement methods used to collect splash and spray data.

5.1.1 Spray Measurement Methods

The brunt of these experiments dealt with qualitative data collection using photographic and other means. Photographs were taken of the test vehicle during the test run using three cameras that were positioned around the path of the vehicle (at either side of the vehicle, as well as above). It was later noted, however, that these photographs were unreliable in providing reproducible quantitative data, although they were useful in showing the distribution and extent of the spray.

In a plan to devise a more quantitative means of spray data collection, RRL devised a "water collection" system, where disposable collectors (measuring 4.5 in by 30 in [114 mm by 762 mm]) were constructed using several layers of absorbent paper with non absorbent backings.

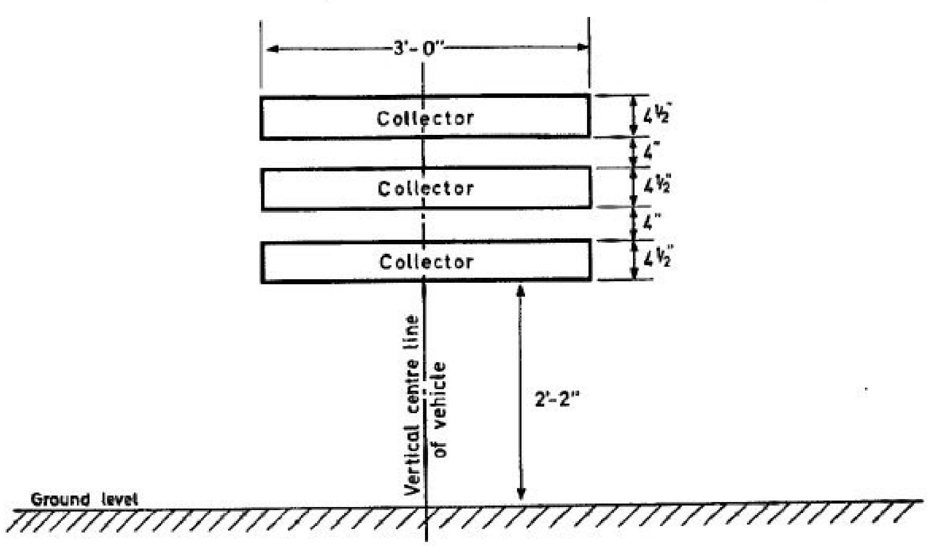


Figure 11. Water collector system for a single pair of rear wheels.

These collectors were mounted to the front of a car that followed behind the test vehicle, collecting the spray caused by the test vehicle. The spray was absorbed by the collector apparatus and measured by comparing the difference in weight before and after the experiment. From this water collection, a spray density was determined.

This type of water collection was used to estimate the spray from a single pair of rear wheels and from all wheels, respectively. Different collection arrays were used for both types of runs, shown in Figures 12 and 13.

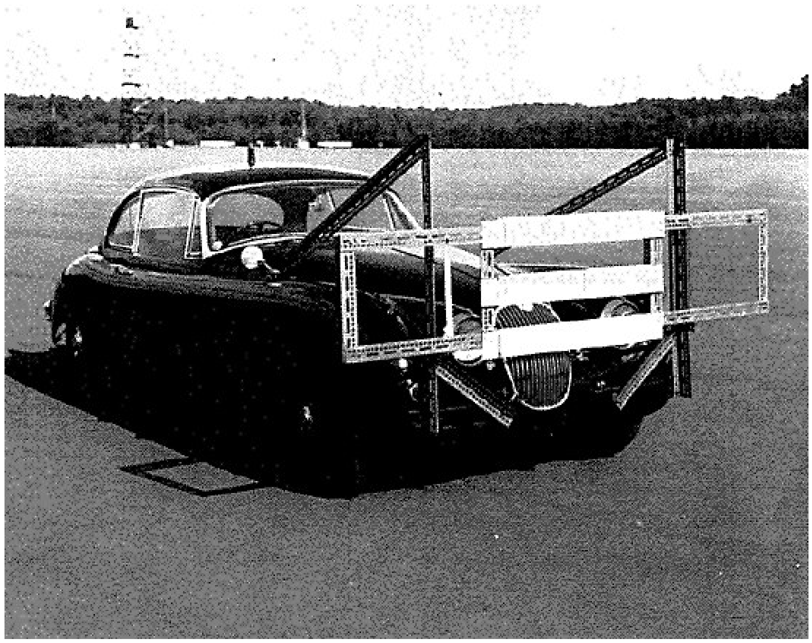


Figure 12. Collection array for single pair of rear wheels in the RRL experiments.

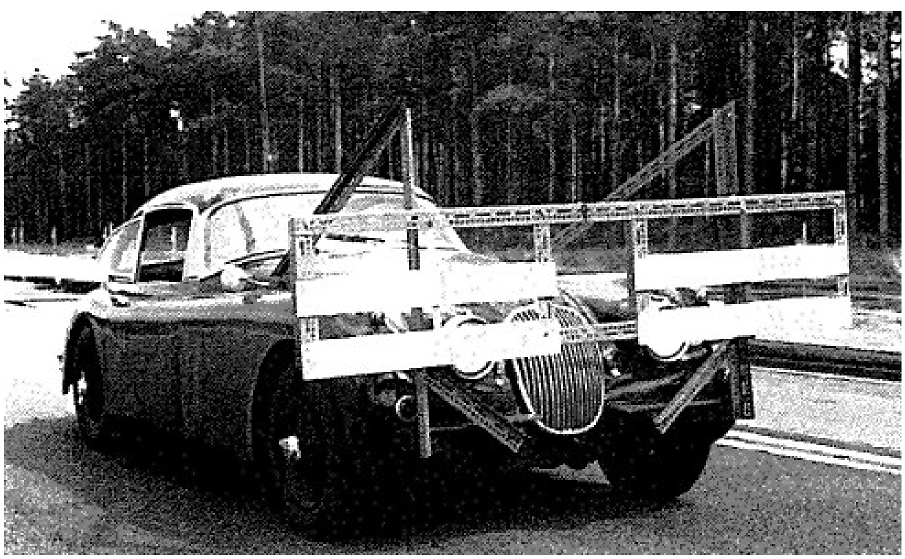


Figure 13. Collection array for "all wheel" test runs in the RRL experiments.

The test vehicle was a commercial water tanker, which also provided its own water source, as shown in Figure 14. An outlet was located in front of the rear vehicle wheels, and water was fed from the tanker to the outlet, wetting a section of the road surface about 18 in. (0.46 m) in width. As reported in the document, "outflow was about 80 gallons (300 liters) of water per minute…which resulted in a depth of the order of 0.010 in (0.25 mm) at the test speed of 50 mph (80 km/h)". Three different test tires were used for the spray tests, as well as the splash tests (discussed later).

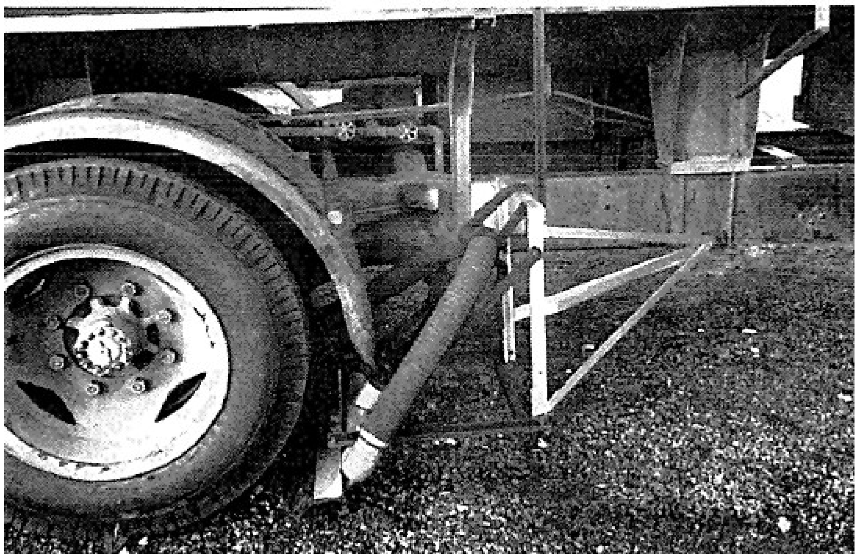


Figure 14. Water supply outlet for test vehicle.

For the single rear wheel test runs, the measurement vehicle traveled at a distance of 22 ft. (6.7 m) from the rear axle of the water tank (the test vehicle), right behind the test tires. Two different types of tires (labeled "worn" and "heavy", respectively), were used for this test.

The "all wheel" collection test runs were conducted similarly to the single rear wheel test runs, except that the measurement vehicle traveled at a distance of 30 ft. (9.1 m) from the rear axle and to the side of the vehicle, where the "offside pair of collectors was behind the center of the test vehicle with the nearside pair approximately in line with the nearside" (Figure 16). All three tire types were used for this test.

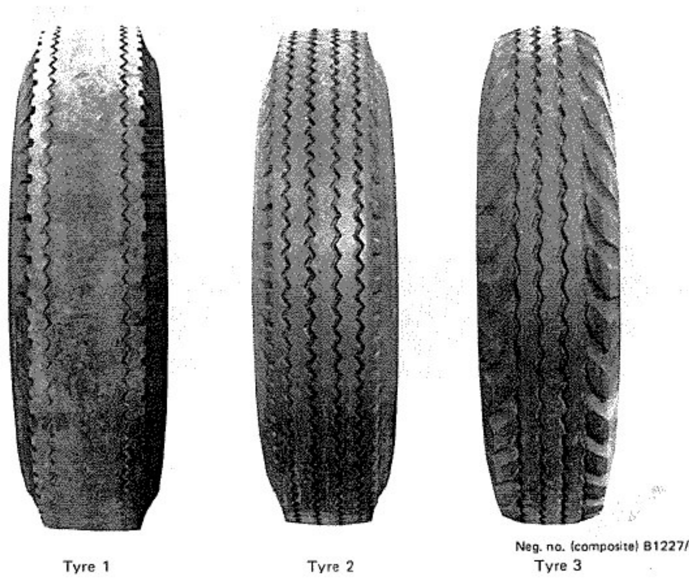
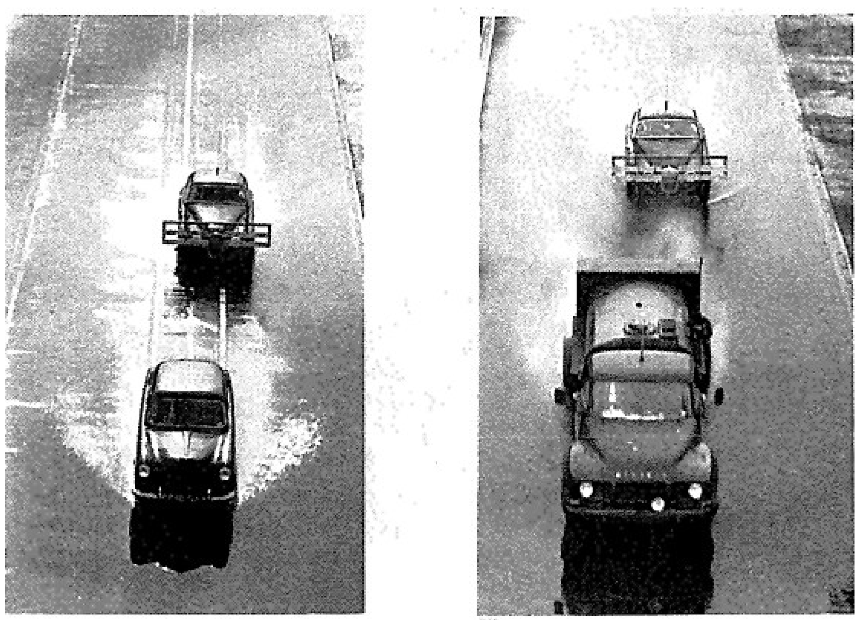


Figure 15. Tires used in the RRL study
(Note: "Tyre 1" – Worn tire; "Tyre 2" – Zig-Zag Rib; "Tyre 3" – Heavy-Duty Block).



(a) (b)

Figure 16. Spray collection tests for "all wheel" runs in RRL testing.

Built-in spray bars were used to wet the test section, which were turned off about 10 seconds before the test vehicle reached the test section. The pavement type used for the test section was "fine cold asphalt", and the water depth was kept between 0.02 and 0.04 in. (0.5 and 1.0 mm). Three runs were conducted for both experiments, and an average was used to determine the amount of spray collected.

It should be noted that an attempt was made to collect the amount of splash generated by the front tires. The first method consisted of four tapered scoops (located one behind the other), “attached to the underside of the car in line with the front wheel”. Due to problems with air turbulence around the scoops at 60 mph (97 km/h), this measurement method was shown to be ineffective and test runs were stopped. The second method consisted of plastic foam adhered to hardboards which were attached to the underside of the sills of the test vehicle. However, this collection method was observed to be ineffective.

5.1.2 Splash Measurements

The amount of splash was collected using five polythene bottles which were mounted on a frame that was positioned behind the testing vehicle. The bottles were identical in size and shape, and were mounted on an angled iron frame towards the rear axle and very close to the pavement surface. The bottles were approximately 8 ft. (2.4 m) from the rear axle of the test vehicle, with the center bottle located between the rear vehicle tires. The total splash was quantified by obtaining the total amount of water collected from all five bottles. As with the spray measurements, three different tire types were used for this measurement method.

Figure 17. Spray collection by use of polythene bottles during the RRL tests.

5.1.3. Observations

The amount of spray generated in relation to speed was measured using both the water tanker (with mudguards and flaps) and a conventional car (referred in this report as a “saloon” car, without flaps). The collectors (mounted on the collection car) were located 30 ft. (9.1 m) behind the test vehicle. The results show that the spray density is minimal at a speed of 30 mph (48 km/h), but increases drastically after that (see Figure 18)

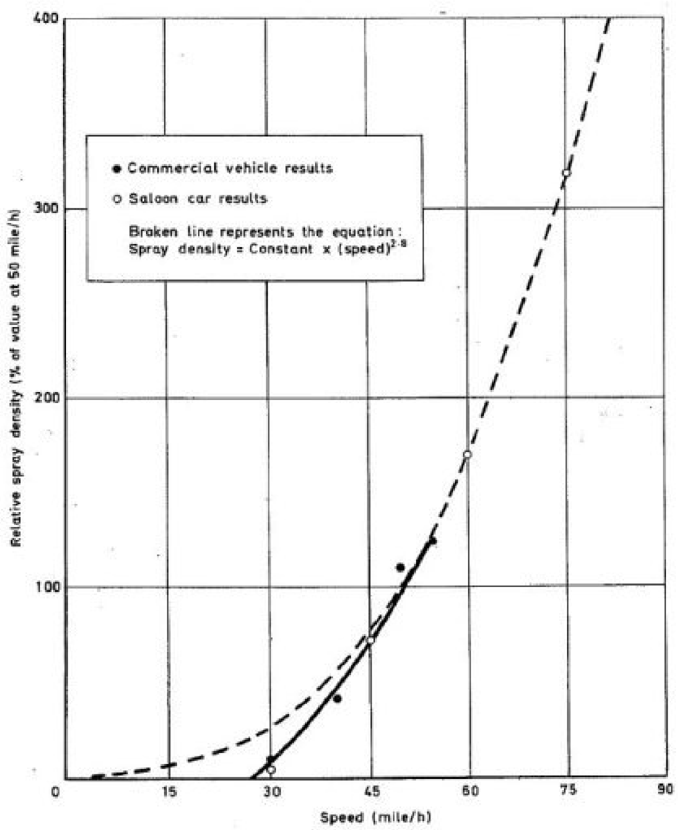


Figure 18. Effect of speed on spray density.

It is reported that the water displaced by the tire at speeds below 30 mph (48 km/h) did not form into light drops (spray), and instead fell back down to the ground and were not collected by the collectors. The water drops seemed to decrease in size with the increase in speed, becoming a finer spray.

Splash measurements were conducted using the three types of tires (worn, zig-zag rib, and heavy duty block). It was observed that under the same test conditions, the "patterned" tires produced similar splash distribution, with the bulk collected in the center bottles, and the worn tire seemed to throw more water towards the sides of the vehicle. However, when it came to spray measurements, it was observed that the, "differences in fine spray produced by the three tire treads are not significant in practice".

The "all wheels" collection measurement was employed to determine the amount of spray generated by six different pavement types, using the "saloon" car, traveling at 60 mph (97 km/h):

1. Fine cold asphalt.
2. Asphalt with embedded chippings.
3. Bridport surface dressing (chip seal).
4. Meldon surface dressing (chip seal).
5. Mixed aggregate.
6. Quartzite aggregate.

(see Figure 19 for more information on these pavement types)

The surface test sections were 300 ft. (91 m) in length, with water being supplied to the test section by means of "a single set of built-in sprays the angle of which was adjusted so that as much of the water as possible fell on the test section". The cross slopes of all the test sections were identical, and all sections were level except for Section 3 (Bridport). It was observed that, although some puddles had formed due to the areas where the sections had worn, there was not much difference between surfaces. The exception to this observation was the quartzite surface.

	Surface	Details	Average quantities of spray collected (g)	
			Expt 1	Expt 2
1	Fine cold asphalt	Cold asphalt to B. S. 1690 using blastfurnace slag aggregate - impervious	87	93
2	Asphalt with chippings	Hot rolled asphalt to B. S. 594 with $\frac{1}{2}$-in meldon white chippings rolled into surface (120-140 yd^2/ton) - impervious	111	133
3	Bridport surface dressing	A surface dressing made with 3/8-in rounded gravel - impervious	76	71
4	Meldon surface dressing	A surface dressing made with 3/8-in meldon white chippings (100-120 yd^2/ton) - impervious	66	75
5	Mixed aggregate	Bitumen-macadam to B. S. 1621 with 3/8-in aggregate of 50% rounded gravel and 50% crushed quartzite rock - slightly pervious	-	107
6	Quartzite	Bitumen-macadam to B. S. 1621 with an aggregate of 3/8-in crushed quartzite rock - pervious	0	-

Figure 19. Effect of pavement surface type on amount of spray emitted by test vehicle in RRL tests.

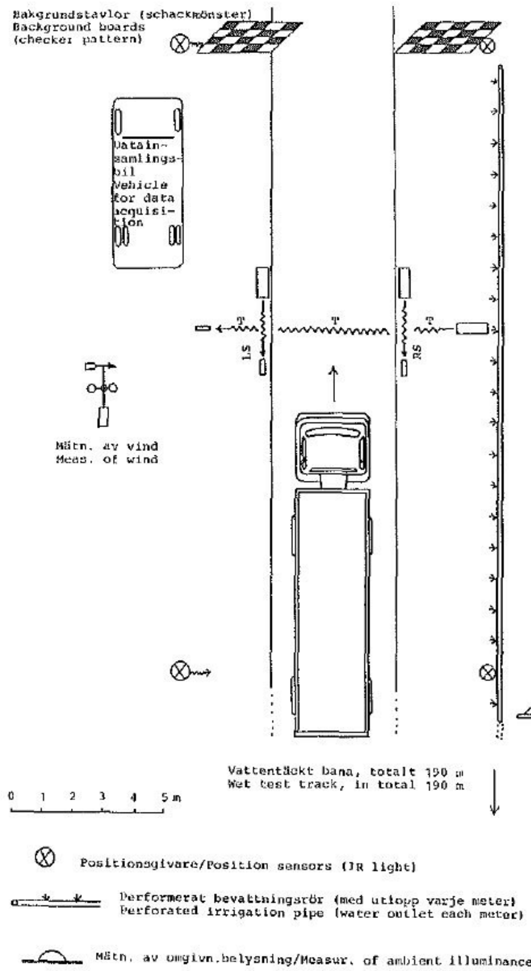


Figure 20. Layout of test track.

In addition to this measurement method, photographs, video, wind speed, water depth, ambient illuminance, and vehicle speed were also measured. Details of these measurements are described below.

In addition to light transmission measurements, digital imagery was also used. Similar to the SAE J2245 method, two large "checkerboards" were used, with the runs photographed "65 m (213 ft.) from the main instrumentation area at a direction behind the vehicle at a pass-by". These photographs were also taken 164 ft. (50 m) at the side of the vehicle.

5.1.4 Observations

Visibility reduction may not be increasing with increased water depth, due to the fact that larger water drops may "give smaller light transmission loss than small droplets"; however, smaller water droplets are "more important concerning visibility reduction.

5.2 Transport and Road Research Laboratory (TRRL), 1973

Key Citation: Brown, J.R., "Pervious Bitumen-Macadam Surfacings Laid to Reduce Splash and Spray at Stonebridge, Warwickshire," Transport and Road Research Laboratory, TRRL Report LR 563, 1973.

The objective of this experiment was to evaluate the "efficiency of the various surfacing materials in reducing splash and spray and to find out the extent to which their effectives lives are reduced by subsequent compaction and deformation by heavy commercial vehicles and the filling of voids by detritus". This report covered the findings and information gathered in 22 months (from time of construction – June 1970 to spring of 1972).

The study found that surfacings 1.5 in. (40 mm) thick designed with 20% air voids will "accept 8mm of rain", given that the surface is dry. Therefore, if during a rainfall the depth of water collected on this type of surfacing is below 0.3 in. (8 mm), this type of surfacing will prevent spray from developing. However, if the material becomes heavily saturated during a rainstorm, its effectiveness will be void. Once the surfacing is able to drain water, or become unsaturated during light rainfalls, its spray reduction properties will become effective again.

In June 1970, six types of open-textured bitumen-macadam surfacings were evaluated. The location of the experimental sections was in Stonebridge, Warwickshire, UK. "The carriageway is 24-ft (7.3-m) wide and has curbs along both sides over the 2600-ft. (800-m) length of the experiment. This length is mostly straight and very slightly undulating. The transverse gradient varies between a cross fall to the central reservation, a camber, and a cross fall to the nearside kerb [sic]."

Rainfall was documented during the trials. In addition, "cine films and still photographs" were taken to compare the amount of spray emitted from the vehicles while traveling on the different types of surfacings, compared to the non-experimental section located adjacent to the site (experimental section is noted as an "asphalt road"). The "plates" were taken within minutes of each other, and show the difference in spray as produced by the vehicles traveling on the two different types of surface (experimental vs. non-experimental).

5.3 The National Swedish Road and Traffic Research Institute (VTI), 1978

Key Citation: Sandberg, U., "Spray Protectors Testing of Efficiency", The National Swedish Road and Traffic Research Institute (VTI), Report 171A, Linköping, Sweden, 1978.

In the 1970's, Sandberg at VTI developed a special and unique measuring method for splash and spray, measuring the visual light transmission through a spray cloud. Measurements were made both along the two sides of a vehicle and across the traveled lane. The system also included equipment for measuring vehicle speed, wind speed, wind direction, and water depth. Furthermore, the measurements included visual observations by a panel of observers who looked at filmed vehicle passages to estimate the extent of the spray cloud at the sides of the vehicle against a checkerboard background. The measurement method was described in the VTI report *Measurement of Splash and Spray Generated by Vehicles on Wet Roads* (Sandberg, 1977).

Nine different spray protectors were evaluated, and the experiments focused on measuring the spray from the rear wheels of the test vehicle, while the front wheels were enclosed. The tests were conducted using a two-axle truck running at two speeds, 45 and 55 mph (70 and 90 km/h) – through two different depths of water, 0.059 and 0.079 in. (1.5 and 2 mm). Spray intensity was determined by means of visibility reduction (light transmission) at different distances along the vehicle. In addition to these quantitative measurements, a visual evaluation of spray generation was also carried out by comparing image slides from films of the spray.

The test track, referred to in the report as a “Mantorp racing track”, was kept wet by a sprinkler system. The pavement type in this study was an asphalt concrete “type HAB12T”. At the time of this report, this pavement type was very common in Sweden. Measuring equipment was set up on both sides of the test track (to take crosswind into consideration). Three different light transmission measuring devices were used, each consisting of a transmitter (taking sunlight into consideration) and a detector (receiver). The three meters included:

- One to measure the visibility reduction over a distance of 26 ft. (8 m) perpendicular to the driving direction, and
- Two to measure the visibility reduction over a distance of 6.5 ft. (2 m) parallel to the driving direction.

According to the report, the spray the spray propagation behind and beside the vehicle was able to be measured with a resolution of approximately 6.5 ft. (2 m). This resulted in an, “output signal during the vehicle pass-by corresponding to a spray intensity (represented by the reduction of light transmission over the 6.5-ft. (2-m) long distance as a function of distance **behind** the vehicle”. Checkerboards were constructed alongside the test track (similar to the Society of Automotive Engineers Specification “Recommended Practice for Splash and Spray Evaluation” method) in conjunction with the imagery analysis.

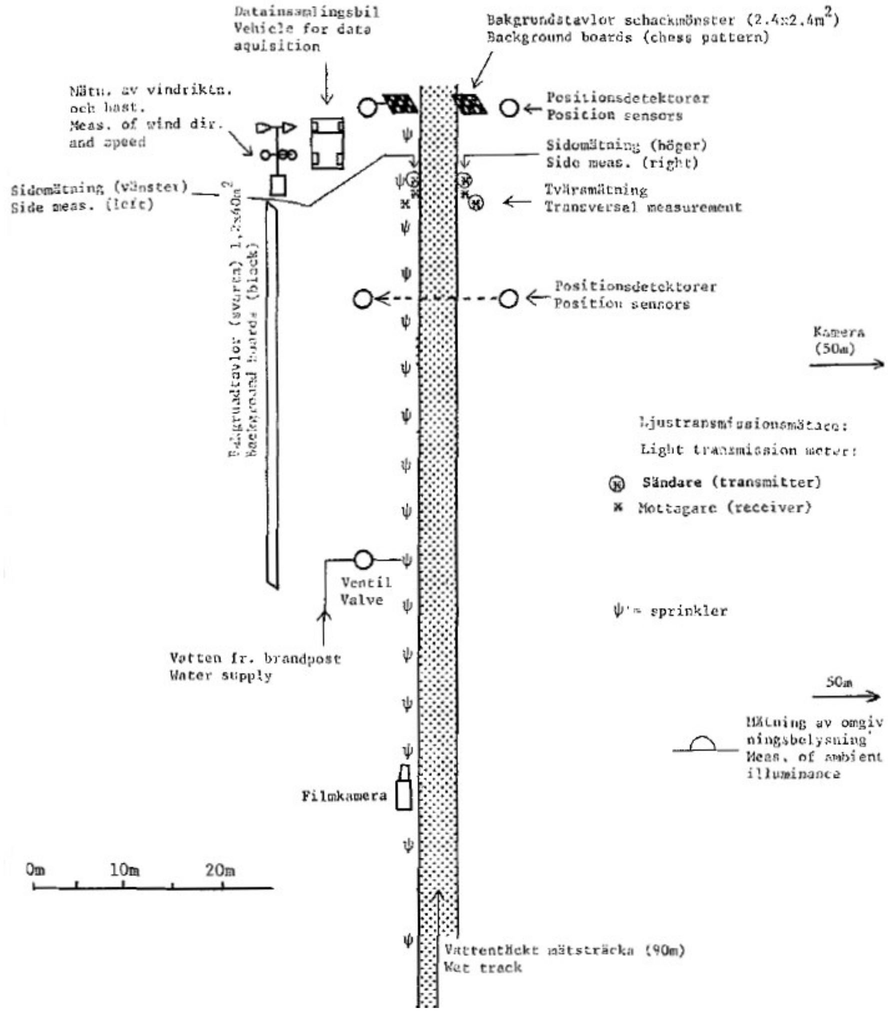


Figure 21. VTI Test layout.

Table 1. Equipment used in VTI tests.

Types of Equipment	Details
Light detectors	UDT PIN 10DP, CIE filter and luminance probe. Step response (total) = 0.1s. Relative calibration by a special diffuse sheet.
Speed measurements	Microcomputerized equipment, triggered by sensors positioned on the track. Sensors also activated digital imagery. Accuracy approximately ± 0.1km/h.
Wind speed/direction measurements	Monitored by electronic equipment, model SMHI, momentary or average (10 minutes).
Ambient illuminance measurements	Photometer, model UDT 40x with CIE filter and diffuser (lux).
Water depth measurements	Measured on 24 defined positions by use of a: 1) "Electric needle type" with lamp display, and 2) Metal comb type.
Video capture	Beaulieu 16R Automatic (16mm).
Film camera	Pentax KM.

5.4 The National Swedish Road and Traffic Research Institute (VTI), 1980

Key Citation: Sandberg, U., "Efficiency of Spray Protectors: Tests 1979", the National Swedish Road and Traffic Research Institute (VTI), Report 199A, Linköping, Sweden, 1980.

This measurement methods conducted in this study are a continuation of the VTI testing conducted in 1978 (previous report). Differences between the testing done in this round are as follows:

- Two trucks are used in this study: a three-axle truck and a pair of "British 4-axle articulated vehicles with semi-trailers loaded with containers". Both vehicles were driven together (either a few seconds before or after) to maintain a consistent environment for both vehicles.
- The vehicles were tested at a speed of 50 mph (80 km/h) over a wetted test track.
- Water depths maintained between 0.039 and 0.059 in. (1 and 1.5 mm).

Each test vehicle passed the measurement devices several times for each tested case. The pavement type used in this study was an asphalt concrete pavement (type HAB12T); additional details about the pavement type can be found in this report.

In this study, the spray generated by the test vehicles, as well as the propagation of the spray cloud, was measured by use of light transmittance using visibility meters. The visibility meters and photographic equipment, as well as their locations, were identical to the previous testing conducted by VTI.

5.5 The National Road and Traffic Research Institute (VTI), 1980

Key Citation: Sandberg, U., "Improved Spray Protectors for Commercial Vehicles – An Approach to Increase Traffic Safety," The National Swedish Road and Traffic Research Institute (VTI), Linköping, Sweden, 1980.

To test the efficiency of spray protectors for commercial vehicles in Sweden, a test method was devised using "specially constructed optical transmission meters" as measuring devices. The report summarizes the test methods and results from the VTI 1978 and 1979 tests (sections 5.3 and 5.4).

5.6 Texas Transport Institute, 1984

Key Citation: Koppa, R.J., et.al, "Heavy Truck Splash and Spray Testing – Final Report: Volume 1 Summary and Findings", Texas Transportation Institute, Project RF7002, Motor Vehicle Manufacturers Association, September 1984.

This report describes the testing conducted by the Motor Vehicle Manufacturer's Association (MVMA) over a period of six months, refining past measurement efforts of the last 10 to 15 years. Prior to this study, the National Highway Traffic Safety Administration (NHTSA) conducted their own study; the data complied from this report was used to "fill in" the gaps of the NHTSA data.

The test track was located at the Texas Transportation Institute (TTI) Proving ground; the track was a 400-ft. (122 m) asphalt overlay (constructed over the original pavement), 18-ft. (5.5 m) wide (12-ft. [3.6 m] vehicle lane). The track was wetted using a PVC pipe, drilled with 1/8-in. (3.175 mm) holes every foot and the water depth was kept between 0.05 and 0.06 in (1.27 and 1.5 mm). A still camera was located on one side of the test track, as well as a video camera; both cameras were housed in a portable building to protect the equipment from water. Two checkerboards wee located on both sides of the track, near the end. A second still camera (located 200 ft. [61 m] from the checkerboards) was used to record images of the checkerboards as the test vehicle passed.

Eight powered lasers were used in this study; light meters or photodiodes were employed to receive data from the lasers. Four lasers were used to consider crosswind effects (as opposed to only two lasers used during the NHTSA study). The lasers were also enclosed to prevent the equipment from getting wet. Rugged mounts were also used to hold the lasers to prevent any vibrations or movements from affecting the recordings.

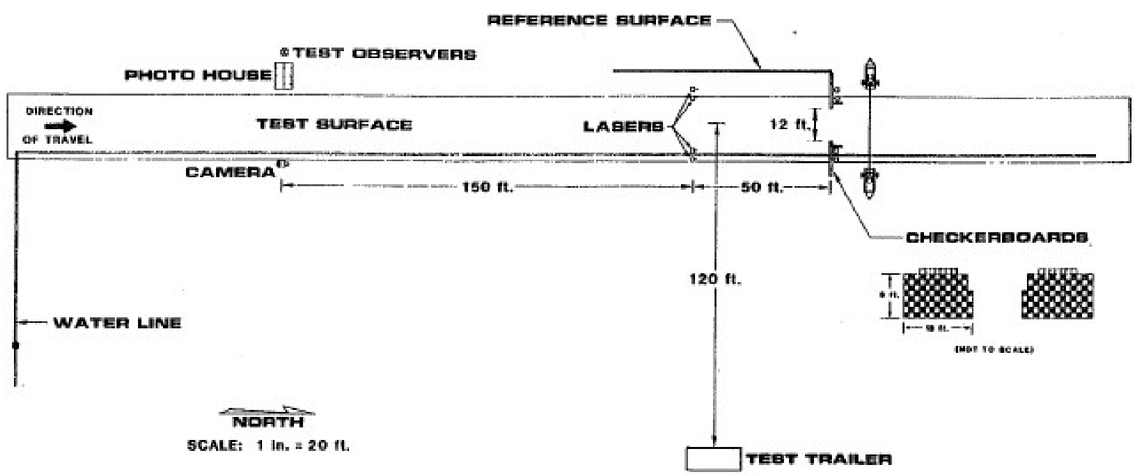


Figure 22. Test layout.

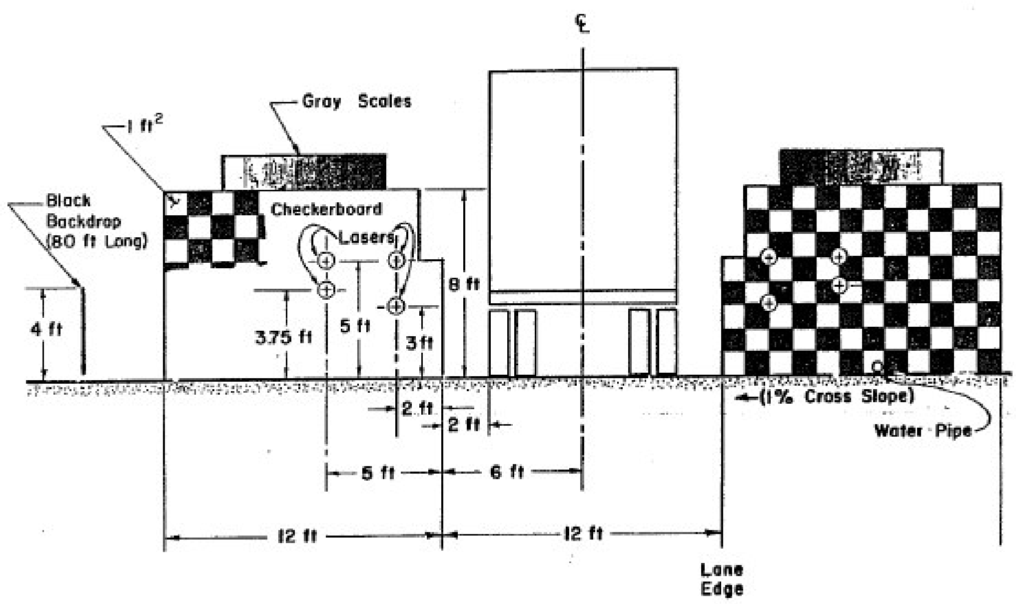


Figure 23. Back view of test layout.

Three vehicles were used for this study:

1. Test vehicle – this vehicle wore the spray suppression device
2. Baseline vehicle – similar to the test vehicle, only wore plane flaps behind rear tandem axle of trailer
3. Calibration vehicle – plain flaps behind rear tandem axle of the trailer and remained the same for all of the runs

The test runs were started (at a minimum) 30 minutes after sunrise, with the last run at a minimum 30 minutes before sunset. If precipitation was present, the runs would stop once the beams would pick up the precipitation; in addition, tests were suspended when wind speeds exceeded 10 mph (16 km/h).

A description of the equipment used in this testing is described below.

Table 2. Equipment used.

Types of Equipment	Details
Cameras	35mm camera @ left side and right side (1st time used on right side), 35mm camera perpendicular to track, high speed cine camera and video camera w/ recorder.
Laser Transmissometers	Eight low power (5mw/cm^2) aimed at photodiodes or light meters.
Wind speed/direction	Calibrated anemometer.
Vehicle speed	Police radar gun, located past checkerboards.
Water depth	NASA water depth gauge; check made every 5 runs.

All the information gathered from the lasers were pooled together and calculated (as a mean); from there, comparisons between the left and ride sides were conducted. It was found, however, not to be the best way to handle this data. Variability in wind led the researchers to compensate said variability by addition additional sensors in the testing.

The second report under this study, titled *Heavy Truck Splash and Spray Testing: Phase II*, provides a more detailed description of the test procedures (Koppa et.al., 1985).

5.7 University of Michigan, 1984

> *Key Citation: Campbell, J.D., "Instrumentation for Measuring the Effectiveness of Truck Spray Suppression Devices," University of Michigan, Transportation Research Institute, Texas Transportation Institute, Report No. UMTRI-84-27, August 1984.*

This paper describes a methodology for evaluating and measuring the splash and spray from suppression devices placed on heavy trucks. This study, developed by The University of Michigan Transportation Research Institute (UMTRI) for TTI was to evaluate, "advanced instrumentation for the measurement of the improved visibility obtained by the addition of spray suppression devices to heavy trucks." Several laser transmissometers were used on each side of the test vehicle, "expanded collimated laser beams" were also used to grasp a larger area of the spray field, and photometric measurements were captured (of light reflected or scattered by the field).

This report also discusses the problems encountered with veiling luminance and its effect on accurately recording spray data. This report proposes developing a new instrumentation system that is able to lower the affect of veiling luminance by "illuminating the high-contrast target with the modulated light and then measuring apparent object contrast by the two-photometer method using bandpass-tuned photometers responding only to modulated light".

Table 3. Differences between scattering light and transmissivity systems.

Scattering Light Measurement System	Transmissivity systems
• Lower received light levels; require use of modulated light source and bandpass-tuned photometers in order to detect low light level and reject background illumination. • Spray density in a localized volume of the field determined by the light acceptance angle of the collector at the receiver and the positioning of the receiver with respect to the scattering light. • 1/1x107 of light that arrives at receiver.	• Low output power necessary. • Must be spaced far enough apart to measure cloud density along the length of the truck. • Good to relate to visibility.

Figure 25 illustrates the equipment that was proposed in the report. The author proposed increasing the diameter of the beam laser (before the laser passed through the spray test area); this would be used instead of the narrow laser beam, resulting in better spatial averaging and better measure of spray density through a space along the side of the truck (which is more closely approximating what a passing motorist would see).

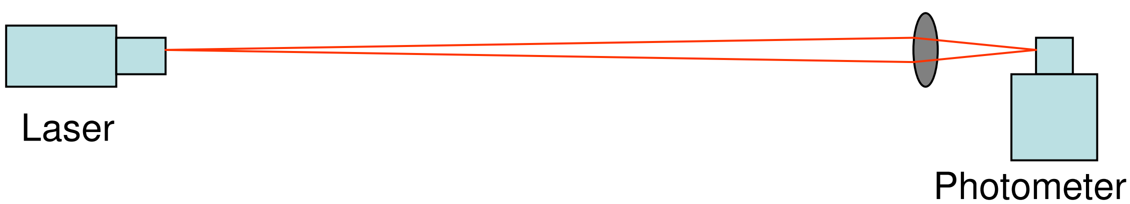


Figure 24. Laser beam

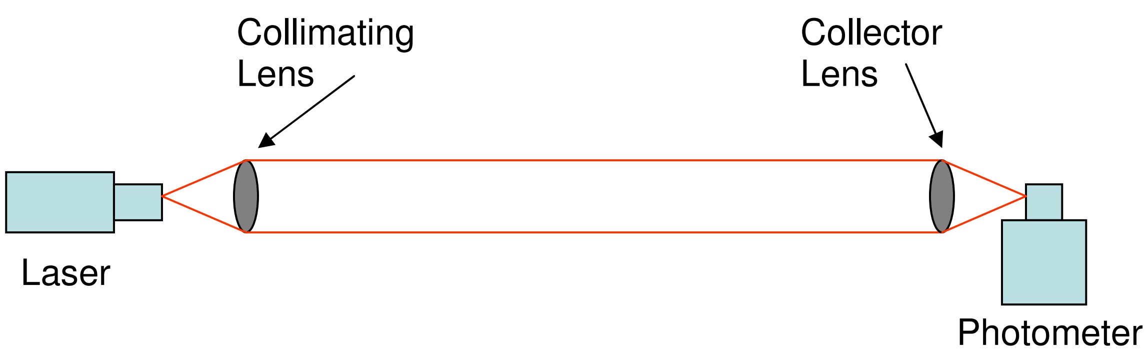


Figure 25. Collimated beam.

5.8 Transport and Road Research Laboratory (TRRL), 1987.

Key Citation: Colwill, D., Daines, M.E., "Development of Spray-Reducing Macadam Road Surfacings in the United Kingdom, 1967-1987," Transport and Road Research Laboratory, Department of Transport, Crowthorne, England, Transportation Research Record 1115, 1987.

This report discussed the advantages of developing spray-reducing macadam road surfaces to improve spray suppression, as well as noise reduction. At the time this report was developed, it was suggested that spray measurements be conducted using a, "vehicle-mounted optical back-scatter measuring device", which was employed in past research efforts and has shown this pavement surface to generate, "only about 10 percent of the spray level that is generated from the hot-rolled asphalt surfacings used in the United Kingdom.".

5.9 Society of Automotive Engineers, 1987.

Key Citation: Scheltens, J., Luyombya, M.A., "Spray Cloud Measurement System Based on Computer Analysis of Video Images," SAE Technical Paper Series, PACCAR Technical Center, Truck and Bus Meeting and Exposition, Dearborn, Michigan, November 16-19, 1987.

This report describes the development of a quantitative video-based measurement system to determine the amount of splash and spray emitted from the interaction between a wet pavement and a vehicle. Similar to the SAE J2245 method, checkerboards were used, and spray densities were calculated for each test run. The cameras were triggered by sensors, referred to in this report as "electric eyes", were activated as the test vehicle passed their location. The first image captured was taken before the test vehicle reached the test area to capture an image of the checkerboards without spray. The second image was captured when the truck passed the second set of electric eyes, 24 ft. (7.3 m) from the checkerboards. At the moment the second image was captured, wind speed and direction were also recorded. Sprinklers used to wet the test pavement were turned on a minimum of 3 minutes before the scheduled run. The images were analyzed on the track for immediate results. Tests were halted when wind speeds exceeded 8 mph (12.8 km/h).

Details of the testing equipment are given in Table 4.

Table 4. Equipment used for the quantitative video-based measurement system.

Types of Equipment	Details
Cameras	Two cameras with telephoto lenses (located 200 ft. [61 m] away from checkerboards), shutter speed of 1/60 s.
Checkerboards	8 ft. tall (2.5 m) x 12 ft. wide (3.6 m), grids 1 ft. (0.3 m)
Video I/O board	Microprocessor-based video interface board, IBM computer

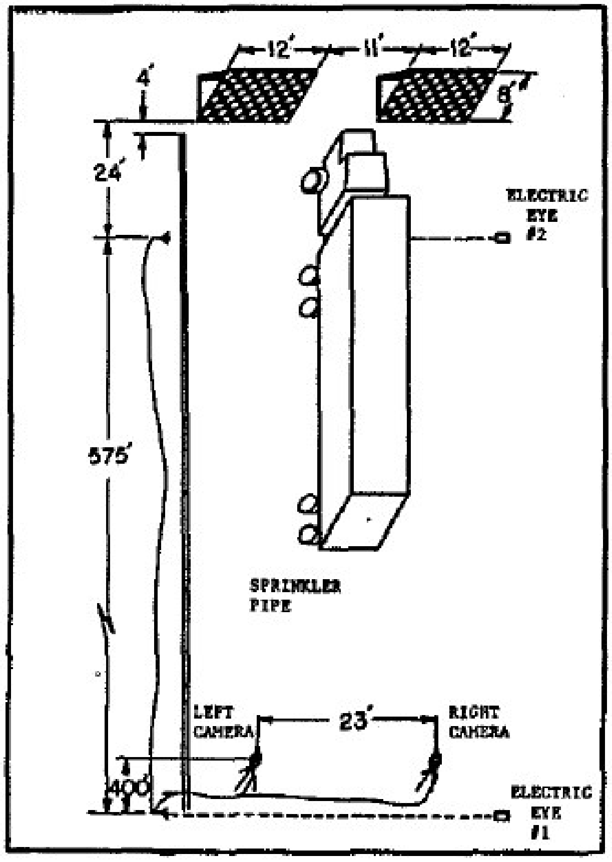


Figure 26. Test set-up for the quantitative video-based measurement system.

5.10 Society of Automotive Engineers, 1987

Key Citation: Koppa, R.J., Pendleton, O.J., "Splash and Spray Test Results," SAE Technical Paper Series 872279, Truck and Bus Meeting and Exposition, Dearborn, Michigan, November 16-19, 1987.

This report details TTI's (Texas Transportation Institute) efforts in developing a splash test method using laser transmissometers, in particular testing that occurred in 1984 (cited later). This report also mentions that visual evaluations of spray emissions were conducted by the Transportation Research Center of Ohio, and the laser transmission method developed by the Western Highway Institute. The test method described in this report deals with the laser transmission method.

The test track is a 400-ft (122 m) long asphalt concrete pavement, with an 18-ft. (5.5 m) wide test section (12-ft. [3.6 m] lane). The water was supplied by a 4-inch (102-mm) pipe distribution system, drilled with 1/8-in (3.2 mm) holes every two feet. The water depth was kept between 0.04 and 0.06 inches (1 and 1.5 mm). The test set-up consisted of four laser transmissometers, as shown in Figure 27. In addition to the laser measurements, two video cameras located on each side of the test section were also employed to record the test runs. Two vehicles are used: a test vehicle and a "chase vehicle" (1979 Pontiac Grand AM 4-door sedan that followed the test vehicle and recorded video imagery of the test from the chase car perspective). The targets placed at the end of the test section (to be used as part of the subjective visual evaluation of spray emission) comprised of an 8-ft by 12-ft (2.4 m by 3.6 m) white plywood board; a flat black ring (5 feet [1.5 m] in diameter) was painted in the center of the board (Figure 28). These targets were based on 20/20 ring where observers describe the gap they are able to notice (measurement of visual acuity using Snellen Lines)

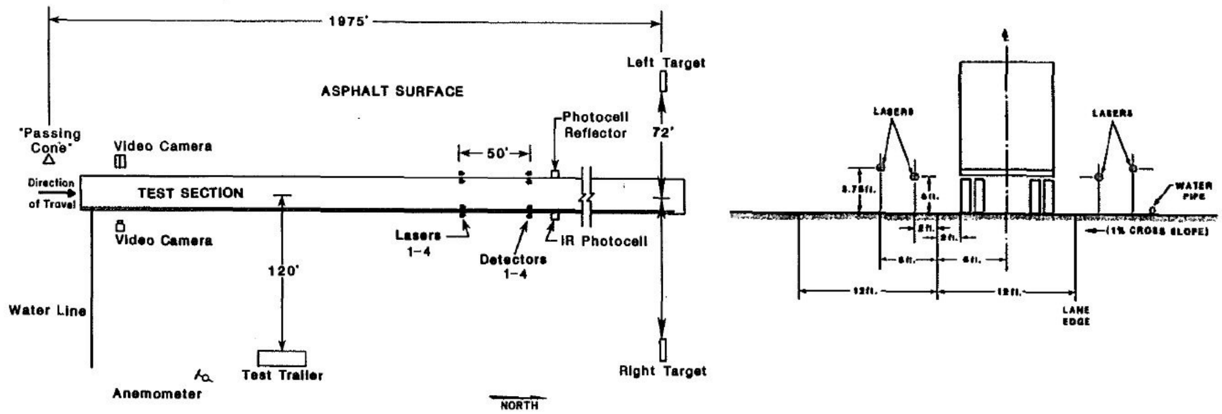


Figure 27. TTI's laser transmissometer test set-up.

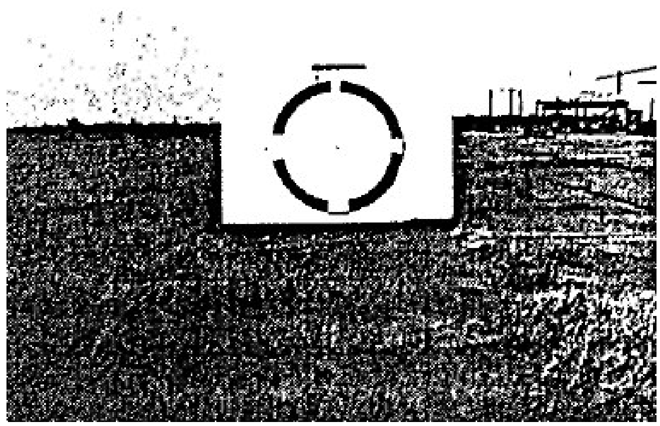


Figure 28. Image of target for visual evaluations used in conjunction with the laser transmissometers.

The observers used the following data collection sheet when participating in the visual experiment (Figure 29):

CHASE CAR OBSERVER DATA

OBSERVER________________________________ DATE____________

Circle the number of gaps that you could definitely see on the target ring when the driver said "PASSING". If you could see no gaps, circle "None", if the target itself was not visible, circle "not visible". Please make your circles as soon as you can after you have ridden through the test section.

RUN #	Gaps					
____	4	3	2	1	None	Not Visible
____	4	3	2	1	None	Not Visible
____	4	3	2	1	None	Not Visible

Figure 29. Chase car observer data sheet.

A description of the equipment used in this testing is described in Table 5.

Table 5. Equipment used.

Types of Equipment	Details
Video Cameras	Audio video cameras (monochrome and color), as well as two black and white still cameras. Located "256 feet (78 m) distant and on both sides of the vehicle path". One other camera located on a second vehicle that follows the test vehicle (driver's side).
Laser Transmissometers	Low power (5mw/cm2) aimed at photodetectors – lens system to focus 0.75 in. (19 mm) spot back to a pinpoint on the 10mm photocell. Located at 3.75 feet (1.1 m) outboard and 3 feet (0.9 m) inboard to represent driver eye and height, parallel to photodetectors.
Wind speed/direction	Calibrated anemometer (located 150 ft. [45 m] from test surface).
Vehicle speed	Police radar gun, located approximately 500 feet (152 m) from test section (beyond end).
Water depth	NASA water depth gauge; check made every 5 runs.

Testing was halted when wind speeds exceeded 20 mph (32 km/h), and if ambient precipitation was dense enough to be detected by the lasers.

This paper reports the amount of variability in the test data in the following statement: "From run to run, even when the vehicle is undergoing evaluation is unchanged, a considerable amount of variability exists in the data. Experience over the last four years indicates that this variability on adjusted data runs around 13% standard deviation, but can run as high as 24% or as low as 3% standard deviation on a given set of repeated measures on the same vehicle. This variability in measurement necessitates the high number of test runs and use of inferential statistical methods in order to evaluate differences among different splash and spray measurements."

It was also observed that wind speed under 3 mph (4.8 km/h) seemed to have a negligible effect on direction effects. In addition, it is also reported that a change in vehicle velocity of 5 mph (8 km/h) can, "produce a change in laser readings of as much as 15%". Relative humidity seems to have an effect on the amount of time that spray "hangs" in the air.

5.11 Transport Research Laboratory (TRL), 1992.

> *Key Citation: Nicholls, J.C., Daines, M.E., "Spray Suppression by Porous Asphalt", Highways Resource Centre, Transport Research Laboratory, Second International Symposium on Road Surface Characteristics, Berlin, 1992.*

The data collected in this report represents 33 trial sections of porous and rolled asphalts constructed over several years. From this, a mathematical model was developed for spray generation on road surfaces.

This spray apparatus used during the measurements was mounted on the back of the test vehicle, and evaluated the amount of spray generated by the test tire driving over a wet road. The instrumentation included a combined emitter and detector, and was able to measure spray up to 40 in. (1.0 m), "behind and in line with the center of the nearside rear wheel".

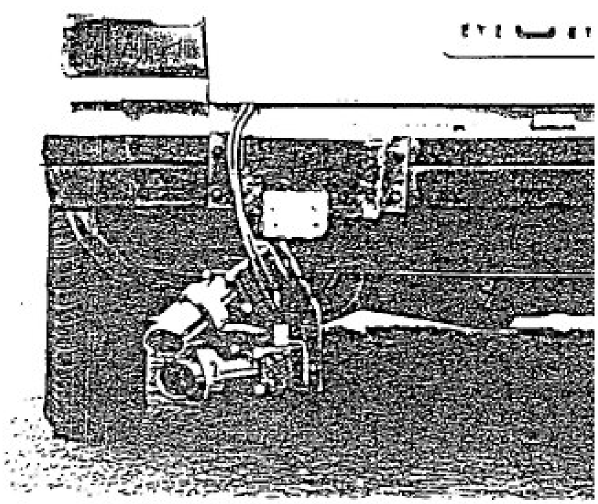


Figure 30. TRL equipment.

Infrared light from the emitter was cast upon the spray generated by the tire, and was captured by the detector, which was "gated electronically from the emitter pulse". Additional information about the output of the device can be found in this report.

5.12 Society of Automotive Engineers, 1994

<u>*Key Citation: Society of Automotive Engineers, "Recommended Practice for Splash and Spray Evaluation", SAE J2245, April 1994.*</u>

5.12.1 Digitizing Method

This method uses a combination of video images and checkerboards are used to analyze contrast measurements caused by a spray cloud as the test vehicle drives over a wet pavement by the checkerboards. Sensors, cited as "electronic eyes", are located around the test pad to trigger the cameras to capture images during the test. The first sensor is located 80 ft (24.4 m) before the cameras and the second sensor is located 35 ft. (10.7 m) before the checkerboards and outside of the field of vision of the cameras. Locations of the cameras and other test equipment are shown in Figure 31.

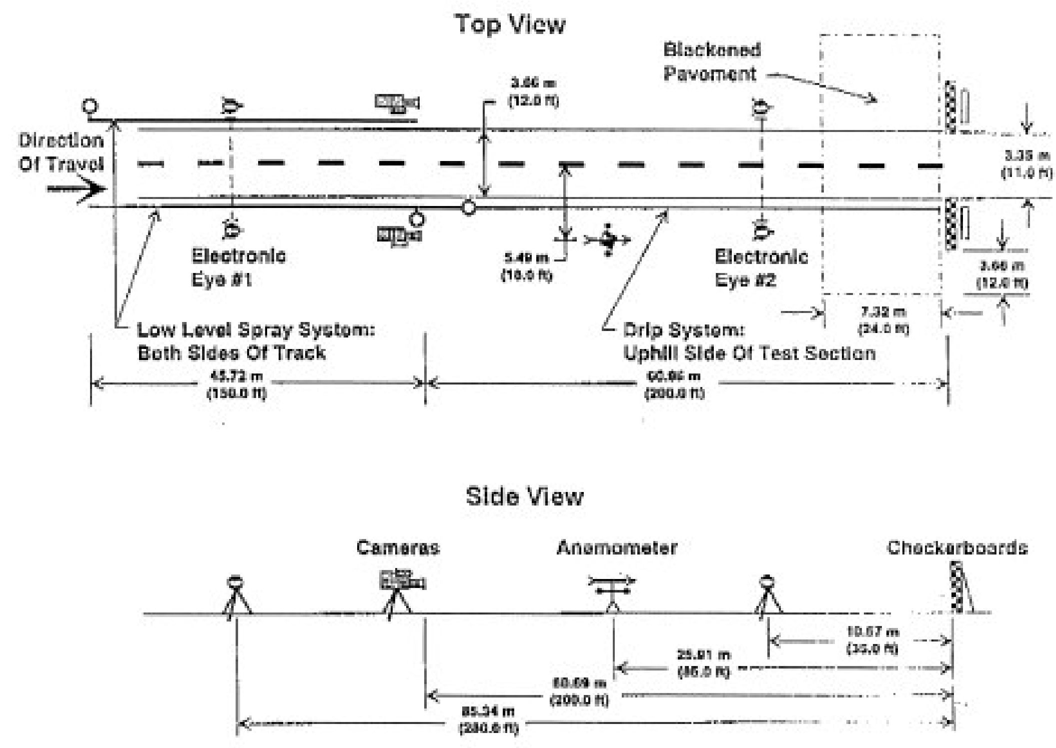


FIGURE 2—TEST SECTION LAYOUT—DIGITIZING METHOD

Figure 31. Test section layout for SAE testing.

In the test track, a section of the pavement (in front of the checkerboards) is blackened to "reduce variability from reflected light". The checkerboards used in this test are 12 ft. by 8 ft. (3.6 m by 2.4 m) (the width of the checkerboard must remain fixed); the grids are 1 ft^2. (0.1 m^2) (at a minimum), with the upper left-hand square painted white.

5.12.2 Laser Method

The laser method described in this specification states that the distance between the laser and the sensor "shall be separated by at least the length of the longest vehicle which will be evaluated in the test section, or a minimum of 15.24m (50 ft.)". Figure 32 illustrates the locations of the four installations. The beams are located at a height of 3.5 ft (AASHTO Design Driver Eye Height).

Table 6. Equipment used in the SAE procedure.

Types of Equipment	Details
Cameras	Two cameras and matches lenses (hi-res, black and white, able to produce an 8×12 ft. (2.4 m×3.6 m) image at 200 ft (61 m). Two "framegrabbers" also specified to capture simultaneous images from both cameras. Framegrabbers should be capable of measuring a pixel intensity (or gray scale) of 256 (an illumination scale of 0 to 255 is common). Sensors are located near the test pad to trigger cameras.
Computer Equipment	"Minimum 386 computer with a math coprocessor and a 200MB hard disc". Backup tape (150MB) also specified to store test images.
Wind speed/direction measurements	Triggered by first sensor. Anemometer located 85 ft. (26 m) from the checkerboards, center-height to the boards (0-20 mph [0-32 km/h], direction ±1°)

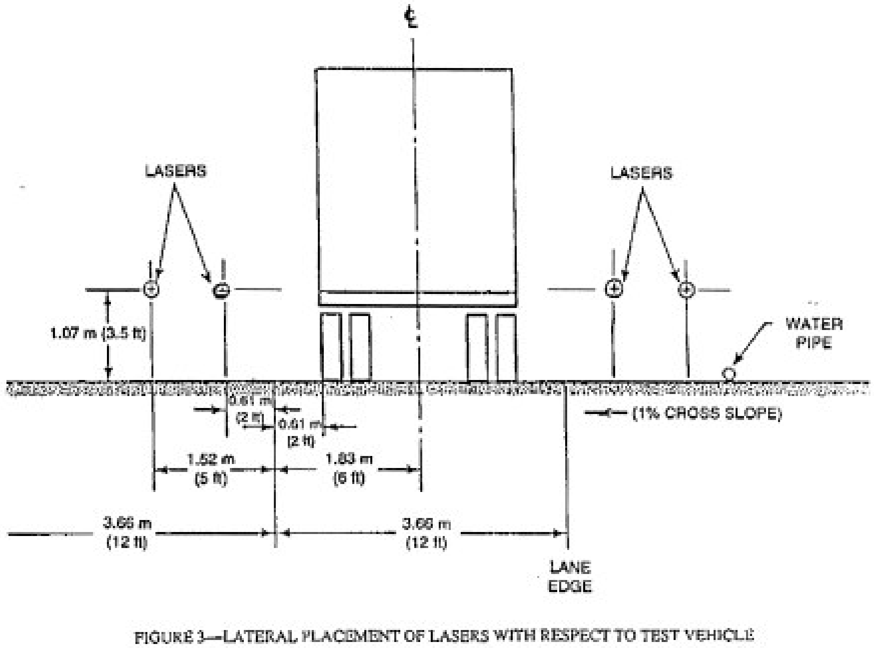


Figure 32. Back view of the SAE test layout.

5.13 Proceedings in the 9th International Pacific Conference on Automotive Engineering, 1997

> Key Citation: Mousley, P.D., Watkins, S., Seyer, K., "Video-Based Measurement and Analysis of Truck-Induced Spray", Proceedings in the 9th International Pacific Conference on Automotive Engineering, Technical Paper 971377, pp 67-72, 1997.

In this report, a video-based spray measurement method was developed to determine and evaluate the spray-reducing properties of spray guards. This method, developed by RMIT University, used "contrast variation (as opposed to changes in image brightness)" of video recorded images to measure both the size and density of spray clouds. It was reported that using contrast variation led to more "repeatable results" and a "better correlation of results from different test sections", giving the researchers more confidence in their overall findings. This differs from the other tests where brightness change is measured; as a result, testing can be performed in different light settings since this factor is not as crucial to the end results.

Similar to the SAE J2245 method, large checkerboard targets were used. The test track consisted of a 10.5-ft (3.2 m) oval fine-grade asphalt pavement (656 ft [200 m] of "wet section" with a downhill gradient of 1-in-200 (parallel to the direction of travel) and a cross-slope of 1-in-75 (perpendicular to direction of travel) (see Figure 33). Sprinklers kept the test pavement wet; in addition, they were turned on 30 minutes before the test run, and maintained a water depth between <0.04 in and 0.1 in (1 mm and 2.54 mm). Testing speeds were kept at 62 mph (100 km/h) using a "Freightliner FL106, cab-over-engine, tandem-axle tractor unit and a Lucar 13 ft. (4.0 m), tandem axle box trailer. The video cameras were triggered approximately 65 ft (20 m) before the truck passed the cameras and recorded for 8 seconds. Wind speed/direction, ambient temperature, and humidity measurements were monitored during the testing runs.

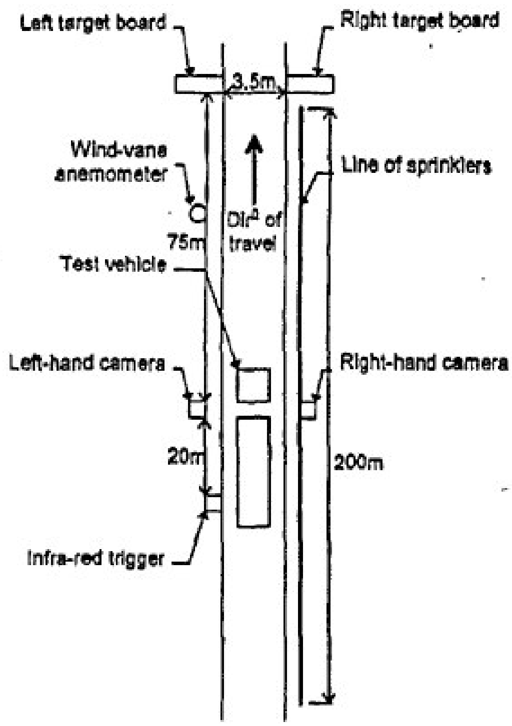


Figure 33. Test set-up.

Table 7. Equipment used.

Types of Equipment	Details
Cameras	CCD cameras (charge-coupled device), including video capture cards, adjustable iris and shutter speeds. Images captured at 12.5 frames/s, 8-bit (256 level) grayscale. Software for cameras was supplied with the capture boards. Cameras on tripods at 1 m (3.28 ft.) high and aimed at center of board – to represent line of vision for passenger of affected car
Checkerboards	2.4 m x 3.2 m (8 ft.×12 ft.) , 192 squares (each 195mm [7.6 in.])

It should be noted that although the "checkerboard" test method is very much similar to the SAE J2245 method, the procedure was modified as follows:

- The SAE J2245 procedure records 4 frames at 30 frames/second. This test method records at 12.5 frames/second.
- The distance between the cameras and the target boards, size of grid squares and vehicle speed differs as well.

5.14 National Highway Traffic Safety Administration (NHTSA), 2000

Key Citation: National Highway Traffic Safety Administration (NHTSA), "Update on the Status of Splash and Spray Suppression Technology for Large Trucks: Comprehensive Review and Evaluation of Spray Suppression Measures That Could Be Employed on Heavy Duty Vehicles (over 8,500 pounds GVWR) to Provide Clearer Highway Visibility and Safety During Periods of Adverse Weather Conditions," Report to Congress, March 2000.

This report mentions three basic methods of evaluating anti-spray devices:

- Full-scale road tests
- Laboratory tests
- Computational tests

Full-scale road tests, much like the SAE J2245 method, use cameras and lasers to measure the amount of spray as a test vehicle passes over a wet pavement (water depth kept monitored). Some test procedures, such as Laval Universities, employs lasers in up to 14 different locations (SAE only specifies two locations). The Mercedes Benz method was also briefly described.

5.15 AAA Foundation for Traffic Safety, 2003

Key Citation: Manser, M.P., "Evaluation of Splash and Spray Suppression Devices on Large Trucks During Wet Weather", AAA Foundation for Traffic Safety, Washington, D.C., October 2003.

Lemay, J., Dumas, G., Venisse, A., François, G., "Conception et ´évaluation par essais routiers de prototypes de systèmes anti-éclaboussures pour véhicules lourds, Rapport final, Action concertée Fonds Nature et Technologies – MTQ – SAAQ," Programme de recherche universitaire en sécurité routière, Département de génie mécanique, November 2005

This report describes the devices that were used to determine which spray reducing devices were efficient in reducing spray on large trucks during wet weather. In addition, this study sought to determine a testing methodology that can efficiently evaluate spray protectors.

5.15.1 European Union Method

This testing method is performed in the laboratory; the European Committee for Standardization (CEN) decided to adopt laboratory methods to evaluate spray devices. This method was developed to, "quantify the ability of a device to retain the water directed against it by a series of jets. The test assembly is intended to reproduce the conditions under which the device is to function when fitted to a vehicle as regards the volume and speed of the water thrown up from the ground by the tire tread"

This testing setup consisted of a spray device that was placed close to a high-pressure spray nozzle. The water from the nozzle is projected onto the spray device, and the water is collected the amount of water dropped and retained.

5.15.2 SAE J2245 Digitizing and Laser Method

This report references the Society of Automotive Engineers specification J2245 digital method. For brevity, this test method will not be discussed since it has already been described. The SAE J2245 Laser method was used to evaluate existing / prototype products for this research report. As stated in the AAA report, the SAE J2245 method was used, "because it has proved to be one of the most valid and reliable testing protocols available for spray device testing."

5.15.3 Mercedes Benz Scattered Light Method

Researchers at Mercedes Benz developed a method to measure spray produced by large and small vehicles, termed in the AAA report as the "Mercedes Benz Scattered Light" method. The two components of this test method are a light source and a light detector. The light source is placed, "above and to the side of the vehicle, which produces a light curtain directed at the ground". The light detector is placed near the bottom of the vehicle, on the same side as the light source. The vehicle drives at two speeds – 38 and 50 mph (60 and 80 kph) – over the wet pavement, where water thrown from the wheels, "flow through the light curtain", resulting in this light being reflected. With more water flowing through this light curtain, more light is reflected, resulting in less light being captured by the detectors. Because the instrumentation can be situated behind several types of vehicles and not very much light from other sources (such as sunlight) interferes with this process, it is an advantageous method to use.

5.15.4 PLM 16

This test method is a modification of the SAE J2245 Laser Method, now referred to as the "PLM 16". A research project under the Quebec Ministry of Transport called *Comparison of Anti-Splash Systems for Heavy Vehicles* developed a system for, "measuring spray that would evaluate the transverse direction of a spray cloud, evaluate the longitudinal density of the spray cloud, prove to be reliable, and would be reasonable in cost and complexity."

The test track for this test method consists of a 1200-ft. (366-m) track (100–ft. [30.5-m] wet zone followed by a 200–ft. [61-m] wetted test zone); the test is conducted at a criterion speed of 48 mph, and the water depth (at the wetted zone) was kept at 3/64-in (1.2 mm). An illustrated layout of the test zone is shown in Figure 34.

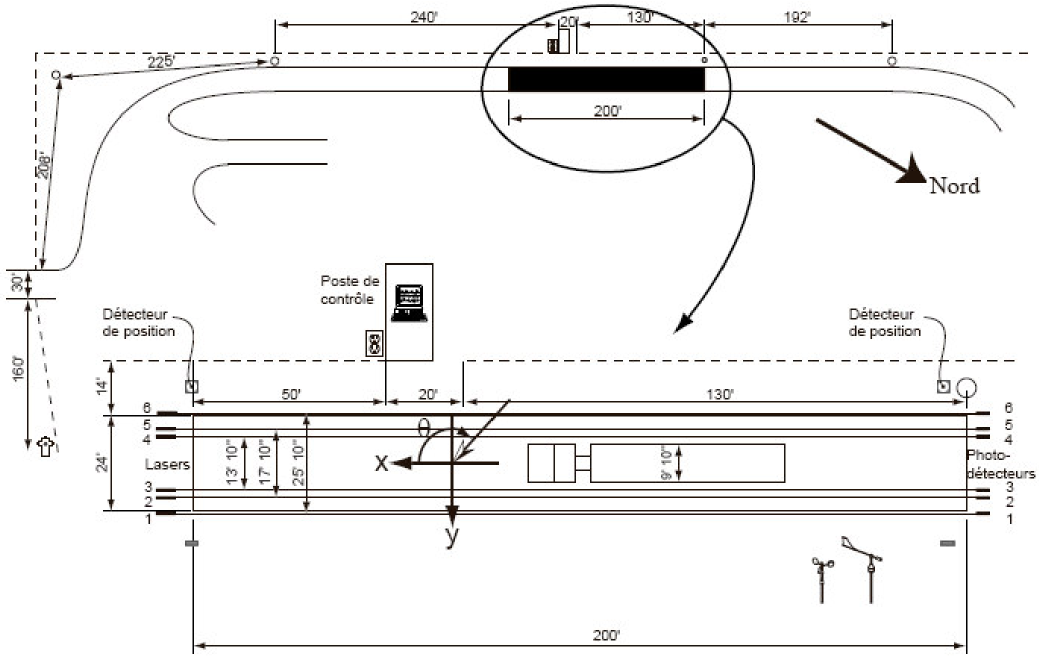


Figure 34. Test layout of the PLM 16 test method (in French).

In the PLM 16 method:

- 16 photodiodes detector assemblies were situated in a line, next to each other;
- The laser was placed at the end of the 200-ft. (61-m) wetted test zone (next to the test pad, same side as photodiodes); and
- Spray was measured by the laser system as a, "reduced level of light passing between the horizontal scanning beam and the photodiode detectors and is referred to as an opacity index."

One advantage that this test method has over the J2245 method is that this test method allows data to be collected from 16 photodiodes, which is able to capture the spray cloud image with additional resolution.

Figure 35. Heavy truck on test track.

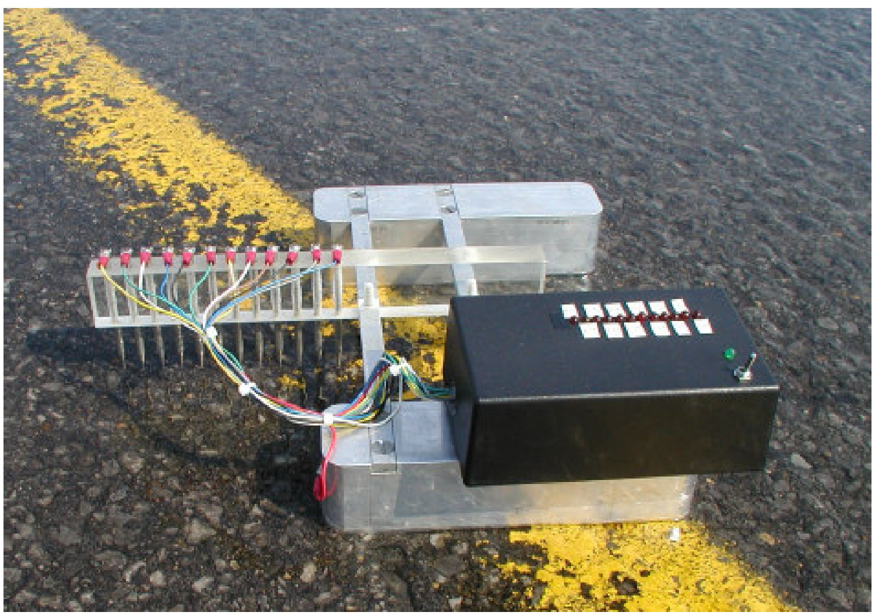


Figure 36. Instrument to measure water depth.

The instrument shown in figure 36 was designed as the "water film gage". It was used to monitor the depth of the water on the test track. The device is composed of 12 stainless needles, supported by a plexiglass bracket, used to prevent the current from jumping from one needle to another. Each of the 12 needles is connected through electrical wires to an LED light located at the top of the black box in figure 36. This device was designed to measure the film of water on the surface, ranging from 0 to 0.12 in. (0 to 3 mm) in thickness. In order to achieve this, the height of each needle was adjusted to where the difference between its adjacent needle is 0.01 in. (0.25 mm) (see figure 37).

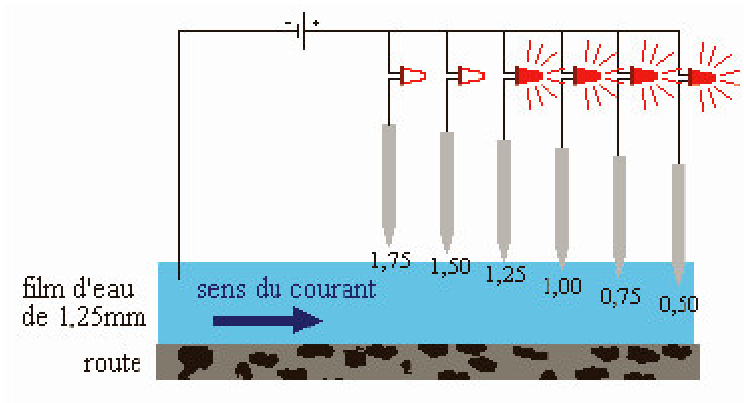


Figure 37. Illustration of LED lights illuminated in relation to the needles in contact with water film.

The device is then placed on the pavement track with the water flow in progress. The LED light will turn on for each needle that is in contact with the water, therefore identifying the thickness of the water film. As in the case in figure 37, the LED light for the 0.05-in. (1.25-mm) height needle is illuminated, yet the 0.06-in. (1.5-mm) needle is not; therefore, the thickness of the water film is approximately between 0.05 and 0.06 in. (1.25 and 1.5 mm).

Figure 38. Test vehicle passing through lasers.

5.15.5 Video-Based Method

This method is similar to the SAE J2245 digitizing method. However, this method is able to collect 100 frames of video at 12.5 frames per second, as opposed to the digitizing method, which collects four frames of video at 30 frames per second. Advances in technology have made it possible to collect more precise data.

5.16 Transport Research Laboratory (TRL), 2005

Key Citation: Knight, I., et. al, "Integrated Safety Guards and Spray Suppression – Final Summary Report," Published Project Report PPR075, Department of Transport (TRL), November 2005.

This report documented an investigative effort at TRL into methods of measuring spray. Specifically, the investigation was to establish a reliable measurement method using a specific technique by which spray could be quantified for future use in comparing devices that would suppress spray caused by heavy goods vehicles (HGV).

The literature review conducted for this paper reported three particular methodologies for testing and quantifying spray. These methodologies, along with their individual advantages and disadvantages as presented in the report are shown in Table 8.

Table 8. Advantages and disadvantages of measurement methods.

Measurement Method	Advantage	Disadvantage
Longitudinal	Can measure spray at the most dangerous position (where a car would be if it were passing)?	Strongly influenced by lateral position of the vehicle relative to the measuring station.
Cross track	Measures larger quantity of spray and is less sensitive to the lateral position of the vehicle.	Cannot be related to the human driver's experience because it measures spray at right angles to the direction of travel.
On-board	Records a constant spray measurement	Sensors exposed to vehicle "shake" and vibration, affecting the accuracy of results.

According to this report, the laser transmissometer was used as a common means to measure spray in the past because of its accuracy and its ability to not be affected by ambient light levels. Consequently, this device is able to measure spray effectively if it is properly set-up and aligned. In addition to laser transmissometers, telephotometers have also been used along with a calibrated light source to determine transmittance and veiling luminance. Much like the laser transmissometer, this device must be set up accurately and properly in order to obtain reliable results.

Video imaging was shown to be an advantageous measurement device. Using video imaging as a means for spray measurement allows the researcher to collect a larger area of spray, as opposed to small area measurements with laser transmissometers and telephotometers. In addition, transmittance, luminance contrast, and veiling luminance could all be captured at the same time.

Laboratory methods were also evaluated in this report. In this case, four miniature scale model trucks were created and tested in a "wind tunnel" environment. The path of spray due to cross winds was simulated by the flow of smoke for these mini replicas. Video images were taken for all three methodologies and compared.

Figure 39. Model scales used for laboratory "wind tunnel" tests.

The subsequent field measurement methods consisted of three phases. In Phase 1, the following conditions affecting the testing were considered:

- Tire tread: although it did not pose an issue in evaluating test methods, and therefore was not considered.
- The HGV was not loaded.
- The road was watered by spray bars built into the sides of the lanes from which a controlled amount of water was ejected and directed onto the wheels of the HGV. An electronic water depth measuring method was used to monitor the water depth.
- All road surface texture and environment conditions were kept similar. A weather station was employed to monitor ambient conditions, recording humidity, ambient temperature, and wind speed/direction.

Testing then proceeded as follows:

- A Firewire (IEEE 1394) digital interface camera was chosen (PixeLINK PL-A662) to better simulate the human eye response.
- 20 runs of a length of track at speeds of 50, 70, and 90 mph (80, 113, and 144 km/h) were performed.
- A checkerboard target was set up at the measuring point.
- Video images were taken for one cross track measurement, one longitudinal measurement on each side of the HGV, and one on-board measurement at the point where the checkerboard target was set up

Video images generated at a rate of 25 frames per second for 4 seconds captured what happened as the HGV passed the target. The checkerboard method (similar to SAE J2245) was used as the target to capture the amount of reflected light as spray was generated (measuring the transmittance). Maps, plots, and integrals were generated from the transmittance values in order to compare the effects of speed and amount of spray for each speed. Since all three scenarios were tested (cross-track, longitudinal, and on-board), five separate measurements of spray were obtained.

This video digitizing method showed that the cross-track spray method had the most potential for accurately evaluating video images. The other methods were discarded for being unsafe or impractical, according to the report.

Phases 2 and 3 addressed the concerns and issues that were derived from the Phase 1 testing. The following lists some of the issues that were addressed:

- Color cast – to avoid the blue tint, a black and white image was decided to be more useful
- Color graduation –images of target were analyzed before and after vehicle passed to avoid the affects of perceived brightness at the top of the target.
- Camera exposure control – this was addressed by changing the lens aperture to keep within luminance range, and by keeping conditions as similar as possible in hopes of avoiding the need to change the aperture. The affects of this detail are recorded as "clipped" images, or images that are washed out with parts missing.
- Camera timing – timing difference between the camera and computer combinations needed to be addressed. It was suggested that use of specific software might help; else testing to measure the timing response difference would have to be run.
- Camera range – to avoid "clipping" of the "white" value, ND filters and amplifier gain would be necessary.
- Lighting levels and lens flare – over exposed images were the result of flare from direct sunlight, so testing was kept to times of overcast.

In Phase 3, a laser beam was used in conjunction with the video method for comparison reasons. The laser was employed to measure transmittance at mid-height, on the side of the target. The tests in this phase were conducted "with two cameras and a laser operating in parallel".

The results of this report showed that video imaging was reported to be 81% reliable. It is assumed that veiling luminance is the cause of the 19% reliability difference. The results also indicated more accuracy of the video imaging technique at lower speeds.

Recommendations provided by this report indicated that it would be useful to, "break the target board into a number of horizontal bands or zones", in order to apply a weighting scale in relation to the amount of spray at different heights. Each zone would range in "hazard type". In addition, it was shown that although, "it would be reasonable to expect that measuring spray over a larger target area would be better than using a narrow beam laser, the results from this test program show that the differences are minimal."

5.17 Danish Road Institute, 2005

Key Citation: Bendtsen, H., Raaberg, J., Thomsen, S.N., "International Experiences with Thin Layer Pavements," Road Directorate, Danish Road Institute, December 2005.

This paper briefly describes literature over splash and spray test methods. For brevity, a table summarizing the findings of this report is shown in the figure below.

Table 9. Literature findings.

Authors	Institution	Year of publication, country	Title	Research questions included
McDaniel and Thornton	Purdue University	2005, USA	Field Evaluation of a Porous Friction Course for Noise Control	Qualitative evaluation of splash and spray on porous pavement.
C.J. Baughan and P.K. Hart	TRL Limited	1988, United Kingdom	Water spray from road	Method for measuring splash and spray using laser. Different analysis methods are evaluated.
Andrew Puclin and Simon Watkins	RMIT University	1996, International Conference, Australia	Quantitative truck spray measurement	Low costs equipment (digital camera) for measuring splash and spray is tested.
Olga J. Pendleton, Rodger J. Koppa, and Ofelia Gonzales-Vega		1988, Truck and Bus Meeting, USA	Prediction of the effect of wind on splash and spray results	Laser used for measuring, model for predicting how the aerodynamic of a truck influence on the splash and spray
Hans Goetz and Ronald Schoch		1995, International Congress, USA	Reducing splash and spray of trucks and passenger cars	Mostly concerning investigation of reducing splash and spray. But the method measuring that is using light and measuring the reflecting light.
Michael P. Manser		2003, AAA Foundation for traffic safety	Evaluation of splash and spray suppression devices on large trucks during wet weather	Gives a very good overview of the methods which have been used for detecting splash and spray
J.C. Nicholls and M.E. Daines	1992, TRL	1992, TRL	Spray Suppression by Porous Asphalt	Here a paper refers to test on different surfacing layers. The method used here use infra red light

5.18 Council for Scientific and Industrial Research (CSIR), 2007

Information provided by: Dr. David Jones, University of California (Davis)

The Council for Scientific and Industrial Research (CSIR) in South Africa developed a splash and spray measurement device called the Spraymeter shown in figures 40 through 42. The development of this device was based on a dust measuring device called the Dustmeter, which measured "dust from unsealed roads". The Spraymeter "consists of infrared sender and receiver units on either side of a steel frame. A high-speed rotating glass screen in front of the transducers prevents water build up on the lenses". In addition, the device reports an opacity index by measuring opacity "between the transducers"; in turn, this index can be "linked to public acceptability criteria". The reason for developing the device was to "have a less subjective measure for assessing spray performance of open graded asphalt concrete, chip seals, etc., and to introduce criteria for spray on road surfacings". The Spraymeter has not been commercialized as of yet.

Figure 40. Splash and spray measurement device, The Spraymeter, developed by CSIR (Photo courtesy of Ken Fults, University of Texas)

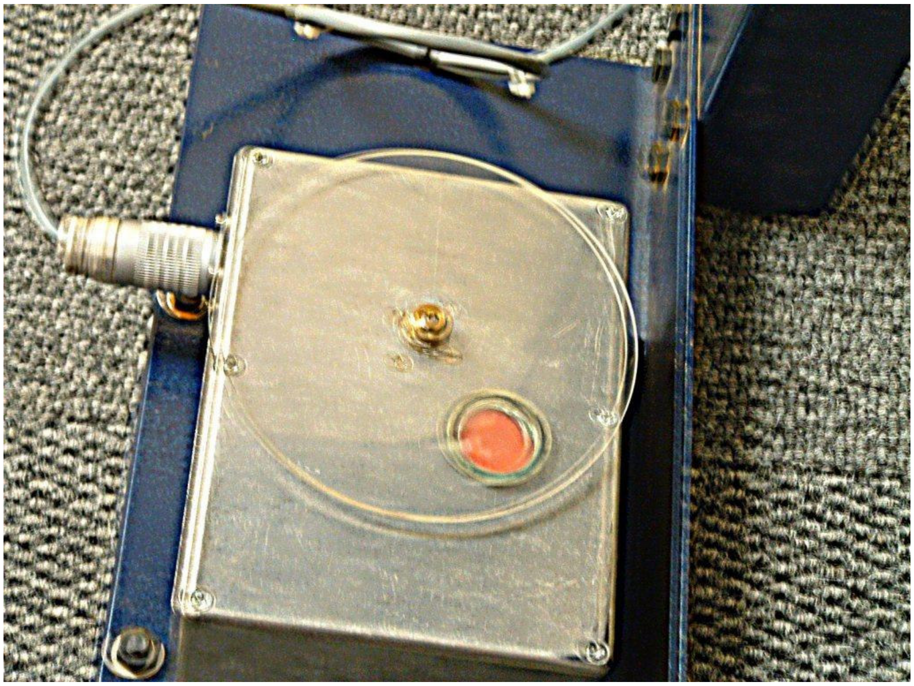


Figure 41. Close-up of Spraymeter (Photo courtesy of Ken Fults, University of Texas)

Figure 42. Photo of device on a poster board (Photo courtesy of Ken Fults, University of Texas)

5.19 Transport and Road Research Laboratory (TRL), 1988

Key Citation: Baughan, C.J., Hart, P.K., "Water Spray from Road Vehicles: Transmittance Analysis Methods", Transport and Road Research Laboratory, Department of Transport, Research Report 162, United Kingdom, 1988.

This report describes the work conducted at TRRL (now TRL) to evaluate different methods to analyze time-varying signals produced by beam detectors used for measuring splash and spray of a passing vehicle. When a vehicle travels along a wet road at high speeds, the water ejected between the vehicle tires and the wet pavement results in small and large water droplets (splash and spray). The small water droplets, referred to as spray, are generally noted to be expelled in the form of a cloud (a cloud of spray) that forms on the side and behind the traveling vehicle. As mentioned in this report, one of the methods used to measure the amount of splash and spray is using a beam of light that is "shot" through the spray cloud, and determining the density by analyzing the transmittance.

This report discusses the methods used in "analyzing and interpreting…transmittance measurements" of the sort. The instrumentation, often a transmissometer directed across the path of the vehicle (traveling over the wet pavement) onto a reflecting mirror and caught by a photodiode located in close proximity to the transmissometer, is located along the side of the wet track where the vehicle will pass. A "time-varying signal" is collected from the photodiode, which is then "amplified and recorded". Using this signal, "the proportion of light (T) transmitted b the portion of the spray cloud in the transmissometer beam may be easily obtained"; an illustration of this is shown in Figure 43.

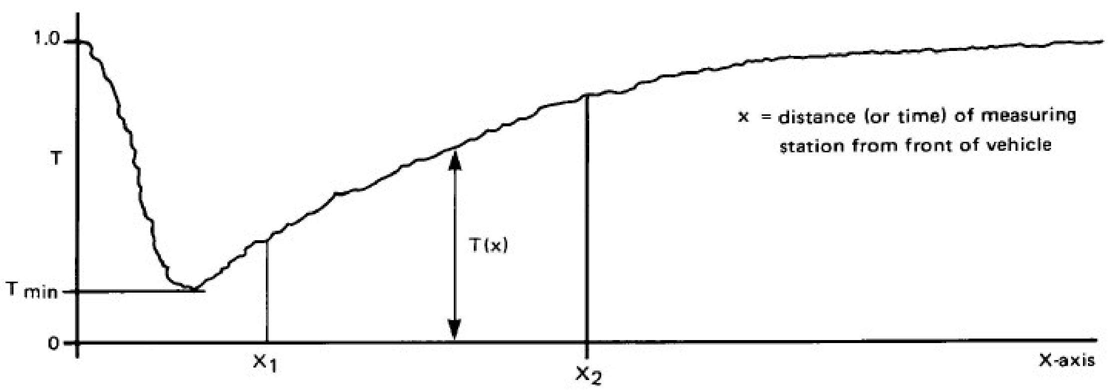


Figure 43. Variation in proportion T of light transmitted as vehicle drives past the transmissometer

6. DISCUSSION OF THE USEFULNESS OF MEASUREMENT METHODS FOR CHARACTERIZING PAVEMENTS

Accurate measurement of splash and spray characteristics of pavements and/or vehicles is an extremely complicated task which constitutes a challenge to the research community requiring a wide application of state-of-the-art knowledge in vehicle-tire-pavement interaction. A measurement method for characterization of the pavement effect on splash and spray should be reproducible and representative. The present knowledge, experience, and technology do not promise such characteristics for any method.

Under actual road conditions it would be difficult, if not impossible, to control parameters such as water depth, wind speed, wind direction, contamination of water, light conditions, etc. Other variables difficult to control in an accurate way include cross slope. One would also have to standardize the tire and the vehicle in case one would like to have full-scale conditions.

Instead one might prefer to limit pavement testing to test tracks. Even still, many of the above problems would be difficult to control also on the test track, including wind and light conditions. Under test track conditions, however, a watering system can be used which may give acceptable repeatability. A major problem on a test track is that one would not be able to test pavements subjected to actual traffic for a reasonable time. A test track surface would therefore not be representative of the long-term characteristics of a pavement. For example, a new HMA or SMA normally absorbs quite a lot of water until the water collects on the surface. This does not happen after some time of compaction and wear by traffic. Porous pavements perform the best in new condition and often rapidly lose their advantageous characteristics due to clogging.

It is difficult to imagine a promising and realistic method for either testing on actual highways or testing on test tracks where a sample of the test pavement has been laid.

Instead, one goal may be to seek out a model to calculate the splash- and spray-suppressing characteristics.

7. MODELS RELATED TO SPLASH AND SPRAY

By means of a set of models one should be able to relate splash and spray characteristics of pavements to a few proxy parameters which would either be relatively easy to measure or set at standardized values. These variables would include rainfall intensity, rainfall duration, texture depth (e.g., MPD), megatexture, cross slope, type of texture (e.g., tined PCC), air voids (considering clogging effects), porous layer thickness, longitudinal gradient, vehicle speed, etc. From such data one would be able to assign a certain splash and spray "rating" to each pavement type, for virtually any set of conditions.

At this time, the only models available are those to calculate the water depth on a pavement.

For example, one model to calculate the water depth in ponds on the pavement was developed at VTI some years ago (Nygardhs, 2003). The task of developing the model used data from the Laser Road Surface Tester to detect road sections with risk of aquaplaning. A three-dimensional model based on data from road surface measurements was created using MATLAB. From this general geometrical model of the road, a pond model was produced from which the theoretical risk ponds are detected. A risk pond indication table is further created. The pond model seemed to work well assuming that the data from the road model is correct. Figure 40 is an illustration of calculated ponds.

An alternative model has been produced at PTI in USA (Andersen et al, 1998). This study found that, "the prediction of the water film thickness is based on the use of the kinematic wave equation as a model to predict the depth of flow on pavement surfaces. Data supporting the model were obtained from the literature and from studies conducted to measure Manning's n for a brushed concrete surface and for porous asphalt surfaces. Expressions for Manning's n as a function of Reynold's number were developed for portland cement concrete, concrete, asphalt concrete, and porous asphalt surfaces. Full-scale skid testing was also conducted on grooved and brushed concrete surfaces and on porous asphalt surfaces; texture measurements were obtained for all of the tested surfaces (laboratory and field). The results have been integrated into an interactive computer program, PAVDRN. This interactive program allows the pavement design engineer to select values for the critical design parameters. The program then predicts the water film thickness along the line of maximum flow and determines the hydroplaning potential along the flow path."(Andersen, et.al., 1998)

These models may be a good start for a more advanced and complete model to relate proxy parameters to splash and spray characteristics.

Note that these models do not consider the water created by condensation on the pavement. Air temperature and air humidity may work together when temperatures are just a little higher than freezing, to create substantial condensation of water on the pavement. The author has seen examples of puddles and ponds being created in this way. The models may need to be supplemented in this way.

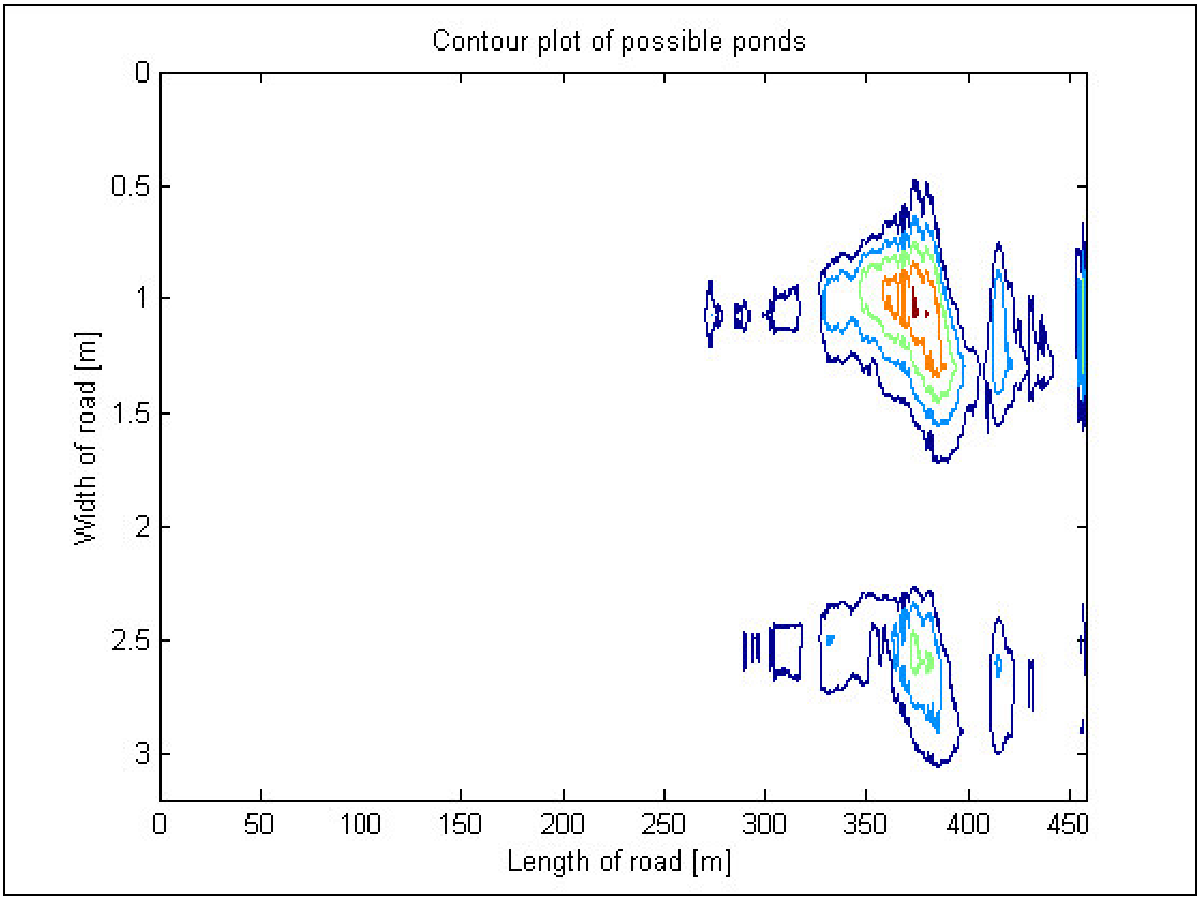


Figure 44. Illustration of calculated ponds along a road
(Note: The ponds are located in the two wheel tracks (ruts) on the road (Nygardhs, 2003)).

8. CHARACTERIZING THE SPLASH AND SPRAY POTENTIAL OF PAVEMENTS

Given the numerous complexities of developing an objective and repeatable splash and spray measurement system, it is instead proposed that a composite model be developed by which one can predict the splash and spray characteristics of pavements. For this purpose, it is useful to distinguish between splash and spray, which means that developing both a splash and a spray sub-model will be necessary.

For the prediction of spray, this may be limited to the prediction of the volume of water which is picked-up by vehicle tires. This would likely be appropriate since the spray emission, independent of vehicle and wind conditions, must be proportional to this amount.

A Splash Model may supplement the Spray Model by predicting the amount of water which a tire must displace from the pavement once the tread is filled with water.

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 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 depth 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 liters/m) of pavement before the tread is saturated. Thus, 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). Models used in hydroplaning evaluations should be consulted to refine this statement.

While the example given here is based on a number of assumptions, the model itself does not have to be limited in the combinations of these parameters. Looking at the fundamental mechanisms at play – even if in a simplistic manner – can result in a model that can be reasonably extrapolated to a wide range of conditions.

As a first approximation of a model, one would need to calculate the water depth, expressed as the water which the tire needs to displace. The water in lower parts of the texture which are not enveloped by the tire will not be counted.

Models for water depth calculation are already available, although how well they can take texture into account should be investigated. Supplementary investigation, or at the very least validation, may be necessary to demonstrate this. If conducted, model validation will be necessary under a range of typical conditions on a variety of pavements. The more fundamental the model is, however, the fewer the number of conditions would be needed in order to reliably validate the prediction.

If the desire exists to develop a model that can accommodate porous surfaces, further complexity may arise, since it may be difficult to take into account the pumping of water in and out of the voids. However, this part of the model may not be too difficult to develop. There should be a good relationship between air voids content, possibly turtuosity, and the pumping affect. Research on this would also be necessary, which probably can be done in a laboratory, or even by theoretical calculations.

In summary, while it would be ideal to develop and implement a model that captures the numerous parameters affecting these phenomena in the most fundamental way possible, this may be too ambitious of a goal at first. It would instead be worthwhile to explore the development of hybrid models that would opt for physical analogies and other simplifying assumptions in order to reduce the number of model inputs at first. Calibration of these models would be necessary to align predicted and measured responses.

It is further recommended that as the simpler model is verified, additional parameters be added in an orderly fashion. Ideally, priority would be given to the most sensitive parameters: either adding them as direct inputs and/or better characterizing them. Throughout this process, maintaining the practical nature of the model should be a goal. The modelers should ask themselves if the parameters that are being added will be easy to measure or derive once the model is eventually put into practice. Furthermore, the variability of the parameters should also be realized, and ideally considered in a way that captures the stochastic nature of the prediction (e.g., the incorporation of reliability concepts).

9. CONCLUSIONS

Splash and spray from vehicles driving on wet roads can be a serious problem, both from the viewpoint of traffic safety and pollution. Neglected by many, it has now been demonstrated that the pollution alone has had serious economic effects, both on vehicles and on roadside objects. The road environment, including forests and other vegetation, has also been affected, with economic impacts following suit.

Wet pavements play a significant role in the creation of splash and spray, where several properties contribute to the overall pavement influence. It may be possible to control splash and spray by proper pavement and highway design, for example through the use of deep macrotexture or porous pavement types.

Spray may be reduced by proper vehicle design. This is applied in Europe where there are regulations requiring heavy vehicles to be equipped with advanced spray protection devices.

It is concluded that neither known methods for measurement of splash and spray, nor foreseeable future methods seem to be suitable for a reproducible and representative characterization of splash and spray properties of pavements. The uncontrolled parameters are too numerous and too difficult to handle, much less characterize.

Instead, it is proposed that the splash and spray properties of a pavement be predicted by means of a Splash Model and a Spray Model, largely based on prediction of water depths on the pavement. The influencing parameters can then be set at some agreed standard values typical of highway conditions. The major input parameters which one would need to know for a certain pavement would be air voids content (after considering clogging), porous layer thickness (if any), and texture depth (e.g., MPD).

The enveloping effect of tires over the texture profile curve may also have to be determined in order to know how much of the texture depth which will not be in contact with the tire. Furthermore, rainfall will of course be another critical input. Predictions by way of historical rainfall intensity can be done, which will make the resulting model more practical since it will localize the prediction. This will further ensure that pavements are not "over engineered" to mitigate splash and spray when it may not necessarily be a critical factor.

Research, development, and validation will be needed to accomplish the above. For example, the models to calculate water depth need to be confirmed or validated. The way that these models take pavement texture into account would also need to be verified. Furthermore, for porous pavements one would need to determine a relation between air voids and the water pumping effect in and out of the pores. One may also need to calculate water depth based on condensation of air humidity into water on the pavement.

Finally, while many of the visual techniques identified herein would be of little value in model validation, they may still be a useful part of a validation program. Integrating a photographic-based test, for example, may assist in implementing the findings of subsequent studies, since the measures of splash and spray magnitude are still a mystery to many people.

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