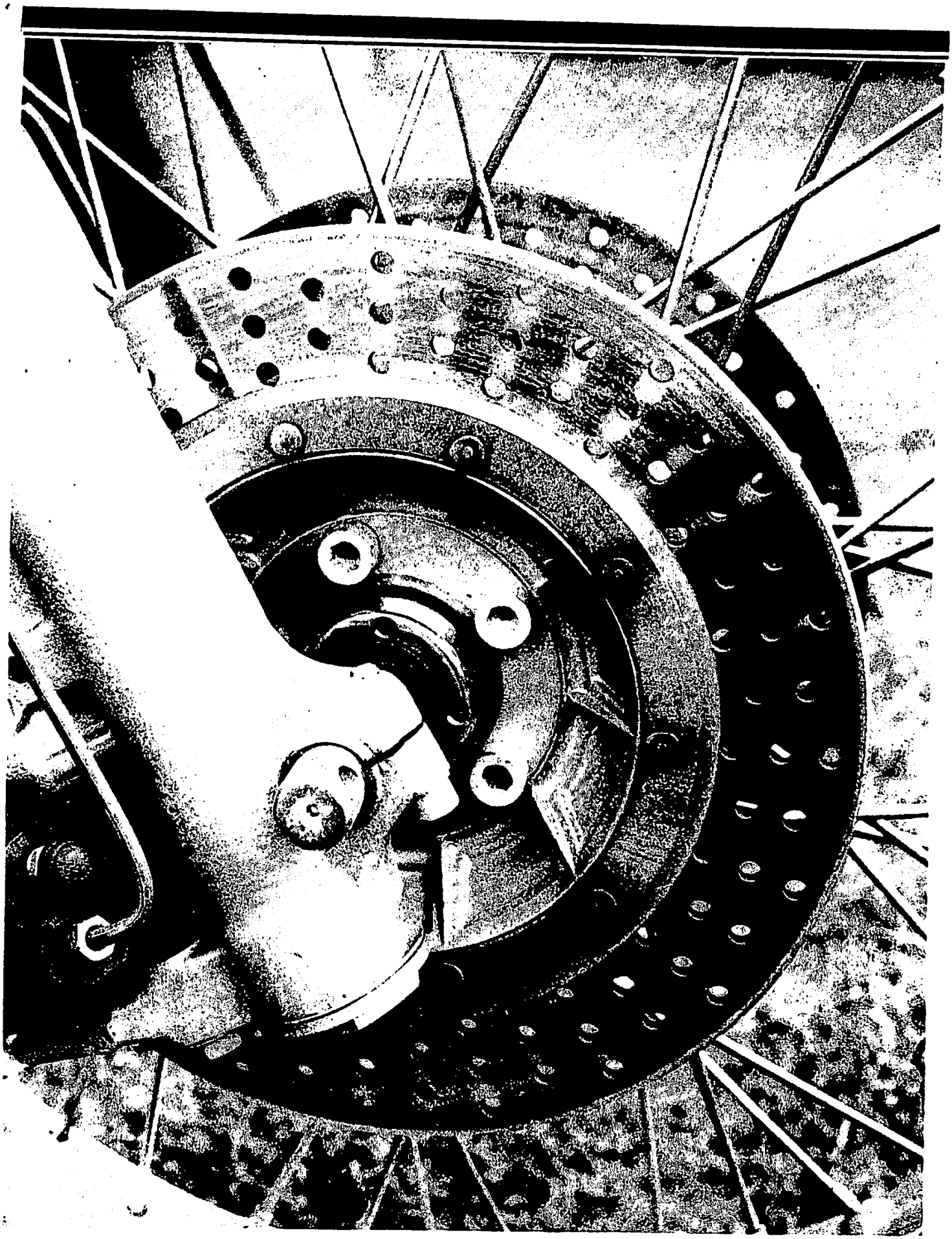


DISC BRAKES IN WET WEATHER

Motorcyclists can expect prompt action following the TRRL initiative

FOR MANY years there have been on sale motorcycles which simply do not stop in wet weather. Suzuki even went so far as to put a warning sticker on the front-fork leg on several of their models, yet the riding public has been really remarkably quiet about it, and have pushed the market to a position where two – if not three – disc brakes are essential to "all right looking" motorcycles offered for sale. The excellent performance of disc brakes in dry weather, allied to their evident reduction in manufacturing cost over drum brakes of equivalent performance, formed an alliance between user and manufacturer which has only recently been audibly broken. The dissident chorus has been heard on an increasingly querulous note from Canada, the USA, the UK, and Australia over the last two years or so. The American National Highway Traffic Safety Authority is the body in the USA which deals with Motor Vehicle Standards, Defect Notices, and carries out or sponsors safety research with a view to taking steps to improve driver safety, education, licensing, traffic regulation, and vehicle design and inspection among many other issues – including motorcycle helmet standards. The Defects Office gets a heavy load of post from disgruntled vehicle users on a wide range of subjects, and the long reaction times and markedly reduced efficiency of disc brakes on motorcycles was one complaint examined by this part of the NHTSA. One of the worst offenders named in the letters was the Honda CB750; while the Canadians had their attention drawn more to the Honda Gold Wing for the same fault.

The use of motorcycles as almost purely recreational machines has dominated the US usage pattern for some years, although there are signs that this is changing with the increase in average age and average experience of motorcycle users in that country. One obvious aspect of such a recreational approach is to cut riding in the rain to a minimum! This might well help to explain the long slow build up of user knowledge and indeed alarm over the deficiencies in wet weather reaction times for disc brakes. The American Honda organization in Gardenia, California carries out a remarkable amount of work for itself and on behalf of Honda R&D, at least in part due to the presence in California of some very competent consulting firms, and the availability of and access to the impressive Highway Safety Research Institute at Michigan University. Other US sources of sophisticated motorcycle safety R&D competence include Biokinetics of Falls Creek (a suburb of Washington DC), CALSPAN, the consulting laboratory associated with the University campus in Buffalo, and the labs of AMF Harley-Davidson. The motorcycle safety work carried out in these and several other organizations in the US is too little known and too little disseminated even within the USA.

Honda America were able to help get the reaction time of CB750 disc brakes down by quite a fair amount, but as recently as August 1977 Honda R&D in Japan were still not able to report any further advances, beyond confirmation that pad material was almost certainly the key variable concerned. The usual suck-it-and-see *ad hoc* ameliorative measures identified or promoted by motorcyclists (and indeed by many manufacturers) include the use of cast-iron discs rather than stainless steel, the use of drilled and slotted discs, and of course the simple return to well-sealed drum brakes. My own experience over the four or five years of this phase of brake development was to throw away the front wheel of a BMW 750 to fit a four-leading-shoe Fontana, to be horrified by the vestigial performance of even twin-disc brakes when I fitted them to a Z1A, and to become almost resigned when the twin drilled cast-iron Brembo brakes on two successive big desmo Ducatis behaved in exactly the same way as the twinned Kawasaki stainless-steel discs in heavy rain. More recently trials on a TZ350E showed that if the pad material was of high enough friction material, and the straights were short enough, rain simply boiled off both stainless steel and plasma sprayed aluminium front discs to give excellent wet weather braking if used hard and continuously enough. Here the stainless steel discs were definitely an improvement over plasma sprayed aluminium once they had warmed up.

This sort of desperate casting around is typical of the 1974-8 period but a recent further variation on the machined disc theme was the use of three radial slots machined right to the periphery of the disc at a trailing angle to the radial axis of about 30°. This is the subject of Registered Design protection in the UK, and is the result of racing car experience employed by the small specialist firm of ART, which has close links with Dunlop in tyre and chassis tuning and development for karts. Dunlop's association with brake improvements will recur as this story develops. This type of machining is literally the only variation which shows a genuine and consistent improvement over untreated discs! It is a significant if not large effect, typically 20 per cent or so, but it is complemented by a notable improvement in consistent brake performance in the dry. This common heritage from racing car experience can be traced directly to the 1972/3 season Matich racing cars which developed precisely this form of brake, and to more recent European racing car conventions from which Wardle at ART drew his ideas. It should be noted that temperature balancing and other obviously related factors quickly lead one to favour stainless steel discs once again. ...

> The dangers inherent in a front-wheel lock-up are so vividly appreciated that a world-wide problem exists with riders who simply will not use the front brake!

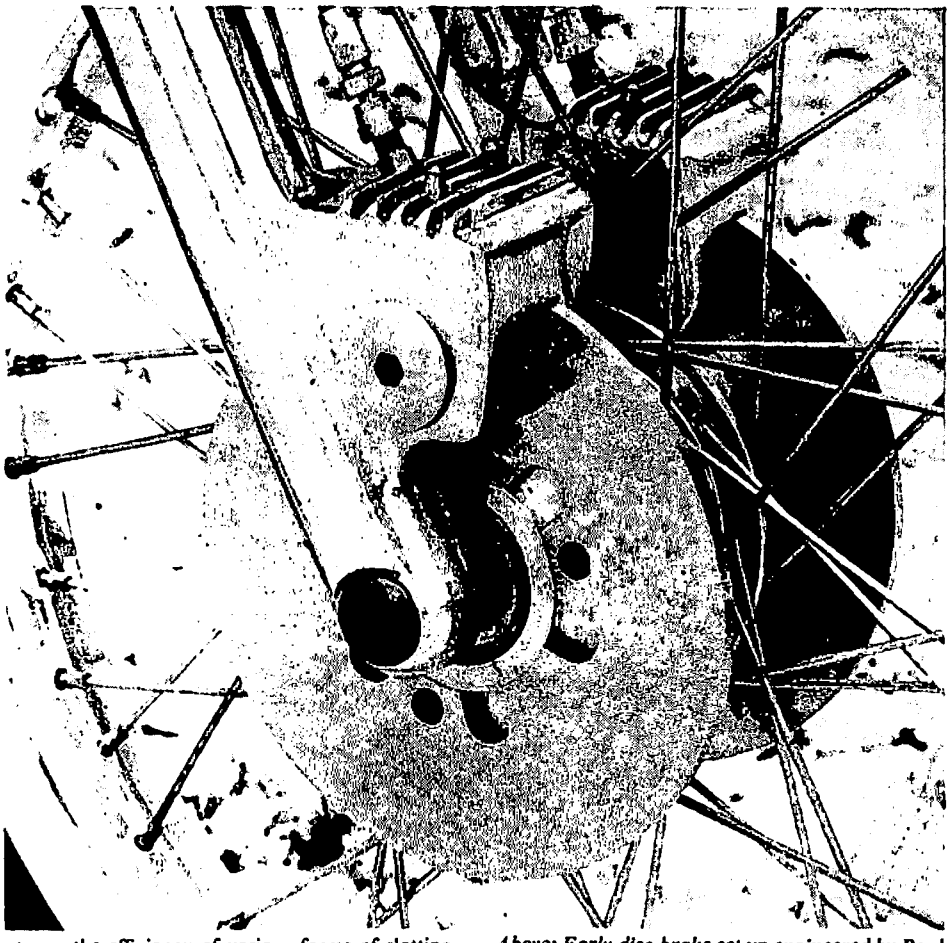
I tried out an ART machined disc of the latest pattern ($\frac{1}{8}$in width, 15° to radial axis – as tested by *Motorcycle Mechanics)* on a TZ350 recently, and noted a softer feel to the brake in the dry, matched to a noticeably more consistent dry weather performance. Wardle at ART pointed out that differing slot angles and dimensions were required for best results on road and track and for wet and dry conditions due to the different speed regimes and the altered balances between water clearing and dust clearing in the performance of the slots, and that the "softer" feel of the brake can be compensated by the use of softer pads and shifts from DS11 to 2340 Ferodo materials have proved to be beneficial for cars.

Consistency is a vital parameter in the assessment of motorcycle braking performance. The substantial weight transfer effects inherent in motorcycle braking, and the comparative scarcity of even the simplest form of load proportioning devices to share front and rear wheel braking forces in some manner responsive to the weight available to ensure adequate tractive forces on the road for effective non-skid braking, mean that the flexibility of the independent front and rear wheel braking systems can be used by motorcyclists with as much as skill as each individual can muster. Of course, the dangers inherent in a front-wheel lock-up are so vividly appreciated by most riders that a world-wide problem exists with riders who simply will not – or cannot – bring themselves to use the remarkable braking power at their fingertips even in dry conditions. The weight transfer effects show up so substantially that many riders back off their rear brakes or reduce their power by drilling or cutting away lining or pad area to reduce the danger of locking up when making full or effective use of the front brake.

This attitudinal problem means that riders are even less likely to make use of the potential of their front brakes if their biting response or stopping distance becomes inconsistent in wet weather. If a consistent response could be assured in terms of braking effect from the same lever pressure in wet or dry, much of the available braking power would once again become genuinely useful to the rider. This means that in practice even if a certain loss of braking distance was to be a side effect of some measure to improve the brake consistency of performance that the *effective* braking power in use could be very materially improved thereby. The world is littered with evidence of riders not daring to use their front brake to the full even in the dry (and thereby travel huge and uneccessary distances with their rear wheels locked up in a vain attempt to stop without using their far more efficient front brakes). Clearly the achievement of a measure to equate wet and dry braking performance with close consistency between wet and dry conditions would be a major and valued advance – but would not in any way reduce the need for anti-lock braking systems. Anti-lock braking systems will form the subject of a further article later, and here it suffices to emphasize the complementary nature of the different measures.

One of the first things that the TRRL had a go

DISC BRAKES IN WET WEATHER



Above: Early disc-brake set up engineered by Paul Dunstall with twin solid discs, of comparatively modest size, and forward-mounted calipers. Right: Partial shrouding for a single disc in an old-time drum; the designer is Rickman, the equipment Lockheed

at was the efficiency of various forms of slotting and drilling of discs. The motorcycle programme at the TRRL has been due to the efforts and leadership of Peter Watson, who has brought the programme from a small beginning to the present stage of numerous devices at demonstration and pre-production stages of development. This has taken five or six years to build up, but is now a productive and effective use of resources. The frequent public arguments on the need for further restriction of motorcycle use due to the large and growing percentage of road deaths associated with this mode of transport is rarely if ever matched to the level of public investment in primary safety research on such an obviously important matter.

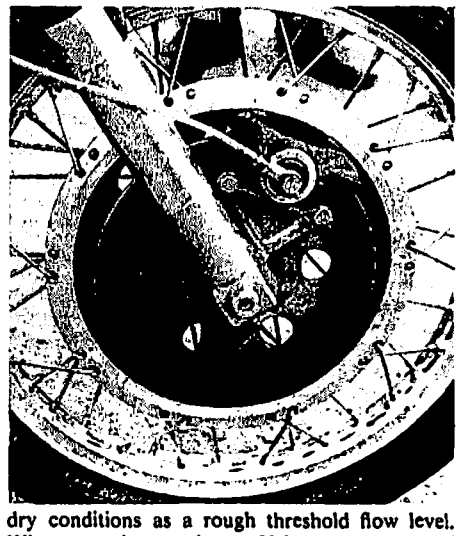
The gross underinvestment in such work for motorcycle issues must give grounds for serious doubt that the allocation of research and development resources within the Department of Transport (or whatever it is called this week) has yet become fully responsive to the Rothschild organization of Research Requirements Committees or that the net of inputs to such Committees has been so narrow and restricted. The work carried out and funded under Watson's direction is but a tiny fraction of the massive investment on safety work even within the TRRL. As a result, to be able to report that the small wet weather braking programme has achieved implementable results *within a year* has a bittersweet taste in view of the long years of official neglect of more than a token concern with primary safety for motorcyclists.

Effective results have been obtained. In essence the use of sintered metal disc pads is a resurrection of aircraft technology and provides finsistent braking performance in the wet and the dry with side effects on wear, cost, and heat transfer which are evidently well within the capacity of industry to eliminate in time for early and substantial production volumes. This much you may have already heard from other sources by the time you read this, but there is considerably more which can be – and has been – extracted from this particular programme. Much of this came to light as a result of a small seminar held in brilliant weather in the TRRL's country retreat in Mid-September.

Peter Watson reviewed the programme and its history to an audience of about 30 people from trade, government, and the press. The TRRL programme started in mid-1977, as the priority for such an investigation rose to the top as a result of numerous complaints from the public, and TRRL involvement in court cases where riders had been unable to stop at traffic lights due to lack of wet weather response and efficiency of their disc brakes. As so little was really known, the research programme first checked on all of the canards and nostrums in common currency using a dynamic test rig consisting of a disc mounted in a lathe and fed with water from a simple spray head. This set-up can provide easily controlled and repeatable conditions, and the hydraulic pressure in the brake line provided the necessary link to operating conditions. The rotational speed of the disc was set at 30 mph for almost all tests to date, and line pressures of 200, 400, and 600 psi were used as standards. It is amusing to see the official press release quotes 48 km/hr and a value of 2,758 KN/m^2 beside 400 psi. I very much doubt that the line pressure was monitored to the implied 0.1 per cent accuracy or that the speed was always within 1-2 per cent – but such is the result of thinking in metric terms and and making over-precise conversions....

The first exploratory work showed that whatever was done to discs or pads, any improvement obtained rapidly disappeared with mileage – and sometimes very quickly. This widening of the wet/dry gap between braking distances arose with both cast iron and stainless steel discs. Organic material (ie conventional) pads *do* absorb water: consequently one trial was made after soaking the pads in water overnight. Only a small change in braking distance could be detected compared to using dry pads, but with a water spray switched onto dry pads alarmingly long braking distances instantly came into effect. By this time the programme had been running for three months, and the summer weather was breaking: the number of phone calls per day was rising and a press notice was issued confirming the problem and reporting continuing work to correct it.

By this time the test procedure had been standardized to three key conditions: 8 gallons/hour and 16 gallons/hour (36 and 72 dm^3/h for the obsessive metricationist) delivered from three 0.063in (1.57mm) holes in feed bags on each side of the front disc of a Triumph or Kawasaki motorcycle. The water feed could be switched off at any time, and the third test condition was to switch off the water feed the instant before braking. The feed rate was set by several brass restrictors in the water line, thereby ensuring that changes in the head of water during the braking were damped out. Eight gallons/hour gave the maximum difference between wet and



dry conditions as a rough threshold flow level. When using the UK ratings of light/medium/heavy/torrential rain, 8 gallons/hour with the water switched off before braking equalled the breakpoint between medium and heavy rain. Honda were represented at the seminar and mentioned that their field tests had given them a value of 60 cc/min for water flows onto the disc for strong rain. Of course this test procedure is concerned only with wet *discs* and dry *roads*, and so the other factors such as the choice of tyre and the coefficient of friction of the road are deliberately excluded. The test is so easy to set up that it should immediately become part of every decent motorcycle road test – can you think of a faster way to ensure that riders get the benefit of brake improvements? or a better way of

giving a commercial encouragement to manufacturers and importers to accelerate such advances in the brakes fitted to their range?

The key to success was buried in a paper by Ferodo reporting that if the disc brake on one side of a car was made of cast iron with small inclusions of niobium, titanium and other trace metals and the other disc had no such additions that the car slewed under braking in both the wet and the dry. There are metallurgic problems inherent in applying this measure to stainless steel, and disc materials were dropped as a promising line of attack for motorcycles as a result. However this clue was not ignored, and attention was turned to the water flow over the disc as the next stage. High speed photography was the key: the water layer in contact with the disc displays laminar flow – a smooth flow of water in a thin contact layer a few micro-inches thick. If the disc is drilled, turbulent flow shows up clearly (as can be seen on the photograph) and therefore slows the rate of water flow over the disc. Clearly this means that there is effectively more water on the disc at any given spray level if the disc is drilled: the water above the surface layer flies off at a very rapid rate and contributes little or nothing to the problem. This result should not really surprise anyone, as holes and slots are cut into bearing surfaces for the explicit purpose of *aiding* lubrication! If only one could guess in advance which "obvious" answer was correct. ... Obviously the next stage was to break up this boundary water layer by disc or pad high spots. Even shot-blasted discs were tried before attention was finally switched to pad materials.

Tests showed that a plain stainless steel disc and a plain organic pad could produce stops from 30 mph at 400 psi brake line pressure of 75ft in the dry, which shot out to 300ft at 8 gph and 500ft at 16. Drilling the disc gave the same dry stopping distance, but an improvement to 200 and 210ft with water feed. This sounds good, but within 500 miles of use the performance had degraded to the same as the plain disc. Patterning the pads helped but once again the rate of degradation with wear was very rapid, and only the slotted disc (ART pattern) gave a consistent improvement, albeit small.

The solution found by the team was the use of sintered metal brake pads on stainless steel discs. Dunlop helped with a rapid response in producing a wide range of different sintered metal combinations in a short time, and the results were dramatic: wet or dry the sintered metal pads arrived at stopped in the same distances wet or dry, with complete consistency. The final nail in the popular motorcycling mythology was that under all conditions cast iron discs were worse than stainless steel.

Obviously the test and development programme is not yet over: the choice of 30 mph as a test speed might draw criticism from many, but certainly not from me, as in-depth studies all over the world suggest that around 30 mph is the median speed for the average motorcycle accident. One such recent study covered 950 motorcycle accidents over a wide area and came up with 32 mph as the median speed. Speeds higher than 30 mph clearly form part of the ongoing work, but it should be noted that five immediately repeated crash stops from 100 mph using sintered pads caused no detectable degradation in early exploratory trials. The results so far are equally encouraging, as the standard test cycle is a stop at 0.4g every half a mile over and above all normal on-the-road braking in normal traffic. Some test combinations have already covered 1,000 miles of this strict sequence with no deterioration of the wet/dry performance

The first exploratory work showed that whatever was done to discs or pads, any improvement obtained rapidly disappeared with mileage – and sometimes **very** quickly indeed

A TRRL bike (from Triumphs) fitted with water reservoir and metering equipment for the recent tests

DISC BRAKES IN WET WEATHER

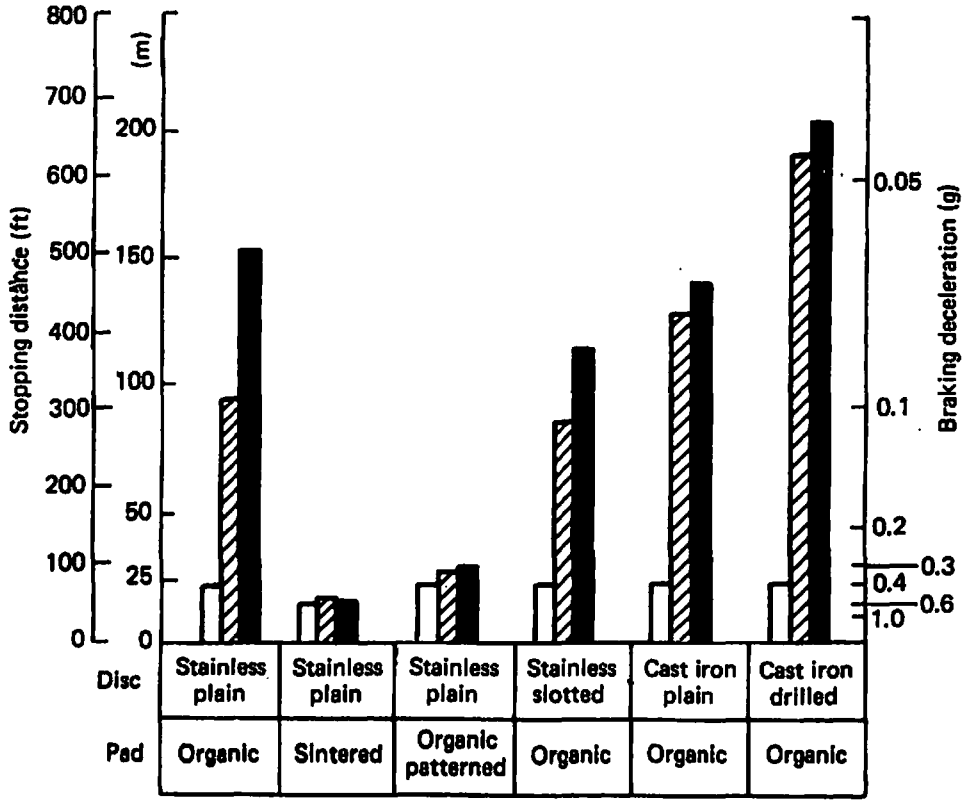


Fig. 1. Braking consistency in wet and dry. TRRL figures

and braking consistency in both wet and dry conditions. Typical test results are shown in Fig 1 (drawn from TRRL Leaflet LF 697).

One of the most ironic features of this story is that the whole technology was available in 1965. The Bendix Corporation in the USA developed both brake and pad systems for aircraft use in 1965, and Dunlop took out a licence on the brake while Ferodo did so on the sintered metal pads. Subsequently the motorcycle market has been pursued with different degrees of vigour by the two companies.

Dunlop took up the story and pursued the technical details somewhat further. Figs 2 and 3 summarize the mechanism of wet braking. The assumption made is that water films about one thou (or micro-inch) thick determine the braking force available when the disc has a stable laminar flow layer of water running over it. The viscosity of water is stable at about 1 centipoise on the way up to 500 atmospheres, and so the simple picture of Fig 2 is all that is needed. Fig 3 is the prediction, where the normal dry weather friction between pad and disc has been assumed to be 0.35 (a fairly modest value in practice). The lower straight line is the laminar flow theory prediction, which is exactly what we observe to happen. The objective is therefore to break up the water film with small high points where the temperature will also rise. This type of material is available from aircraft technology, and a whole range of different sintered materials can be used. Dunlop have paid special attention to three of these, and have obtained results consistent with those reported by TRRL. The variations of sintered metals employed suggested that different sintering mixes would be necessary to get the best out of cast iron and of stainless steel discs.

Wet weather responses are, of course, only one of many aspects of a road-suitable material; and not all problems have yet been resolved. A test programme using both static dynamometer and dynamic vehicle test beds is under way and due for completion by the end of 1978. Some of the initial results are encouraging. Wear rate appears to be likely to be comparable with organic materials. The coefficient of friction is sufficiently close to organics to require little or no change in braking system design, although a slight change in mechanical advantage at the master cylinder on the handlebar would seem to be likely. Fade performance is shaping up to be better than organic pad material performance, but squeal may yet turn out to be a problem. The only aspect so far identified as requiring remedial treatment is that of heat transfer. Sintered metals are – not unexpectedly – better at conducting heat than organic materials, and it seems probable that a fairly thin layer of about 1mm or 2mm on the back of the pad may suffice to control temperatures. Fig 4 shows how sintered and organic pad materials compare under similar test conditions.

The key question was of course that of cost: Mr Davis cautiously suggested that there was as yet no reason to suppose that the cost would need to be any higher than that of the current organic pad materials.

One of the encouraging aspects of this TRRL programme is the active involvement and

One of the most ironic features of this story is that the whole technology of wet-weather braking was available as long ago as 1965

commitment of industry and trade bodies. Kawasaki has been extremely active, and supplied both machines and prototype brake parts, and Triumph of Meriden has not only been working in with Dunlop and TRRL, but has been instrumental in the calling in of the Metropolitan Police Motorcycle fleet to carry out field trials of the new brakes. The two motorcycles laid on for press demonstration purposes after the seminar were both Triumphs, and one of the senior men from Meriden was present to outline their involvement. This had started in October 1977 as an inquiry about anti-lock brakes, and the question of wet weather braking problems had subsequently arisen. Triumph had been carrying out tests in parallel with TRRL on pad shapes, disc modifications and materials – and had already come to the conclusion that the only lastingly useful measure was the ART slotting procedure, which they found gave a reliable 20 per cent improvement. Of course the plating had to be removed before machining. From the results cast iron therefore appears less effective basis even for slotting. Subsequent to the work already discussed, Triumph are now concentrating on cast iron discs. Sintered pad materials have now been found to give virtually identical results to the best organic pad materials in the dry, to give adequate wear rates in use, and the current problems now being resolved are those of obtaining good appearance finish on the disc.

Of course, sintered pad materials are a well-matured – if not aged – production technology, and present Dunlop and Ferodo capacity is limited to pilot scale production levels. This can of course be fairly quickly corrected, but as users

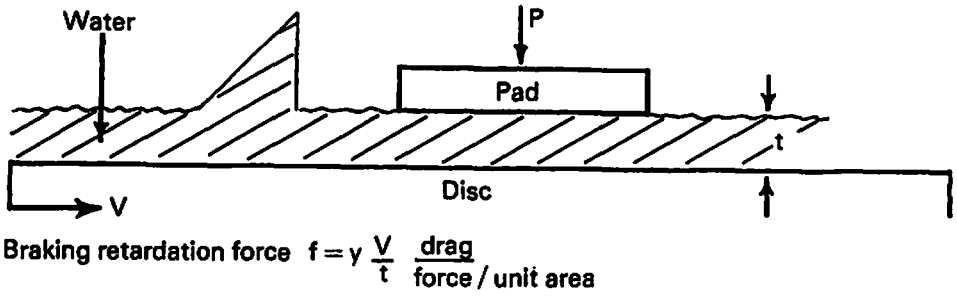


Fig. 2 y = dynamic viscosity lep

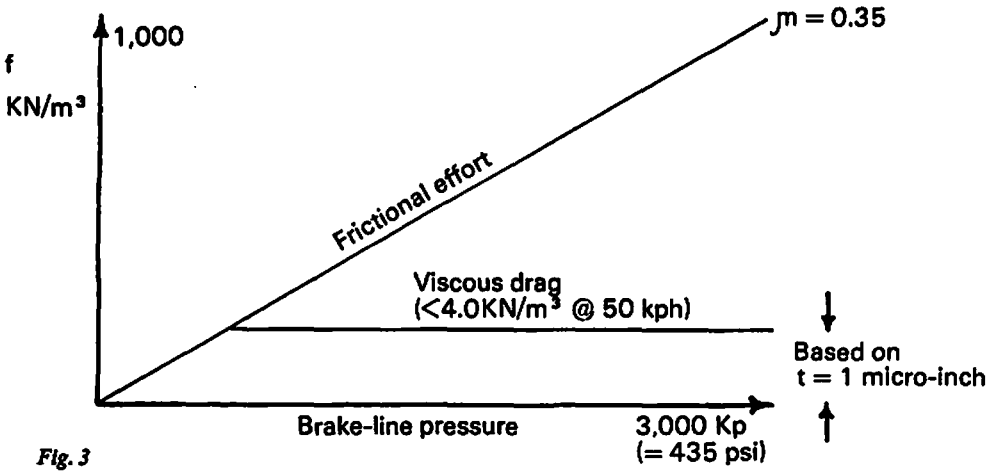


Fig. 3

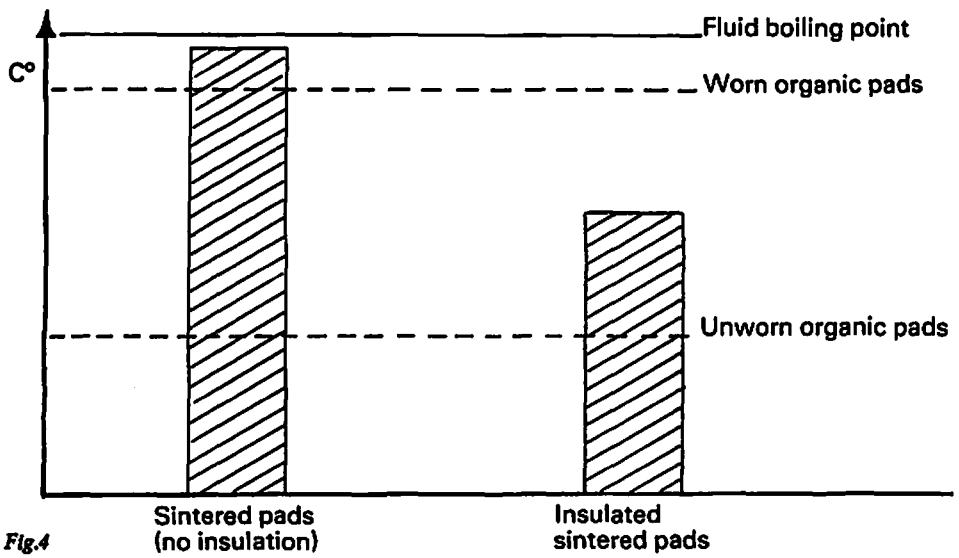


Fig.4

one should be aware of the tendency for such firms to aim first for original equipment markets rather than the huge replacement market. This is logical as the survival lives of motorcycles in several countries around the globe all seem to lie around six years for half to disappear from the register ... this rapid fadeout rate is further emphasized by the rapid decline in annual mileage travelled as a motorcycle gets older. This might make the bias towards OEM and recent models more understandable in commercial terms, although it would be interesting (and probably most surprising) to hear that such market analyses were a normal part of consideration in the motorcycle market. Kawasaki already have launched a new 250 cc motorcycle fitted with sintered pads and stainless steel discs, and it is devoutly to be hoped that public pressure can be brought to bear on the Japanese manufacturers to make sintered pads available for their current and recently discontinued models. Perhaps Suzuki is the most exposed, as I recall the small warning notices on the front forks of some of their models warning of possible ineffectiveness in the wet. No doubt Honda will be acting as soon as their own programme has come up with suitably tailored sintered compounds to make available retrofit pads for the much maligned earlier CB750 series, which, due to their sheer numbers on the road, have perhaps attracted most attention. However it should be known that in 1970 when the first CB750s appeared Ferodo supplied me with a set of heavy metal pads which squealed but worked well in the wet: no doubt these were sintered.

An elegant irony surfaced towards the end of the seminar when the Director of Technical Services of AMF-Harley-Davidson stood up to outline his own firm's experiences. HD have actually been experimenting with disc brakes since 1965 due to the very high mass of their V-twin product line and the consequently pressing need to continually maintain and improve braking performance. The HD drum proved difficult to beat for quite a long time, and only with the introduction of the braking standard FMVSS 122 did the pace hot up. FMVSS 122 is an odd standard put out by the US Government to ensure compliance of braking systems on motorcycles to a reasonable level of performance. The drafting of this document is eccentric and in some places downright dangerous to the tester – a point made with surprising force in the sober engineering literature I might add – and the drafting remained unsullied by practicality through to legal enforcement by the NHTSA: FMVSS 122 is a warning of all the dangers of not taking an active and informed role in the manoeuvring towards possible measures promoted by Government and Government agencies. The domino effect of a published – if inept – standard has ground on with alarming momentum over the last half decade. The Australians produced their Design Rule ADR33 in close correspondence with FMVSS 122, warts and all (although it must be said that they are now thinking about improving ADR33), and even the production of a vastly better test procedure by Michigan University under contract to NHTSA itself, and with a top member of the Honda R&D team on the project (Watanabe) has little prospect of replacing FMVSS 122 until 1981. This warning should make you all aware of the importance of a simple, sound, practical and relevant test for ensuring that wet weather braking performance is consistent and at an adequate level of effectiveness, and that agreement on such a specific test is very far from a trivial piece of administrative confusion.

Amongst other things FMVSS 122 includes a requirement for brakes to be fully immersed in water, stationary, for some minutes and then to perform to a specified level. Those of you who might have wondered why perfectly good water excluding brakes on many machines were redesigned in the early and mid '70s now know why.

One of the good effects of this clause was to press HD forward with their disc brake programme, and led to the use of sintered pads on a hard chromed mild steel disc as early as 1972. The effectiveness of these brakes in wet and dry was excellent, but service life was very unsatisfactory due to chrome peeling problems and subsequent deterioration of pad and disc. By 1974 the use of stainless steel discs in conjunction with sintered metal pads had produced good overall performance at the price of hydraulic fluid boiling problems. It should be appreciated that American Police riders travel mile after mile at crawling speed on escort duty with the rear disc brake dragging, so that overheating is hardly a surprising result. The cure seemed to be to use DOT 5 specification brake fluid exclusively. This is a silicone based compound with excellent high temperature performance assured by the DOT 5 specification. Customer responses were critical of the high rate of disc wear initially encountered, and further HD work on varied levels of friction from different sintered compounds led to good performance with an adequate service life by using a pad with the very high coefficient of friction (on the Ford dynamic test) of 0.65. I must add that the overall effectiveness level of HD discs would seem to have room for improvement, but as this is more a question of number of discs, pad area, and lever pressures thishas little to do with the subject of wet braking.

DISC BRAKES IN WET WEATHER

"Harley-Davidson have been experimenting with disc brakes since as long ago as 1965; due to the very high mass of their V-twin product line ... the H-D drum proved difficult to beat for quite a long time ... and I must add that the overall effectiveness level of H-D discs would seem to have room for improvement ..."

The wear patterns of sintered pads and organic pads on stainless steel are quite different. The grooving and uneven wear patterns common with organic pads on stainless discs are obviated by the use of sintered pad materials, as the pad and the disc share the wear and therefore leave a smoothly worn flat contact annulus. This also helps the wet weather braking action as the rougher the disc surface the thicker the irreducible thickness of the lubricating laminar water layer. Corrosion of the materials seem to present little difficulty, as the ambient air quality in which the HD discs were monitored was so poor that any corrosion problems would have rapidly become acute: in the event *organic* pads proved to be the more vulnerable to corrosion!

The problems now are twofold, once the

development programme is complete: (1) How do we get aftermarket, retrofit, and outdated models fitted with suitable replacement sintered pads, and who is going to do the testing to ensure that these pads are well matched to the discs on the older models? (2) How can we get a consistent and enforceable standard test procedure for wet weather braking degradation to be applied to all brakes? Don't forget that the test must also be phrased and set up in a form suitable for on-vehicle testing of drum-braked systems too.

It seems that at last motorcyclists can press for and expect prompt and constructive action by both DTP administrators and the industry in the train of this TRRL initiative. It will be a welcome and refreshing change from the routine measures of administrative restriction which are usually all that can be expected from the official machine until real data and results can be placed before them as a result of such small scale efforts on primary safety which occasionally come to hand. It is important to note that TRRL and its industrial collaborators have only found *one* possible method for reducing wet braking problems: others may well exist, and test, standard, or regulation should be phrased in terms of *performance* and not of method of achieving such performance. TRRL have already drafted a proposal to put the ISO on this subject, which is a whole area to itself.

Given active support and endorsement of wet braking improvement measures and their translation into general effect, is it too much to hope that anti-lock brakes might receive a greater degree of support from manufacturers and others? The Electrical Engineer's Seminar on anti-lock braking to be held in mid-November might begin to publicly address this question. M.R.W.