Development of an Anti-Lock Brake System for Light-Weight Motorcycles

by C D Walker

TRL Report 196
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DEVELOPMENT OF AN ANTI-LOCK BRAKE SYSTEM
FOR LIGHT-WEIGHT MOTORCYCLES

by C D Walker

Prepared for: Vehicle Standards and Engineering Division, DOT (Mr B Frost)
Project: Motorcycle Anti-Lock Trial (S105A/VD)

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EXECUTIVE SUMMARY

The task of braking a motorcycle is a relatively complex one, requiring the rider to operate two separate levers; usually, a hand lever for the front brake and a foot lever for the rear brake. It requires the brake lever pressure to be modulated in accordance with changing tyre/road-surface interface friction characteristics to provide the degree of deceleration required without locking either wheel. Therefore, it is not surprising that a large proportion of reported injury accidents involving motorcycles, record skidding as a factor. The inherent primary instability of a motorcycle means that if the front wheel is locked, vehicle capsize is most certain. This fact, deters many motorcyclist from making full use of the front brake where, due to load transfer to the front wheel under braking, the greatest potential for rapid deceleration exists. There would seem to be little doubt, that making anti-lock brakes available to all motorcyclists has the potential to reduce the number of accidents involving motorcycles and encourage apprehensive riders to explore the full potential of the front brake.

ABS brakes for motorcycles have been available, commercially, since 1988. However, six years on, there are still only three manufacturers offering ABS and then only on large, heavy and expensive touring type machines. One of the reasons that manufacturers do not offer ABS on lightweight machines is, simply, the high additional cost of such systems (typically of the order of £700-£1000). Clearly, it would not be commercially prudent for motorcycle manufacturers to offer ABS on machines retailing for £2000-£3000. However, it is likely to be the riders of these lightweight machines who would benefit most from the availability of ABS, as they tend to be either young and inexperienced or commuters continually exposed to the dangers of 'cut and thrust' motoring. The Transport Research Laboratory has had many years of experience in researching ABS for motorcycles and, with the financial backing of the Department of Transport, undertook a design and development programme to produce a low-cost ABS suitable for fitment to light-weight motorcycles.

The system specification finally decided upon was a hybrid design based on an electronic system produced by Mullard and a completely mechanical system produced by Lucas-Girling. Initial design started, in earnest, around 1989, but the bulk of the work was conducted between 1991 and 1994. Early trials of the prototype system produced encouraging results and an estimate of the likely cost suggested that a production system would add around £240 to the retail cost of a motorcycle (1991). Several developments of the system were produced which, ultimately, resulted in a very compact and lightweight installation contained in the front and rear road-wheel hubs of a Kawasaki AR125 motorcycle. However, the system was plagued with problems, not least of which was an unreliable mechanical deceleration sensor, most of which were resolved, but at a high cost to the project in terms of available resources. When functioning, the system performed on a par with the 'Mark 1' FAG/BMW ABS system fitted to a BMW K100 motorcycle and, it is believed, could have been made reliable through further development of 'electronic' deceleration sensing. Unfortunately, an in-depth cost analysis of producing the system commercially, revealed that the production costs of the final system would not have been any lower than the systems already available to the consumer. The decision was therefore taken to discontinue development work on the system.

A potentially significant problem arose during track testing of the system against the ECE vehicle braking Regulation 78; in that the efficiency of the rear brake, when used in isolation, was only 59% when tested on a high friction coefficient surface, whereas the Regulation requires it to be 70%. This problem was not considered to be a 'fault' of the system, but was thought to be related to load transfer under braking, due to the motorcycle's high centre-of-gravity and short wheel-base. This is a phenomenon which warrants further investigation, as it could present motorcycle manufacturers with problems in producing ABS for light-weight motorcycles to meet the current ECE Regulation and delay the introduction of ABS to the wider motorcycle market.

It must be concluded that the prevention of wheel lock is not an insignificant task and manufacturers appear to have done a thorough job in producing efficient motorcycle ABS at a fair and reasonable cost to the consumer. It is unfortunate that the cost is such that many more motorcyclists cannot benefit, at present, from a significant road safety device. However, the outlook for motorcycle ABS is optimistic: with the ever reducing cost of electronics and a steady increase in production volumes of ABS, there will come a time when ABS can, realistically, be offered on light-weight, low-cost motorcycles.
DEVELOPMENT OF AN ANTI-LOCK BRAKE SYSTEM FOR LIGHT-WEIGHT MOTORCYCLES

ABSTRACT

Skidding is a contributory factor in a large proportion of reported accidents involving motorcycles. Anti-lock Brake Systems (ABS), if fitted to all motorcycles, may significantly reduce the incidence of this type of accident. ABS has been fitted, since the late '80s to a very limited range of large engine capacity motorcycles, to which only experienced motorcyclists have access. It would seem reasonable to assume that the largest benefit, in terms of accident reduction, may be realised by making ABS available to inexperienced motorcyclists. However, inexperienced (learner) motorcyclists in the UK are restricted to small engine capacity motorcycles (125cm³), which tend to be of lower cost and are, therefore, not commercially viable for fitment of the relatively expensive ABS currently available.

This report describes the development and testing of an ABS, which TRL undertook in an attempt to demonstrate that a mechanical ABS, suitable for light-weight motorcycles, could be produced economically. The final prototype system which was compact and aesthetically pleasing, was fitted to the front and rear brakes of a Kawasaki AR125 production motorcycle. Track testing of the system produced encouraging results; the performance of the system being on par with a production ABS fitted to a BMW motorcycle. However, the deceleration sensor used in the system proved too unreliable for the planned road-trials to take place and there was, ultimately, some doubt over the financial viability of the system. The report includes a brief history of TRL’s involvement with motorcycle ABS since the 1960s and detailed design drawings of the system developed.

1. INTRODUCTION

Correct brake application on a motorcycle is a relatively complicated task, requiring the rider to control the brake effort, individually, to front and rear brakes according to the available level of adhesion. The available adhesion being directly proportional to the friction coefficient between the tyre and the road surface, which is also dependent on the load applied through each tyre. The situation is further complicated by the high degree of load transfer due to the relatively short wheelbase and high centre-of-gravity of a motorcycle. When required to brake in an emergency or when the tyre/road interface friction level is low (e.g. black ice or diesel spillage on the road surface), the average rider would do well to avoid locking either wheels, especially the front. In such circumstances, Anti-lock Brake Systems (ABS) increase the rider’s ability to maintain control of the vehicle and remain upright.

The first commercially available ABS, fitted to a motorcycle, was produced by BMW and was fitted initially to their K100 motorcycle in 1988. The availability of this system (now in a revised form) has been extended to a greater range of models, but is still not available on a machine of less than 750cm³ engine capacity. The Japanese manufacturer, Yamaha, followed the lead set by BMW and introduced their own ABS on the FJ1200, this system is now also available on their more recent 1000cm³ touring machine, the GTS1000. Honda were the third manufacturer to offer ABS on a standard production motorcycle, again a large capacity touring machine in the form of the ST1100. It is considered that one reason that ABS is currently available only on large, expensive machines, is simply the additional cost of such systems over the cost of the basic machine. This additional cost to the customer is currently in the order of £700 - £1000, which is approximately ten percent of the basic cost of the type of machine to which they are fitted. Clearly, it would not be commercially prudent to offer anti-lock brake systems, at their current cost, on small engine capacity machines costing in the region of £2000 - £3000, as it is likely that very few sales would result.

The Department of Transport (DoT), however, believe that the greatest benefit, in terms of reducing the number of accidents in which motorcycle skidding is a contributory factor, lies in making improved braking systems, incorporating devices such as ABS, available to all motorcyclists, particularly the inexperienced. Current rider legislation in the UK requires learner motorcyclists to ride machines of less than 125cm³ engine capacity with a power output not exceeding 9 kw (approximately 12 bhp). Motorcycles such as these lie in the lower cost range and are therefore not logical targets for fitting of ABS from the view-point of a commercial motorcycle manufacturer. Also, the riders of this type of machine tend to be younger people (17-19 years) on low incomes and cost conscious commuters. To investigate the feasibility of producing an inexpensive light-weight ABS suitable for fitting to small engine capacity motorcycles, the Transport Research Laboratory (TRL) undertook a design and development programme with support and financial backing from the DoT, the results of which are reported on in this paper.
2. HISTORY

TRL has been researching ABS for motorcycles in many forms since the early 1960's. The very first installation was built around a Dunlop 'Maxaret' unit and was fitted to a Royal Enfield 'Super Meteor' motorcycle in 1963. It is believed that this was the first ever ABS installation on a motorcycle. This installation was never intended to be a practical solution which could be adopted for production, simply a research tool to investigate the benefits that ABS could offer the motorcyclist and any problems involved. The results of track tests with the system showed that, on a slippery surface, stability could be maintained and the braking performance was at least as good as that attainable by a skilled rider.

It was ten years later, in 1973, as a result of a review of motorcyclist injury and accident data, before a formal research programme into motorcycle safety was established. The following year, the next major motorcycle ABS research programme commenced. Emphasis of the work was placed on developing an efficient, robust system which could be easily fitted to a production motorcycle. At that time, Mullard Ltd. had produced an experimental unit for use in cars; which, apart from an electronic control module, was fully contained within the wheel it controlled. A development of the Mullard system, with characteristics slightly modified for motorcycle application, produced a unit which was subsequently tested at the then Transport and Road Research Laboratory (TRRL) on a wide range of motorcycles. In principal, the system was very similar to those currently available on production motorcycles. The system consisted of a toothed wheel attached to the vehicle road wheel which, when the vehicle was moving, provided a signal to the electronic controller via a magnetic induction transducer. The brake fine pressure was modulated by a hydraulic actuator incorporating a fluid pump operated by a cam driven by the road wheel. Reliability problems were experienced with the system which could have been solved through further development. However, development of this system was not pursued as commercial exploitation of such devices was not part of TRRL's remit.

In the mid 1980's, two areas of motorcycle ABS were being investigated. The first, was research into the application of ultrasound to the brake pad to prevent wheel lock, the second, involved the road trial of a prototype mechanical ABS designed by Lucas-Girling. The ultrasound work, which was conducted in the laboratory using a dynamometer, revealed that the pad/disc interface friction characteristics could be modified by the application of high frequency vibration (above 20KHz). The effect was such that a locked wheel could be freed to rotate when the ultrasound was applied. It was also found that the friction reducing effect was greater at lower brake disc speeds, which suggested that the ultrasound could be continuously applied during braking, allowing this speed effect to prevent wheel lock. However, the cost and power consumption of the necessary hardware was too great for the system to be considered for fitment to production vehicles.

The Lucas-Girling Stop Control System (SCS), as it was named, was a self contained mechanical unit consisting of a flywheel based deceleration sensor and hydraulic fluid pump which were both driven by rotation of the road wheel via a toothed rubber belt. The SCS was designed and developed by Lucas-Girling specifically for the motorcycle market. TRRL provided a fleet of BMW motorcycles for a road trial to which Lucas-Girling fitted the SCS units. The organisation, running and reporting of the road trial were the responsibility of TRRL. The road trial machines were operated mainly with Police Forces throughout the UK and, over the course of approximately two years, covered in excess of 125,000 miles without serious problems. Riders' comments on the system were generally favourable. The system was subsequently put into production, in a slightly modified form, and used on Ford 'Escort' and 'Fiesta' cars. Although the Honda motorcycle company in Japan 'purchased' the system from Lucas-Girling and carried out development work on an in-hub version, the system never appeared on production motorcycles.

In the late 1980's, a programme of work was conducted to design an inexpensive mechanical ABS that would function with both disc and drum brakes. There was a need for an inexpensive system that could be fitted to light-weight motorcycles and mopeds and a large proportion of these machines were fitted with drum brakes. The system devised, consisted of a capstan-drum carrying the brake disc or drum, around which was wound a helical torsion spring. One end of the torsion spring was attached to a flywheel the other to the brake drum or disc. In 'normal' braking, the torsion spring remained wrapped tightly around the capstan and transmitted the brake torque to the road wheel. However, when the wheel deceleration was too high, the flywheel would over-run causing the spring to release its grip on the capstan drum, permitting the wheel to rotate and hence spin back up to road speed. The testing and development of the system, conducted on the Laboratory's dynamometer, revealed inefficiencies in the system which made it unsuitable for use on a road-going vehicle (Donne and Cronin, 1991).

Undaunted by the apparent lack of enthusiasm shown for ABS by the motorcycle industry, TRRL continued with research into the application of ABS to motorcycles. Encouraged by the results of previous research and with the knowledge gained through their involvement; TRRL set about the task of designing, developing and manufacturing a prototype, compact, light-weight ABS which, it was believed, would result in a system that could be economically produced. The results of this research form the basis of this report.
3. TRL LIGHTWEIGHT ANTI-LOCK BRAKE SYSTEM

Design and development of the TRL light-weight ABS started in earnest in 1989, although initial work, investigating the various forms the system could take, had been going on at a low-key since the involvement with the Lucas-Girling SCS in the mid 80's. The system finally settled on, was a hybrid electro-mechanical system based on elements of both the Mullard and Lucas-Girling systems.

3.1 BACKGROUND - TRRL/MULLARD SYSTEM

In 1988, TRRL were asked to produce a “learner-legal” safety motorcycle for exhibition at the 12th Experimental Safety Vehicle Conference (ESV) in 1989. It was considered that anti-lock brakes should be a key feature of the vehicle. The Lucas-Girling mechanical SCS was considered for incorporation into the vehicle, but was rejected on grounds of its layout and bulk. It was decided to investigate a redesigned version of the former Mullard/TRRL system. The changes proposed for the system, had always been considered necessary for technical reasons. The opportunity was also taken to reconfigure the system components in order to affect an improvement in mass distribution and appearance. A non-functioning mock-up of the system, installed on a light-weight motorcycle, was exhibited at the ESV Conference in May 1989, the SAE International Congress in February 1990 and a number of smaller events.

3.1.1 Operation of the TRRL/Mullard System

In the original Mullard/TRRL anti-lock brake system, the rotational velocity of the road wheel was continuously monitored by means of a magnetic induction sensor and toothed wheel attached to the road-wheel. The signal from the sensor was interpreted by an electronic control module, which provided some of the system ‘logic’ and supplied power to the hydraulic actuator. The actuator was controlled by a solenoid valve which released brake line pressure when opened. The solenoid valve was an integral part of the modulator and pump assembly, which was mounted to the front forks/rear swinging-arm of the vehicle, beside the road-wheel. Some of the system ‘logic’ was provided by the actuator, which controlled the rate of reapplication of the fluid pressure following a system pressure ‘dump’. The main reason that a hybrid control system was adopted (i.e. mechanical and electronic control logic) in preference to a purely electronic means of system control, was because several solenoid valves would have been needed to implement the complex system ‘logic’. This would have resulted in a bulky and heavy system which was deemed unsuitable for the intended application.

Initial tests of the system, revealed that the rate of brake line pressure reduction was too slow to prevent momentary wheel lock - especially on very low friction coefficient surfaces. This characteristic is tolerable in an ABS intended for use on a car, but is unacceptable for motorcycle systems. The ‘fault’ was produced by the multi-staged brake line pressure reduction designed into the system to prevent over-modulation, and hence better control, when installed on a car. However, because of the lower inertia of motorcycle road-wheels, the design characteristics were unsuitable for motorcycle application. As a result, the system was modified to provide a single-stage pressure reduction and subsequent tests showed an acceptable performance on a wide range of road surfaces.

3.1.2 Deficiencies in the TRRL/Mullard System

Although the TRRL/Mullard system had demonstrated acceptable anti-locking characteristics, there were some concerns about particular areas of the design. These had not been significant factors during research testing, but would need to be addressed before production could be considered for a road trial. There were two main areas of concern:

i) Unsprung Mass. Although the Mullard actuator was reasonably compact and of relatively light-weight (1.5kg approx.), the system layout necessitated that it be mounted adjacent to the road-wheel hub. The mass, was unsprung, and this may have an adverse affect on vehicle handling, caused by the increased demands on the suspension system to control road-wheel deflection when traversing road irregularities. In fact, only the pump needed to be located in the vicinity of the hub, as it was driven by a road-wheel mounted camshaft. All other parts of the actuator (brake fluid reservoir, restrictor unit and solenoid-valve) could be mounted on the vehicle frame, where they would be better protected from vibration and shock-loading. This would, of course, require a redesign of the system to package the system ‘elements’ in separate housings, rather than the single assembly of the original actuator.

ii) Reliability. Two features of the original system caused the majority of the problems during testing. In the electronic control module, a transistor, which controlled current to the solenoid, was damaged on several occasions because of accidental short-circuiting; the suspected cause being water entering the external wiring of the system. The other, major, problem was brake fluid leaking within and from the actuator due to failure of rubber seals and valves.

It was believed that these problems could be overcome by correct design and careful manufacture, along with the selection of appropriate materials.
3.2 PERFORMANCE REQUIREMENTS AND SYSTEM SPECIFICATION

The basic requirement of an anti-lock brake system is the alleviation or, preferably, elimination of the locked wheel condition during braking. However, extended stopping distances need to be avoided by efficient utilisation of the available friction between the tyre and road surface. Also, vehicle stability should not be adversely affected; this latter point being more significant for motorcycles, which have a primary instability, than for cars or HGVs. The requirements of the TRL ABS were:

i) Good performance - the stopping distances and vehicle stability, should match that of the Lucas-Girling SCS. (This system was chosen as a 'yard-stick', because it utilised a flywheel based deceleration sensor similar to that envisaged for the TRL system.)

ii) Compact design - for fitting to smaller motorcycles. (Typically 125cm³ engine capacity.)

iii) Light weight - low unsprung mass particularly important.

iv) Low cost potential (especially important when considering installation on light-weight, relatively low-cost motorcycles).

v) Aesthetically pleasing - should not detract from current 'sleek' motorcycle design/styling. (One of the criticisms levelled at the Lucas-Girling SCS.)

Experience had indicated that even momentary locking of a motorcycle wheel during braking would cause some instability. Even allowing a front wheel to cycle to high levels of slip, without locking, can cause the vehicle to capsise. Therefore, an anti-lock brake system for a motorcycle should ensure vehicle stability is not compromised, even if this leads to extended stopping distances. It has been shown (Holmes and Stone, 1969) that maximum braking force is achieved when the slip between tyre and road surface is of the order of 15 to 20%. If an anti-lock brake system can be made to operate in this region, then stability is relatively unaffected and braking efficiency is of the highest order. However, anti-lock brake systems operate cyclically and have inherent hysteresis, therefore, the inevitable variation in wheel slip needs to be centred around the optimum value and kept to a minimum.

3.3 SYSTEM DESCRIPTION AND OPERATION

The main components of the TRL anti-lock brake system are:

i) Solenoid operated brake fluid restrictor-reservoir unit mounted on the motorcycle frame.

ii) Wheel driven hydraulic fluid recirculating pump, mounted in the road wheel hub.

iii) Wheel driven, flywheel based deceleration sensor, mounted in the road wheel hub.

The operation of the system is based around the deceleration sensor. The drive shaft of the flywheel is driven directly from the road-wheel, with the flywheel attached to the shaft by a control spring. When the vehicle is accelerating or running at constant speed, the flywheel rests against a stop and rotates at the same speed as the drive shaft. If the brakes are applied and the vehicle starts to decelerate, the flywheel, because of its inertia, continues to rotate at its initial speed before brake application. This tendency of the flywheel to over-run is resisted, at moderate levels of wheel deceleration, by the control spring and the flywheel decelerates in harmony with the road-wheel. However, when the braking effort exceeds the adhesion available between the tyre and road surface, resulting in a high deceleration of the road-wheel, the flywheel overcomes the resisting force of the control spring to operate an electrical switch (this occurs at about 1.2g road-wheel deceleration). The electrical signal from the switch operates the solenoid which opens an oil-way in the restrictor-reservoir unit, allowing fluid from the brake control line into the reservoir. When this occurs, braking effort at the disc/pad interface is relieved, permitting the road wheel to accelerate back up to road speed. Whilst this is occurring, the brake fluid released into the reservoir is recirculated by the wheel driven pump. When the flywheel returns to its 'parked' position, fluid pressure to the brake pads is restored. This process can occur many times per second.

3.4 DESIGN AND DEVELOPMENT

Prior to starting work on the design/layout of the system, many calculations were performed to ascertain the forces generated by the system and the likely loadings imposed on the various components. Prototype sub-assemblies were tested and, where necessary, modified throughout the design stage, but certain aspects of the testing could only be performed when a complete system, fitted to a motorcycle, was available for trial. At this stage of the development, many other unforeseen problems occurred which often affected other elements in the system.

The decision to pursue a redesigned version of the TRRL/ Mullard anti-lock brake system for the light-weight ABS motorcycle project, necessitated a solution to the problems associated with the original system. The main features considered in the redesign were as follows:

i) The various functions of the original actuator were separated to allow the restrictor-reservoir and solenoid to be positioned on the motorcycle frame. Thus, only the pump element from the original actuator design remained as unsprung mass attached to the
road-wheel hub. The brake fluid was transferred between the restrictor-reservoir and the pump via flexible hydraulic hoses.

ii) The electronic sensing and control unit was replaced with a mechanical unit utilising an over-running flywheel similar to that previously employed in the Lucas-Girling SCS. However, instead of operating hydraulic valves, as per Lucas-Girling SCS, the flywheel was used to operate an electrical switch to provide current to the solenoid-valve. This method was chosen because it was anticipated that it would be more cost effective and more reliable. It was decided to retain the solenoid-valve as a simple means of providing the interface between the flywheel and the restrictor-reservoir as this would provide the easiest means of reverting to electronic control if the need arose. In the event, it was decided to design a system based around the smallest flywheel which would provide the necessary dynamic characteristics to perform the ‘switching’. This was so that the assembly could be incorporated into the road-wheel hub for improved drive arrangements, protection and aesthetics.

iii) Re-evaluation of the location, type and material of the brake fluid seals used in the system to reduce the likelihood of system failures. As part of this process, simple rubber ‘flap’ seals used in the original TRRL/Mullard actuator were replaced with ball-valves.

A prototype design utilised a brake fluid recirculating pump and wheel deceleration sensor attached to the suspension fork leg of the motorcycle, which were driven by a belt from a gear wheel attached to the road wheel hub, similar to that employed in the Lucas-Girling SCS. Following the testing of the prototype system, the initial design was soon modified to employ a gear driven pump and deceleration sensor, the latter being enclosed inside the road wheel hub, as had initially been envisaged (Figure 1). Whilst development of this system, termed ‘phase 1’, was progressing, work had already begun on the ‘phase 2’ system employing a face-cam driven pump, enclosed in the road wheel hub, alongside the deceleration sensor. There were two reasons for the development of the ‘phase 2’ system. First and foremost, the ‘phase 1’ system had been a front wheel installation only; when a rear wheel installation was embarked upon, there proved to be insufficient space around the rear hub of the recipient vehicle to accommodate the design. Secondly, the more compact installation improved the aesthetics of the system considerably and reduced the unsprung weight. Development work was also carried out on the restrictor-reservoir unit, mainly aimed at reducing its dimensions to aid installation on the vehicle and reduce the overall weight of the system. The main general assembly drawings are included at Appendix A. The overall weights of the ‘phase 1’ and ‘phase 2’ systems were:

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<th>Phases</th>
<th>Hub Unit</th>
<th>Restrictor-Reservoir</th>
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<tr>
<td>Phase 1</td>
<td>1185g (Casting)</td>
<td>848g</td>
</tr>
<tr>
<td>Phase 2</td>
<td>972g (Machined)</td>
<td>564g</td>
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The hub unit of the ‘phase 2’ system was machined from solid aluminium, but it is estimated that the weight of the hub body could be reduced by approximately 15% by the adoption of a die-casting.

During development of the system an alternative deceleration sensor, employing opto-electronic switching, was also investigated. However, due to problems experienced with both the flywheel based deceleration sensors, a third form of deceleration sensing was developed. This was based around a micro-processor control unit fed with a digital signal from an inductive magnetic transducer, the principal of operation was identical to current production systems and the Mullard system. Initial testing and development indicated that electronic sensing and system control would provide a far superior performance to that exhibited by a fully operational flywheel based sensor system. However, due to the severe delays and overspend on the project, and the difficulty in estimating the resources required to produce a fully operational system for road trial, it was decided to suspend development of the system (1994).

3.5 TEST RESULTS

The components and sub-assemblies were tested throughout the development of the system and the operation of the system in its entirety was tested on the brake-dynamometer. However, the easiest and most representative way of obtaining performance data (e.g. stopping distances) was to track test the system fitted to a motorcycle. An example of the performance achieved during early tests of the system, performed on a brake dynamometer, is shown on the chart recorder output at figure 2. This shows that the braked wheel cycled about a slip value of approximately 18%, with extremes of 4% and 30%. This indicated a satisfactory performance. The system was, therefore, developed to the stage where a complete front wheel installation was fitted to a motorcycle and tested on the research track. Tests conducted ‘blind’ (i.e. rider not permitted to familiarise himself with braking on the test surface) on a low friction coefficient surface ($\mu=0.3$ approx.), resulted in an average reduction in stopping distance of around 22% when the ABS was employed, compared with rider ‘best’, without ABS. Additionally, three out of the six subjects involved in the tests recorded braking failures (i.e. vehicle capsizes) at the rate of between 14% and 40% of attempted braking manoeuvres when the ABS was not in use. Figure 3, shows a pair of chart recorder traces obtained during track testing of this prototype system and demonstrates the response
Fig. 1 Schematic drawing of 'phase 1', hub mounted ABS assembly
when braking on a road-surface transition. The road-surfaces used were quartzite macadam and Bridport macadam, which had friction coefficients of around 0.8 and 0.3 respectively. Figure 3a shows the effect of braking across the transition from the high to low friction coefficient surface. The reduction in the deceleration of the vehicle is clearly defined when encountering the low friction coefficient surface. Similarly, figure 3b shows the system response when braking across the transition in the opposite direction (i.e. from low coefficient to high coefficient). In both cases, the change in the deceleration of the vehicle was by a factor of around 2.5, which corresponded with the difference in friction coefficient between the two test surfaces. These results indicated that the system was able to respond rapidly to changes in surface friction coefficient, which is a primary requirement of an anti-lock brake system. Initial testing of the 'phase 1' front wheel installation, involved side-by-side comparison with the braking performance achieved by front wheel braking only of a BMW motorcycle fitted with the Lucas-Girling SCS. This particular vehicle was chosen for the comparison because the Lucas-Girling SCS was similar in operation to the TRL ABS, in that they both employed flywheel based deceleration sensors. The testing was conducted on two wetted road surfaces; one a low friction-coefficient Bridport Macadam ($\mu = 0.35$ approx), the other a relatively high friction-coefficient fine textured asphalt ($\mu = 0.8$ approx). Four riders were asked to perform emergency braking operations using both of the motorcycles on both road surfaces. Three sets of data were recorded; 'rider best' without ABS (performed with the Kawasaki AR125), TRL ABS (fitted to the Kawasaki AR125) and the Lucas-Girling SCS. All braking operations were conducted from approximately 50km/h (actual velocities measured using radar based speed measuring equipment). The results from these tests are shown in table 1.

The track tests detailed above were conducted in the Autumn of 1992 and indicated that the performance of the TRL ABS was acceptable. By this time development work on the 'phase 2' system was well advanced. However, a number of technical problems arose during preliminary testing of the 'phase 2' system, both on the dynamometer and the track. As a result, it was not until April 1993 that the next set of comparative performance test results were obtained. These involved the side-by-side testing of the 'phase 2' TRL ABS (front and rear wheel installation) and the BMW production ABS fitted to a K100 motorcycle. The results of these tests are shown in tables 2 to 5.

The results demonstrate the favourable performance achieved by the Kawasaki equipped with the TRL ABS compared with that of the BMW. The relatively poor results obtained with the TRL ABS by braking front and rear wheels individually, compared with the non-ABS condi-
Fig. 3 Early tests of TRL ABS showing braking across a surface transition.  
(a) High to low coefficient. (b) Low to high coefficient.

TABLE 1

Overall mean decelerations (TRL 'Phase 1' ABS compared with Lucas-Girling SCS)

<table>
<thead>
<tr>
<th>Surface</th>
<th>'Rider Best'</th>
<th>TRL ABS (Kawasaki AR125)</th>
<th>Lucas SCS (BMW K100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bridport</td>
<td>0.28g (0.22-0.32)</td>
<td>0.27g (0.23-0.32)</td>
<td>0.32g (0.24-0.41)</td>
</tr>
<tr>
<td>FTA</td>
<td>0.41g (0.28-0.50)</td>
<td>0.55g (0.54-0.59)</td>
<td>0.54g (0.45-0.62)</td>
</tr>
</tbody>
</table>

Notes:  
(i) Braking from nominal speed of 50km/h - front brake only.  
(ii) 'Rider best' attempts produced 4 instances of failure in 16 runs  
(i.e. locked wheel, leading to vehicle capsize).  
(iii) Figures in brackets indicate range of values obtained.
TABLE 2

Overall mean decelerations (TRL 'Phase 2' ABS compared with BMW ABS) Wet Bridport from 50 km/h (nominal)

<table>
<thead>
<tr>
<th>Brakes</th>
<th>TRL ABS Kawasaki AR125</th>
<th>BMW ABS (BMW K100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front only</td>
<td>0.20g</td>
<td>0.17g</td>
</tr>
<tr>
<td>Rear only</td>
<td>0.20g</td>
<td>0.15g</td>
</tr>
<tr>
<td>Both</td>
<td>0.30g</td>
<td>0.28g</td>
</tr>
</tbody>
</table>

TABLE 3

Overall mean decelerations (TRL 'Phase 2' ABS compared with BMW ABS) Damp FTA from 50 km/h (nominal)

<table>
<thead>
<tr>
<th>Brakes</th>
<th>TRL ABS Kawasaki AR125</th>
<th>BMW ABS (BMW K100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front only</td>
<td>0.36g</td>
<td>0.33g</td>
</tr>
<tr>
<td>Rear only</td>
<td>0.24g</td>
<td>0.27g</td>
</tr>
<tr>
<td>Both</td>
<td>*</td>
<td>*</td>
</tr>
</tbody>
</table>

*Note: ABS malfunction.

TABLE 4

Overall mean decelerations (TRL 'Phase 2' ABS compared with BMW ABS) Dry FTA from 50 km/h (nominal)

<table>
<thead>
<tr>
<th>Brakes</th>
<th>TRL ABS Kawasaki AR125</th>
<th>BMW ABS (BMW K100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front only</td>
<td>0.41g</td>
<td>0.41g</td>
</tr>
<tr>
<td>Rear only</td>
<td>0.24g</td>
<td>0.29g</td>
</tr>
<tr>
<td>Both</td>
<td>0.69g</td>
<td>0.53g</td>
</tr>
</tbody>
</table>

TABLE 5

Overall mean decelerations (Kawasaki AR125 with/without TRL ABS) Dry FTA from 50 km/h (nominal)

<table>
<thead>
<tr>
<th>Brakes</th>
<th>Kawasaki AR125 with TRL ABS</th>
<th>Kawasaki AR125 without TRL ABS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front only</td>
<td>0.41g</td>
<td>0.70g</td>
</tr>
<tr>
<td>Rear only</td>
<td>0.24g</td>
<td>0.34g</td>
</tr>
<tr>
<td>Both</td>
<td>0.69g</td>
<td>0.69g</td>
</tr>
</tbody>
</table>
tion was thought to be due, in part, to the cycling of the ABS and its interaction with the dynamic characteristics of the vehicle suspension system. It was believed this performance could be improved via adjustment of the flywheel control spring, but in practice, only marginal improvement was achieved.

The next significant track test of the TRL ABS occurred in June/July 1993 and involved a 1000km durability test. This test was successfully completed with the system having performed in excess of 1000 brake applications utilising the ABS. The braking was conducted on a dry asphalt surface as it was considered this would provide the severest test for the ABS in terms of forces generated in the system. During this phase of the testing, the system appeared to perform reliably. As a result of this test, the decision was taken to assemble another four motorcycles to the same ‘phase 2’ specification for road trial.

It was now considered that the TRL ABS was nearing a position whereby it could be considered for road trial. However, before the motorcycles could be released for road trial, it was required that the system should be proved to perform in accordance with ECE Regulation 78. The Regulation 78 test for ABS requires the vehicle to be braked from 60km/h to a stop and the time taken for the vehicle to decelerate from 40km/h to 20km/h be recorded. This recorded data is then used to calculate the efficiency of the ABS compared to the non-ABS condition which should be in excess of 70 percent. The test is performed using the same vehicle both with and without the ABS, stopping with the front and rear brakes, independently. The results of these tests on the TRL ABS are shown in tables 6 and 7. A complete set of results could not obtained due to reliability problems associated with the deceleration sensor. This was a recurring problem which had manifested itself several times during previous testing and is discussed at length in section 3.6.9. It can be seen from table 6, that the rear brake, when tested in isolation on the high coefficient surface, did not meet the required efficiency. This was a problem which remained unresolved. The problem may have been due to an interaction between the vehicle chassis geometry, the suspension characteristics and the cycling time of the ABS, but was almost certainly a function of load transfer from the rear to the front of the motorcycle during braking. The problems experienced during the performance testing to Regulation 78 and the failure of subsequent investigation to solve them, resulted in the ABS being adapted to operate with an electronic deceleration sensor, with the system being controlled from a micro-processor, the details of which are discussed in section 3.7. However, it was not anticipated that the change to electronic control would solve the problem regarding the relatively poor efficiency of the rear ABS installation.

3.6 ENGINEERING DIFFICULTIES

The system was developed mainly on the TRL brake dynamometer facility and a number of problems were identified and rectified. However, a number of unforeseen problems arose only during testing of the complete system when fitted on the motorcycle. Other difficulties related to production of components for the system. Some of the primary problems are discussed below.

3.6.1 Use of Castings

It would have been possible to machine all the components for the ABS from solid and, indeed, ‘prototype’ devices had been made in this way. However, it was decided to use alloy castings for the body of the hub assembly on the ‘phase 1’ system, because it was considered that savings would result from the reduction in production time and that the end result would be an aesthetically and mechanically superior component. Unfortunately, delays in the supply of the castings from the sub-contractor nullified the time saved in machining, but the other benefits were achieved.

3.6.2 Pump Plunger

As part of the redesign between the ‘phase 1’ and ‘phase 2’ systems, the hydraulic fluid pump was moved inside the wheel hub to be driven by a face-cam which operated directly on an extension of the pump piston. Contact

<table>
<thead>
<tr>
<th>Brake</th>
<th>Surface type: Course surface dressing (Motorway), Dry</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without ABS</td>
<td>With ABS</td>
</tr>
<tr>
<td></td>
<td>t (s) Zm</td>
<td>t (s) Zm</td>
</tr>
<tr>
<td>Front only</td>
<td>0.563 0.995</td>
<td>0.677 0.827</td>
</tr>
<tr>
<td>Rear only</td>
<td>1.307 0.428</td>
<td>2.223 0.252</td>
</tr>
<tr>
<td>Both</td>
<td>0.567 0.988</td>
<td>0.597 0.938</td>
</tr>
</tbody>
</table>

$ t =$ Time taken to decelerate from 40 - 20 km/h (average of 3 tests)

$ Zm $ & $ Zmax =$ Coefficient of adhesion ($0.56/t$)
TABLE 7
ECE Reg. 78 Braking test results of TRL ABS (Kawasaki AR125)

<table>
<thead>
<tr>
<th>Brake</th>
<th>Without ABS</th>
<th>Surface type: Bridport gravel, wet</th>
<th>With ABS</th>
<th>Efficiency</th>
<th>Zmax</th>
<th>Zmax/Zm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>t (s)</td>
<td>Zm</td>
<td>t (s)</td>
<td>Zmax</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Front only</td>
<td>1.827</td>
<td>0.306</td>
<td>2.260</td>
<td>0.248</td>
<td>0.81</td>
<td></td>
</tr>
<tr>
<td>Rear only</td>
<td>2.047</td>
<td>0.273</td>
<td>2.646</td>
<td>0.212</td>
<td>0.77</td>
<td></td>
</tr>
<tr>
<td>Both</td>
<td>1.330</td>
<td>0.421</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

\( t = \) Time taken to decelerate from 40 - 20 km/h (average of 3 tests)
\( Zm \) & \( Zmax \) = Coefficient of adhesion (0.56/t)

between these parts occurred only when the anti-lock operated. It was decided to apply appropriate heat treat-
ment to these parts in the belief that this would provide an acceptable working life. Tests proved that this was not the case and it was necessary to develop these components further. Several designs incorporating rolling ball-bearings were tried without success. The final solution appeared to be a hardened plain roller which, after extended testing - including the 1000km durability test, showed no significant signs of wear.

3.6.3 Non-Return Valves

The hydraulic fluid pump contains two non-return valves. These were made of rubber in the original Mullard system. For reasons of system integrity, these were replaced in the redesigned pump with commercially produced valves. Although a manufacturer of suitable valves was located early on in the design stage, these were no longer available when the requirement arose. This meant that suitable valves had to be designed and manufactured 'in-house'. These proved difficult to manufacture and assemble and their reliability was suspect. Subsequently, commercial valves became available requiring modifications to the pump body to permit their use.

3.6.4 Use of Adhesives

'Loctite' adhesives were considered to be suitable for securing several parts of the hub assembly, probably the most critical being the fixing of the hub insert into the road wheel. The use of these adhesives simplified the manufacturing process and assembly of certain components. However, during testing on the dynamometer, the hub insert became detached. This necessitated a redesign to allow the use of a more positive means of mechanical attachment. This problem also occurred at a later stage involving other parts fixed with adhesive. On one occasion, such a failure resulted in significant damage to other parts of the assembly. Subsequent investigation revealed that, on the basis of incorrect advice, the wrong grade of adhesive had been used.

3.6.5 Development of Restrictor-Reservoir Assembly

It had been decided, at a very early stage in the design, that the pump should be divorced from the restrictor-reservoir unit, so that the latter could be attached to the frame of the motorcycle. This was deemed necessary to reduce the unsprung weight of the system. In the early 'prototype' versions of the TRL ABS, the design and construction of the restrictor-reservoir was very similar to that employed in the original Mullard unit. As a result, it proved almost impossible to position two of these units, satisfactorily, on the frame of the recipient vehicle, given the limited space available. Therefore, development was undertaken to reduce the dimensions of the restrictor-reservoir and hence reduce its weight. Whilst the restrictor-reservoir was being redesigned, the opportunity was taken to improve the functioning/reliability of certain aspects of the unit.

3.6.6 Spurious operation of solenoid valve

As a consequence of the dynamic properties of the sensor flywheel, the flywheel control spring exerted a very small force. It had been observed on several occasions during on-vehicle testing, that the flywheel had not returned to its 'parked' position when the vehicle had been braked to a standstill. This resulted in the electrical switch, attached to the flywheel, remaining in its 'closed' position. This situation, if allowed to persist, imposed a heavy drain on the battery and could cause the restrictor-reservoir solenoid to burn-out. To prevent this, an additional electrical logic circuit had to be installed to prevent operation of the solenoid unless the brake was applied.

3.6.7 System Over-Pressuring

The problem of over-pressuring of the system first became evident on the development motorcycle. By exerting a high brake line pressure, via the hand or foot brake levers, it was possible to defeat the ABS resulting in a locked wheel. An indication of the cause of the problem became evident after further investigation. The problem occurred at around 1000psi in the rear ABS on the development motorcycle,
but at only about half this pressure on one of the field trial motorcycles. It was this variation in the brake line pressures producing the effect, that indicated the root of the problem. Under normal braking, the ABS fluid reservoir is sealed by a valve. When the ABS is activated, the solenoid is energized inducing a magnetic flux in the ‘pole piece’, this retracts the armature which, in turn, opens the reservoir valve. However, due to tolerance accumulation in the restrictor-reservoir assemblies, the air-gap between the armature and pole piece varied between the assemblies, which resulted in a variation in the lifting forces applied to the armatures. The solution to the problem required the manufacture of adjustable restrictor-reservoir caps, which allowed the air-gaps between the pole-pieces and armatures to be set after assembly of the restrictor-reservoirs.

3.6.8 Brake Master Cylinder Fluid Capacity

During testing of the ‘phase 2’ system it became evident that all the available brake lever travel was being used when the ABS was cycling. It was not clear why this was happening as the redesign of the system between ‘phase 1’ and ‘phase 2’ had not altered the overall fluid capacity of the system. However, in order to affect a solution it was decided to fit larger brake master cylinders to the motorcycles. Suitable alternative cylinders (Magura) were located and ordered in May 1993. Two pairs were supplied ‘ex-stock’ the rest, were placed on ‘back-order’. In August 1993, the supplier stated that the order “could not be completed in the foreseeable future”, and so an alternative source was sought. A second source of suitable cylinders (Brembo) was duly located and the appropriate cylinders obtained. Unfortunately, bracketry had already been fabricated and welded into position on the motorcycles in anticipation of Magura master cylinders being available. This required the fabrication and fitting of new brackets to accommodate the replacement Brembo master cylinders.

3.6.9 Mechanical Deceleration Sensor Reliability

During initial track testing of the ‘phase 1’ system, the TRL ABS had been performing intermittently. The problem produced symptoms which indicated that the deceleration sensor flywheel was ‘sticking’ or that electrical continuity through the switch from the deceleration sensor was faulty. Disassembly of the deceleration sensor proved that both of these ‘faults’ existed and efforts were made to reduce friction in the system and to improve the reliability of the electrical continuity. However, problems with the reliability of the deceleration sensor continued to cause problems throughout the life of the project and though the attention given to rectifying the problem resulted in a much improved performance, the sensor reliability problem was never solved. The sensor unreliability prevented the road trial taking place. A more detailed explanation of the problems associated with the unit are given below.

There were three distinct problems associated with the sensor, two of which produced identical symptoms. The deceleration sensor, as previously described, utilised an overrunning flywheel to close an electrical switch to operate the ABS. Non-functioning of the ABS, via the sensor, occurred in two ways. The first being lack of electrical continuity. The mechanical sensor used slip-rings and carbon brushes, produced ‘in-house’, to convey the sensor signal for the ABS. Continuity through the slip-rings, brushes and brush holders proved to be very erratic. Fettling of the individual assemblies met with limited success in solving the problem, as did increasing the current transmitted through the assembly in an attempt to overcome increased resistance caused by surface contamination/poor brush contact. A pair of modified sensors were produced to accommodate commercially produced brushes. However, the brushes supplied were too soft and left carbon deposits on the slip-ring tracks which ‘shorted’ the switch. Harder brushes were to be tried, but other problems associated with the sensor operation rendered this course of action redundant.

The second problem, which could also result in the ABS failing to function, was poor operation of the flywheel due to friction (i.e. failure of the flywheel to over-run or to return when the need arose). The requirement to package the hydraulic pump and the sensor within the wheel hub of the motorcycle, necessitated a significant scaling-down of the components compared with previous practice (Lucas-Girling SCS and Dunlop Maxaret). The degree of scaling-down was, to a large extent, dictated by the constraints imposed by the use of a commercially produced road wheel, as fitted to the Kawasaki AR125 motorcycles chosen for the project. Scaling-down of the sensor with commensurate reduction in the flywheel inertia and hence potential momentum, resulted in friction becoming a dominant force resisting flywheel motion. When the flywheel assembly was clean and lightly lubricated it functioned as intended under ‘bench test’ conditions. However, when installed in the wheel hub and subjected to road testing, the action of the flywheel soon became erratic and unreliable. This was a problem which it was believed could not be solved, given the imposed design constraints, as all means of reducing friction within the assembly had been adopted.

There was a third and more fundamental problem associated with the operation of the mechanical wheel deceleration sensor, which became apparent after testing the system at higher speeds on a low friction-coefficient surface. When a wheel is over-braked and becomes locked, the time taken for the wheel to recover and spin-up to speed again is dependent on the surface friction coefficient, the lower the friction coefficient, the longer the time taken for the wheel to spin-up. Therefore, the length of time the brakes need to be released, to allow the wheel to spin-up to speed, varies according to surface friction coefficient. In the Lucas-Girling Stop Control System, the flywheel mechanism incorporated a clutch that permitted the flywheel to con-
continue spinning, holding open the brake pressure release valve until the road wheel could accelerate and restore drive to the flywheel. The TRL ABS had no clutch or alternative mechanism to alter the brake pressure release period significantly. Whether this was an oversight or a conscious decision to simplify the sensor mechanism was never ascertained, because the two former project engineers retired during the life of the project. This omission compromised the function of the sensor, permitting the brakes to be reapplied before the road wheel had time to recover speed on very low-friction coefficient surfaces. (Interestingly, this need for a variable brake release period is often not addressed in many of the 'simple' mechanical ABS proposals - a number of which have been patented.)

The unreliability experienced with the TRL ABS sensor was a combination of all three of the problems detailed above. Two of the problems are inherent to the design of the sensor assembly, therefore it would not have been possible to make the sensor work successfully without a thorough redesign. However, given the constraints imposed by the dimensions of the wheel hub, it was ultimately considered unlikely that an effective mechanical sensor could be designed for the selected installation.

3.7 ‘ELECTRONIC’ DECELERATION SENSING

In June 1993, due to the reliability problems experienced with the mechanical deceleration sensor, it was decided to investigate the feasibility of modifying the TRL ABS to incorporate a micro-processor controller and electronic deceleration sensor. A toothed wheel and inductive pick-up were fitted to the front wheel of the development motorcycle and a suitable processor designed and built. TRL had no prior experience in the design and implementation of processor based ABS control logic and very little has been published on the subject. It was initially thought that a wheel deceleration based algorithm was the most sensible approach to adopt and this was reinforced by the available literature (this is also the basis on which the flywheel based systems operate). To this end, a simple control algorithm was designed with a manually adjustable wheel deceleration threshold. Subsequent testing, which also involved experimentation with the number of teeth on the sensor wheel, proved that wheel deceleration was not a suitable characteristic to adopt as the basis for the control logic. Calculation of the effects of this approach revealed that the system could be optimised to work efficiently only for a particular speed and surface friction coefficient. Under these circumstances tyre slip varies with speed and the optimum speed varies with surface friction coefficient. After further consideration it was decided to adopt tyre slip as the control characteristic. With this approach, a threshold can be set for tyre slip which maximises the tyre adhesion by virtue of mechanical losses in the tyre carcass and tread compound (15% - 20% slip). This process is independent of vehicle speed and surface friction coefficient and hence, in theory, lends itself to a concise and elegant control algorithm. However, due to hysteresis in the system, the threshold can only be established, in reality, by experimentation and data analysis. Further, this only determines the point at which the brake pressure should be relaxed; it does not indicate the brake re-application point, which needs careful consideration in its own right.

When work was suspended on the development of the system, the basic algorithm for the TRL ABS controller was functioning successfully using tyre slip as the threshold, but required further testing and analysis to ascertain the optimum threshold for the system. A ‘fool-proof’ algorithm would have required much greater development time to enable it to cope with the variety of situations which were likely to be presented during day-to-day running of the road trial motorcycles.

3.8 PRODUCTION COSTS

It was a primary requirement of the project, that the research and development undertaken, should result in an ABS which was economical to produce. This was necessary, to demonstrate that an effective, light-weight ABS, suitable for fitting to low-cost, light-weight motorcycles (typically of 125cm³ engine capacity), could be produced and marketed at a cost of approximately 10 percent of the purchase price of such vehicles i.e. about £200-£300.

An initial estimate of the likely cost of the system being developed by TRL, suggested a retail figure of approximately £240 (Donne, 1991). This was arrived at by the use of a production engineering approximation, which is based on the overall weight of the system components. However, whilst this method provided a basis on which to proceed, a more accurate calculation was sought.

In June 1993, a consulting engineer was engaged to perform a detailed cost analysis on the system. The consultant was asked to consider ways in which the production of components for the TRL ABS could be modified to reduce costs and to calculate the total production cost of such a system. For comparison, the consultant was also asked to provide production costs, on the same basis, for the Lucas-Girling SCS and for other production motorcycle ABS available at that time. The results of the consultants study, based on production quantities of 50,000 units per year, are shown in table 8. It can be seen from the figures in table 8, that the TRL ABS with either the mechanical or electronic deceleration sensing is comparatively expensive to produce. It is believed that the production cost of the TRL system, redesigned around electronic sensing, could be significantly reduced. However, it is unlikely that the system could be produced any cheaper than the Lucas-Girling or Yamaha systems.
TABLE 8
Comparative production costs of ABS

<table>
<thead>
<tr>
<th>Anti-lock Brake System</th>
<th>Production Cost (£) (Estimated)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRL (flywheel sensor)</td>
<td>365</td>
</tr>
<tr>
<td>TRL (electronic sensor)</td>
<td>344</td>
</tr>
<tr>
<td>Lucas-Girling SCS</td>
<td>255</td>
</tr>
<tr>
<td>Honda (ST1100)</td>
<td>334</td>
</tr>
<tr>
<td>BMW (R1100RS)</td>
<td>349</td>
</tr>
<tr>
<td>Yamaha (FJ1200)</td>
<td>233</td>
</tr>
</tbody>
</table>

*Retail figures will be 2 to 3 times as great

The relatively high cost of the TRL system lies in its complexity and intricacy. The requirement to improve the aesthetics of the system necessitated moving the hydraulic fluid pump inside the road wheel hub. This resulted in the need for close tolerance engineering which added to the production cost of the system. Similarly, the need to reduce weight was a major consideration, which influenced the design and added to the cost in terms of the materials used and the engineering input required. The TRL system is light-weight and compact and with electronic sensing and control was likely to prove reliable, but the cost of production would be prohibitive.

It should be recognised that preventing wheel lock under braking is a relatively complicated problem which demands considerable technical expertise to solve. The success of the motorcycle manufacturers in providing the sophisticated electronic ABS fitted to current production motorcycles at a reasonable cost, must be recognised. It is unfortunate, that the current cost of such systems limits their fitment to relatively expensive motorcycles. However, Mitsui UK (Yamaha) anticipate that as production quantities increase, the retail cost of the ABS fitted to their FJ1200 motorcycle, will fall to the equivalent of £300 at today’s prices (1994) by the end of the decade. At such a price, it would be financially feasible for the motorcycle manufacturers to consider fitting ABS to smaller, less expensive machines.

4. DISCUSSION

In choosing to enclose the mechanical deceleration sensor inside the road-wheel hub of the motorcycle, the decision was taken to adopt the smallest (lightest) flywheel with the necessary dynamic characteristics to perform the deceleration sensing and switching required by the system - this proved to be a mistake. The resultant flywheel performed as intended under ideal 'bench-test' conditions, but in the 'field', proved unreliable because, in a less than ideal environment, the friction losses were greater than anticipated. It is now acknowledged, that a flywheel with greater inertia was required, but it is unlikely that a suitable device could have been accommodated in the space available on the recipient vehicle.

The problem concerning the rear brake efficiency under ABS control, compared with a conventional rear brake, would appear to be a result of the short wheelbase and high centre of gravity of the motorcycle. Tables 6 and 7 gave the results from the ECE Reg.78 test performed using the TRL ABS equipped Kawasaki AR125. The efficiency of the rear brake utilising ABS was 77% on the low friction coefficient surface, but only 59% on the high friction coefficient surface. The Regulation requires a minimum of 70% efficiency. Although results from only two test surfaces are available, it would appear that the trend is for the rear brake efficiency to fall as the surface friction coefficient rises. This is almost certainly due to the increased load transfer to the front wheel associated with higher friction coefficient surfaces. This is likely to present a problem for rear wheel ABS braking efficiency on any motorcycle, but will be particularly pronounced on light-weight motorcycles, which tend to have a much shorter wheel base than larger, heavier motorcycles. The problem is exacerbated by the lighter weight of small motorcycles, as the rider mass represents a larger proportion of the total mass and, being high up on the vehicle, moves the effective centre of gravity much higher than would be the case with a larger, heavier motorcycle. This is a phenomenon which needs further investigation, as if it proves to be a problem, it will create difficulties for manufacturers, developing ABS systems for light-weight motorcycles, in meeting the efficiency requirements of the current ECE Regulation. It may even require changes to the current regulation to encourage manufacturers to provide the obvious benefits of ABS to a large proportion of the motorcycling public.

At the time of the conception of the basic system configuration for the TRL light-weight ABS, there was only one commercially available motorcycle ABS on the market, namely the BMW/FAG system. When introduced, it was only available as an 'optional extra'. The system was relatively bulky and heavy, due mainly to the two hydraulic actuators (a revised system is now available) and considered unsuitable for fitting to a light-weight motorcycle. However, the main obstacle to greater market penetration was the cost of the system, which added around £1000 to the basic price of a BMW motorcycle in the UK. Given the market at which the BMW range of motorcycles is aimed, it was quite likely that many customers would specify the ABS option. This has since proved to be correct, as BMW (GB) Ltd. now only import non-ABS motorcycles, other than those on which ABS is not an option, to special order. However, at such cost, it would not be commercially sensible to fit ABS to low-cost, light-weight motorcycles. TRL, considered on the basis of their experience with the Lucas-Girling mechanical SCS and the TRRL/Mullard...
electro-mechanical ABS, that a low-cost, light-weight, mechanical ABS system could be produced for fitment to light-weight motorcycles. It is now clear that TRL had underestimated the cost and complexity of the task. Also, the cost of producing mechanical components to do the job which might otherwise be achieved through the use of electronics, is comparatively expensive. This cost differential between mechanical and electronic solutions to problems widened during the 6 years since the project was conceived and the trend is likely to continue. This presents an optimistic outlook as far as ABS for low-cost, light-weight motorcycles is concerned, as it should result in current, relatively expensive and sophisticated ABS being available, at a much reduced cost, in the foreseeable future.

5. SUMMARY AND CONCLUSIONS

The Transport Research Laboratory has been involved in research into various aspects of motorcycle primary safety since the early 1960s, and much of this work has been on anti-lock brake mechanisms and combined brake systems. This report has focused on the most recent aspect of that work - the design and development of a low-cost anti-lock brake system for light-weight motorcycles.

The anti-lock brake development programme encountered considerable engineering difficulties which ultimately lead to the demise of the project due to the lack of funds. The main problems centred around the flywheel based mechanical deceleration sensor employed, which proved too unreliable for the planned road trial to be conducted. It is believed that the unreliability was due, in the main, to the scaling down of components to fit inside the road wheel hub. This was considered necessary to provide increased protection for the mechanisms, improve the aesthetics and reduce the unsprung weight of the system. It is likely that the TRL ABS, when fitted with an electronic sensor, would have proved reliable. The limited testing conducted on this system indicated that it would offer a significantly improved performance compared to that of a fully-functioning flywheel based system. This 'electronic' system would also have been cheaper to produce. However, the production costs of such a system were unlikely to have been significantly lower than any of the production systems currently on the market.

There is every reason to believe that, with cheaper electronics and an increase in production, ABS will become commercially feasible for fitment to lower cost, smaller engine capacity machines than is currently the case. The fitment of ABS to smaller machines could be accelerated by permitting fitment of devices to the front wheel only. This would almost certainly offer a large proportion of the benefits to be gained from ABS at a significantly lower cost to the consumer (estimated at 65%-70% of the cost of a ‘full’ two wheel system).

The main conclusions are as follows:

i The performance of mechanical anti-lock brake systems can be optimised only for one angular deceleration of the road wheel. This indicates that the efficiency of such a system changes with surface friction coefficient and vehicle speed (road wheel rotational velocity). However, it would appear that mechanical systems can be ‘tuned’ to provide a beneficial performance for the majority of situations. The only disadvantage is the slightly longer stopping distances on high coefficient surfaces. However, this is more than offset by the increase in stability and hence prevention of capsize.

ii The anti-lock brake system designed and developed by TRL was considered to be too costly to produce and proved to be too unreliable for consideration for road trial. The cause was the intricacy of the mechanisms chosen. Problems with reliability were particularly associated with the mechanical wheel speed sensors. It is likely, that the required reliability could have been achieved via electronic wheel speed sensing and micro-processor control, but the resulting system appeared to offer no significant advantages over current production systems, in terms of both cost and performance.

iii From the tests, it would appear that the relatively large load transfer to the front wheel of a motorcycle under braking, creates difficulties for the efficient operation of rear wheel ABS. This will be a greater problem for light-weight, shorter wheel base motorcycles than for larger, heavier machines. This is an aspect which needs further research, as it could significantly hamper the introduction of ABS to the light-weight motorcycle market.

iv The current cost of production motorcycle anti-lock brake systems is commensurate with the level of sophistication and technology employed. The wider availability of ABS will only be realised through legislation, a willingness by the motorcycling public to meet the cost of such safety features or a significant reduction in their cost, which may be achieved through increased production.

6. RECOMMENDATIONS

It is recommended that all avenues be pursued to promote the wider availability of ABS as this seems to be the general desire of the motorcycling public. The wider availability of ABS may considerably reduce the number and severity of
motorcycle accidents, and may also improve riders' braking skills by allowing them to explore available braking potential and increase the level of use of the front brake by inexperienced riders.

Further research should be undertaken to investigate the apparent problems associated with motorcycle rear wheel ABS efficiency. This is likely to be a significant problem for manufacturers trying to develop ABS for light-weight motorcycles in accordance with the current ECE Regulation. If such further research reveals a definite problem in this respect, then consideration should be given to modifying the requirements of the ECE Regulation for particular types of vehicle. This should then encourage manufacturers to pursue the design and development of ABS for light-weight motorcycles.

7. ACKNOWLEDGEMENTS

The author gratefully acknowledges the advice given by Mr G Donne (former Project Manager) and the work conducted by TRL Technical Services.

The Vehicle Engineering Resource Centre (Resource Centre Manager: Mr G Edwards) of TRL was responsible for the research described in this report.

8. REFERENCES


Holmes and Stone 1969. Tyre forces as functions of cornering and braking slip on wet road surfaces. RRL Report LR254.

9. BIBLIOGRAPHY


APPENDIX A: GENERAL ASSEMBLY DRAWINGS OF TRL ANTI-LOCK BRAKE SYSTEM.

All drawings are of 'phase 2' system, unless otherwise stated. (not to scale).
Fairings and silencer shown in ghost for clarity
For details of electronic control circuit see
drawing 1270 - 18/G01 -S02
Insert item S01-002 (hub) and secure with retainer (high strength) 'Loctite' 638 and M6 x 25 long, csk.socket HD.cap screws (5 off).

Drill and tap radially M5 (5 positions) thro' both wheel and hub at right angles to the centreline (as shown) and secure with M5 x 10 long socket button head screws class 1 fit, spotface to witness.

Use existing 260mm diameter front-wheel brake disc and fixing screws as supplied.
Note - replicate speedometer drive details to hub end
(See existing front wheel before modification, also
DRG No. 1270 - 18/S01 - 001)

Aid to bearing removal
(2 positions)

Profile datums
only

5 holes drill and tap M4 thro' equi-spaced as shown
Drill and tap on assembly with respective front wheel to secure

Section on c/line

5 Holes ø8.40 on 150 PCD.
csk ø16.50 x 90° x 5.00 deep at lowest edge
- to mate with existing M8 holes drilled and
tapped thro' in front wheel from brake disc
mounting (See DRG. No. 1270 - 18/S01 - 001)

6 holes drill and tap M3 x 4.0 deep
on 84.9 PCD. Pos. Tol 0.16

Holes drill and tap M3 x 4.0 deep
on 64.0 PCD. Pos. Tol 0.16

equi-spaced as shown
Drill and tap on assembly with respective front wheel to secure
**Half-section in direction arrow 'D'**

- Drill and ream ø6.00 x 6 deep for idle gear shaft on 32.94 P.C. Rad., and 15.88 P.C. Rad. from sensor c/fine

**Half-section in direction arrow 'C'**

- 2.0 x 45° chamfer
- At offset centre (see enlarged view) machine ø13.00 to break-thru' and core ø18.50 x 14.70 deep. Tap M20 x 1.0 x 7.60 deep.
  - Insert item 1270-18/S02-011 (pinion liner) with 'Locline 638' and m/c external edge to conform with ø9.00 circumference or/in on reverse ø14.20 x 30° incl.

**Enlarged view at 'A'**

- 4.25 cts. true
- Machine to give 0.03 diametral clearance on item 1270-18/S02-011 (valve body)

**Suspension Tape**

- 2 holes drill and tap M5 x 10.0 deep. Position as show on 40.00 PC dia.
Half-section in direction arrow 'D'

At offset centre (see enlarged view) machine ø13.00 to break-chro' and c/bore ø18.55/18.50 x 14.70 deep. Tap M20 x 1.0 x 7.60 deep. Insert item 1270-18/S02-018 (piston line) with ‘Locite 638’ and mic external edge to conform with ø90.00 circumference c/sink on reverse ø14.20 x 30° incl.

2 holes drill and tap M5 x 10.0 deep. Position as shown on 40.00 PC dia.

Half-section in Direction arrow 'C'

Suspension Tape

Drill and ream ø6.00 x 6 deep for idler gear shaft on 32.94 P.C. Rad. and 15.88 P.C.Rad. from sensor c/in

Section on 'B-B'

2.00 inh hard PVC

2 x M3 x 10 long socket HD. csk. screws

At offset centre (see enlarged view) machine ø13.00 to break-chro' and c/bore ø18.55/18.50 x 14.70 deep. Tap M20 x 1.0 x 7.60 deep. Insert item 1270-18/S02-018 (piston line) with ‘Locite 638’ and mic external edge to conform with ø90.00 circumference c/sink on reverse ø14.20 x 30° incl.

4.25 cts. true

2.0 x 45° chamfer

1.5 x 45° chamfer

Machine to give 0.03 diametral clearance on item 1270-18/S02-011 (valve body)
Third Angle Projection

232.95 developed length (360°)

Section 'Y-Y'

Note: 1.0 x 45° chamfer on reverse face, at corners only. (ie. 6 positions)

6 holes drill ø3.4 on 84.00 PCD
Pos. tol 0.16 csk ø5.50 x 90°

232.95 developed length along centre of cam width (w5)

Sheet: 1

Dimensions in millimetres

TRANSPORT and ROAD RESEARCH LABORATORY
Department of the Environment
Department of Transport
Oxfordshire, Berkshire

Drawn based on ISO 286, ISO 2768 and TR75 Standard Tolerances

TOLERANCES

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Material: STEEL En 24T

Finish

HUB CAM

Scale 1:1

Remove all burrs and sharp edges

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Slip-ring shown either side of centre-line for clarity only. See details for true relative positions.

Sensor bearing mount 1270-18/S01-010 Front wheel
Sensor bearing mount (not shown) 1270-18/S02-010 Rear wheel
Sensor gear 1270-18/S01-005 Front wheel
Sensor gear 1270-18/S02-005 Rear wheel
1. * denotes Imperial units
2. Plug-screws (items 35 & 36) are to be seated with Loctite Screwlock 222 whilst carefully positioning with the aid of a near-size pin inserted into the adjacent hole. Use of this pin may involve a particular sequence for assembly
3. Apply self-adhesive PVC tape patch as a weather-seal (3 positions)
Section A - A

Part section B - B
Scale 2:1

Suspension tape

Third angle projection

View on arrow C

Third angle projection

Tell tale mark
see note 8

Part view on arrow D

Section B - B

'Phase 1' System
Notes:
1. Item 0355 to be pressed into item 024 to dimension stated
2. Ensure 'O' ring seals items 031, 032 and Galon back up ring item 033
   valve parts and upper part of plunger above circlip are coated with brake
   fluid - DOT 4 spec.
3. Ensure that no brake fluid reaches the lower part of the plunger below the
   circlip as this fluid is not compatible with the camshaft lubricating grease.
4. Lubricate rotating items using light grease.
5. Fit brush assembly after fitting S03 assembly and ensure that brush item
   039 is contacting the associated slip ring on the S03 assembly
6. Fit brush item 039 into sleeve item 038 allowing for maximum projection
7. Ensure that the connection wires item 037 allow for the removal of the
   brush assembly for routine inspection. Solder wires to lugs as indicated
8. Ensure that tell tale marks are aligned
9. Loctite existing wheel spacer into hub using Loctite 302
10. Test electrical conductivity and mechanical operation

Scale 1:1