BRAKING, STABILITY AND HANDLING OF MOTORCYCLES

by

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A review of the literature relating to braking stability and handling of motorcycles was undertaken. Evidence of relationships between motorcycle characteristics and accidents was sought. Anecdotal evidence of operational problems published in user magazines was also reviewed. Experimental and analytical investigations of motorcycle dynamics, and the effects of accessories, tyres and machine modifications, was surveyed. Problem areas were identified and priorities for further research recommended.

Motorcycles, Handling/Controllability/Directional Control, Vehicle Braking, Accident Causation/Accident Patterns.

NOTES:

(1) ORS research reports are disseminated in the interests of information exchange.

(2) The views expressed are those of the author(s) and do not necessarily represent those of the Commonwealth Government.

(3) The Office of Road Safety publishes two series of research reports
   (a) reports generated as a result of research done within the ORS are published in the OR series;
   (b) reports of research conducted by other organisations on behalf of the ORS are
       published in the OR series.
This report documents the first of two phases of a research project concerned with braking, stability and handling of motorcycles. Phase I constituted a literature review, the objectives of which were to review the state of knowledge, isolate problem areas and recommend priorities for further research. As a result of this review, a Phase II investigation of ergonomic aspects of motorcycle braking control was initiated and reported separately (Juniper and Good, 1983).

The accident literature demonstrated that motorcyclists are more likely to be involved in an accident than other vehicle users, and the consequences are more severe. In the most common accident scenario, the motorcycle's right of way is violated by another vehicle. The accident-avoidance capabilities of riders and bikes are consequently of considerable importance. The literature revealed, however, that riders typically make poor use of the braking capacity of their machines, thereby increasing both accident frequency and severity. The contribution of motorcycle stability and handling characteristics to accident risk has not been adequately determined, in part due to a lack of knowledge of the most appropriate way to describe these characteristics. Virtually all motorcycle accident studies have suffered from inadequate, or a complete lack of exposure data which would allow statistical inferences to be drawn about vehicle-related factors in accident causation.

Other aspects of the literature review included disc brake performance in wet weather, antilock brakes, linked brake systems and brake modulability. Analytical and experimental investigations of rider/cycle stability and handling were reviewed, both for standard machines and those modified by fitting of accessories, structural changes and the carrying of loads.

Recommendations for further research are made on the basis of the problems identified in this review.
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1. INTRODUCTION

1.1 BACKGROUND TO REVIEW

In its report on motorcycle and bicycle safety, the House of Representatives Standing Committee on Road Safety (HoR, 1978, Para. 81) recommended that:

"A literature and research review of existing and potential problems relating to motorcycle stability and handling be undertaken by the Advisory Committee on Safety in Vehicle Design."

Furthermore, the committee recommended experimental appraisal of antilock and linked brake systems. They expressed concern about possible motorcycle instabilities arising through the fitment of fairings and the carrying of luggage. In addition, they said that the safety aspects of the matching of tyres to machines should be investigated.

On the basis of these recommendations the Office of Road Safety of the Australian Department of Transport commissioned a two-phase research project entitled "Braking, Stability and Handling of Motorcycles". Phase I was to be a literature and research review, while Phase II was to be an experimental investigation of a high-priority problem area revealed by the review.

This report documents the Phase I literature and research review. The Phase II investigation has been reported separately (Juniper and Good, 1982).
1.2 OUTLINE OF REVIEW

Chapter two examines the motorcycle accident literature and specifically looks for evidence of involvement of braking, stability and handling problems in accidents.

Chapter three reviews the literature specifically concerning braking aspects of motorcycles, and highlights deficiencies in motorcycle brake design and rider control problems.

Chapter four studies the literature relating to stability and handling of motorcycles. This encompasses both mathematical modelling of the rider/motorcycle system and experimental investigations aimed at quantifying the lateral dynamic behaviour and rider control of motorcycles. Anecdotal evidence of stability and handling problems from the popular press is also reviewed.

Chapter five reviews the literature which looks at the influence of accessories (such as fairings and pannier bags), tyres and machine modifications on motorcycle stability and handling.

Finally Chapter six presents conclusions and recommendations for further research arising from this literature review. It was from these recommendations that the topic for the Phase II experimental program reported in Juniper and Good (1983) was selected.
2. EVIDENCE OF RELATIONSHIPS BETWEEN MOTORCYCLE BRAKING, STABILITY AND HANDLING CHARACTERISTICS, AND ACCIDENTS

2.1 INTRODUCTION

The motorcycle accident literature was examined with a view to ascertaining the degree of involvement of braking, stability and handling characteristics in accidents. There has been no specific study aimed at isolating these factors; consequently the level of their involvement can only be inferred.

2.2 REVIEW OF ACCIDENT LITERATURE

2.2.1 Motorcycle Accident Description

Figure 2.1 shows the number of vehicles on register in Australia from 1960 to 1980. Cars and station wagons are shown separately from motorcycles. Apart from a slight downward trend in the early 1960's, the motorcycle population has consistently increased over a thirteen year period. In comparison to cars and station wagons, motorcycles use much less fuel per kilometre, require a smaller initial capital outlay, and their small size permits easy parking in crowded urban environments. Unfortunately motorcyclists are the most vulnerable of all road users in an accident, primarily because the rider is virtually unprotected (save for a helmet in Australia). The relative hazard for a motorcyclist compared to a motor car or station wagon occupant is shown in Table 2.1 (drawn from Johnston, Milne and Cameron, 1976). Relative hazard is defined as the accident rate for motorcycles divided by the accident rate for cars and station wagons. The relative hazard for the motorcyclist ranges from 2.9 to 16.4 depending on the basis for comparison. The motorcyclist is definitely at very great risk.
Figure 2.1 Total vehicles on register - motorcycles and cars/station wagons.

TABLE 2.1. RELATIVE HAZARD OF MOTORCYCLE TRAVEL COMPARED WITH OTHER FORMS OF ROAD TRANSPORT, VICTORIA, 1971
(after Johnston, Milne and Cameron, 1976).

<table>
<thead>
<tr>
<th></th>
<th>MOTOR CYCLES</th>
<th>CARS AND STATION WAGONS</th>
<th>LIGHT COMMERCIAL</th>
<th>TRUCKS</th>
<th>BUSES</th>
<th>TOTAL</th>
<th>RELATIVE HAZARD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number on register</td>
<td>28,160</td>
<td>1,131,161</td>
<td>136,303</td>
<td>92,323</td>
<td>5,129</td>
<td>1,393,276</td>
<td></td>
</tr>
<tr>
<td>Vehicle kilometres (million)</td>
<td>135.8</td>
<td>18,649.3</td>
<td>2,086.7</td>
<td>1,662.9</td>
<td>132.7</td>
<td>23,062.3</td>
<td></td>
</tr>
<tr>
<td>Occupant kilometres (million)</td>
<td>192</td>
<td>36,225</td>
<td>2,737</td>
<td>2,254</td>
<td>1,327</td>
<td>42,734</td>
<td></td>
</tr>
<tr>
<td>Involvement in casualty accidents</td>
<td>1,333</td>
<td>18,794</td>
<td>1,650</td>
<td>1,246</td>
<td>94</td>
<td>23,117</td>
<td></td>
</tr>
<tr>
<td>Occupant casualties</td>
<td>1,350</td>
<td>15,626</td>
<td>1,219</td>
<td>315</td>
<td>90</td>
<td>18,600</td>
<td></td>
</tr>
<tr>
<td>Accidents per '000 vehicles</td>
<td>47.34</td>
<td>16.61</td>
<td>12.11</td>
<td>13.50</td>
<td>18.32</td>
<td>16.59</td>
<td>2.9</td>
</tr>
<tr>
<td>Accidents per million vehicle km's</td>
<td>7.17</td>
<td>1.06</td>
<td>0.79</td>
<td>0.67</td>
<td>0.71</td>
<td>1.06</td>
<td>7.2</td>
</tr>
<tr>
<td>Accidents per million occupant km's</td>
<td>6.96</td>
<td>0.52</td>
<td>0.60</td>
<td>0.55</td>
<td>0.07</td>
<td>0.54</td>
<td>13.4</td>
</tr>
<tr>
<td>Casualties per '000 vehicles</td>
<td>47.94</td>
<td>13.51</td>
<td>6.94</td>
<td>3.41</td>
<td>17.55</td>
<td>13.35</td>
<td>3.5</td>
</tr>
<tr>
<td>Casualties per million vehicle km's</td>
<td>7.27</td>
<td>0.64</td>
<td>0.55</td>
<td>0.17</td>
<td>0.68</td>
<td>0.81</td>
<td>8.7</td>
</tr>
<tr>
<td>Casualties per million occupant km's</td>
<td>7.04</td>
<td>0.43</td>
<td>0.45</td>
<td>0.14</td>
<td>0.07</td>
<td>0.43</td>
<td>16.4</td>
</tr>
</tbody>
</table>

Notes: 1. Relative hazard = \[
\frac{\text{Rate for motorcycles}}{\text{Rate for all vehicles}}
\]
The typical motorcycle accident involves a collision with another road user: a motor car in about 70% of cases. This pattern is almost universal (Henderson, 1970; Herbert and Corben, 1977; Herbert and Humphreys, 1978 a and b, 1979; Honda, 1977; Hurt, Ouellet and Thom, 1981; Inayoshi, 1973; McLean, Brewer, Hall, Sandow and Tamblyn, 1979; Messiter, 1972; Newman, 1976; Reiss, Berger and Vallette, 1974; Vaughan, Pettigrew and Lakin, 1977; Waller, 1972; Whitaker, 1976; White, 1978). Furthermore White (1978) found that the motorcycle is most often travelling straight when struck by another vehicle (Figure 2.2), that the other vehicle is frequently turning across the motorcycle path (Table 2.2), and that the motorcycle is the striking vehicle two thirds of the time, as the front of the motorcycle is the impact point in 60% of accidents with other motor vehicles, 70% of accidents with fixed objects, and 55% of accidents with pedestrians (Figure 2.3). McLean et al. (1979) found that in 26% of accidents a vehicle turned across the path of the motorcycle, and Hurt et al. (1981) indicated 33.5% of this type. In the study by Hurt et al. (1981) the most frequent accident scenario involved the motorcycle travelling straight and the motor car making a left turn in front of the oncoming motorcycle. This occurred in 26.7% of the 900 accidents studied, and 33.4% of the multiple-vehicle collisions. The equivalent accident type in Australia would be the motor car making a right turn across the motorcycle path, as Australians travel on the left side of the roadway. Newman (1976) found that 23.5% of all accidents involving motorcycles occurred at right-angle intersections, and 19% of all motorcycle accidents were accounted for by a vehicle turning across the path of the motorcycle.

The motorcyclist is usually not to blame when involved in a collision with another vehicle. McLean et al. (1979) declared that in 78% of multi-vehicle motorcycle accidents studied the other vehicle should have yielded. White (1978) affirmed that for the two-vehicle accidents analyzed, police laid charges against 60% of the vehicle drivers. Barry (1970) found that the
Figure 2.2  Motorcycle direction of travel by accident type.
driver of the other vehicle was charged in 52% of the crashes, and suggested that in two-vehicle crashes, it is most frequently the motorist who is guilty of a violation. Figure 2.4 shows a culpability assessment of motorcycle involved accidents for Maryland (U.S.A.), due to Reiss et al. (1974).

Motorcycle accidents are generally located in urban/suburban areas. Hurt et al. (1981) studied a total of 900 motorcycle accidents in an area consisting of a wide variety of urban, suburban and rural regions, and 90% of the accidents occurred in the urban/suburban area. For the state of Victoria, 1976, 58% of fatal motorcycle-involved accidents occurred within Metropolitan Melbourne, and 64% of injury motorcycle-involved accidents occurred in this area (Australian Bureau of Statistics, 1976). Henderson (1970), in a study of 120 fatalities in New South Wales, indicated that 78% happened on roads within the 60 km/h speed limit applying to built up areas. Foldvary (1973) analyzed accident statistics for the state of Victoria collected in 1961, and reported that 71% of motorcycle accidents occurred in the Metropolitan area. Reiss et al. (1974) studied 1191 motorcycle accidents in 1973 in Maryland (U.S.A.), of which 70% occurred within urban area.

Under wet road conditions, it might be expected that motorcycles would be at greater risk of accident involvement. Carraro (1978) claimed that the majority of motorcycle accidents (84% to 96%) occur on dry roads. Reiss et al. (1974) affirmed that 91% of motorcycle accidents were in dry conditions, and Hurt et al. (1981) found adverse weather was not a factor in the majority of accidents; less than 3% involved wet roads. Hurt claimed that motorcycle traffic essentially disappears in adverse weather. However, for the motorcycle traffic that is on the roads, risks are increased. To assess the effects of wet weather, the proportion of the exposed population riding in these conditions which are involved in accidents is required. As an example, Watson and Lander (1974) found that 30% of 120 accidents
### Table 2.2. Vehicle Direction of Travel in Two Vehicle Accidents (White, 1978)

<table>
<thead>
<tr>
<th>Matrix lce Direction of Travel</th>
<th>Other Vehicle Direction of Travel</th>
<th>Merge</th>
<th>Reverse</th>
<th>Stopped</th>
<th>Pulling Away From Curb</th>
<th>Pulling Into Curb</th>
<th>Total Spec.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(9)</td>
<td>(12)</td>
<td>(88)</td>
<td>(15)</td>
<td>(2)</td>
<td>(1330)</td>
</tr>
<tr>
<td>Going Straight</td>
<td></td>
<td>(0.5)</td>
<td>(0.9)</td>
<td>(4.4)</td>
<td>(0.8)</td>
<td>(0.1)</td>
<td>(67.1)</td>
</tr>
<tr>
<td>%</td>
<td>(24.5)</td>
<td>(1.0)</td>
<td>(28.6)</td>
<td>(3.4)</td>
<td>(0.8)</td>
<td>(2.1)</td>
<td>(181)</td>
</tr>
<tr>
<td>Overtaking</td>
<td></td>
<td>(1.4)</td>
<td>(1.0)</td>
<td>(2.1)</td>
<td>(1.1)</td>
<td>(0.2)</td>
<td>(9.1)</td>
</tr>
<tr>
<td>%</td>
<td>(1.5)</td>
<td>(0.6)</td>
<td>(1.6)</td>
<td>(0.9)</td>
<td>(0.1)</td>
<td>(0.2)</td>
<td>(279)</td>
</tr>
<tr>
<td>Left Turn 1</td>
<td></td>
<td>(1.4)</td>
<td>(0.6)</td>
<td>(2.7)</td>
<td>(0.2)</td>
<td>(0.1)</td>
<td>(14.1)</td>
</tr>
<tr>
<td>%</td>
<td>(1.7)</td>
<td>(0.6)</td>
<td>(0.6)</td>
<td>(0.2)</td>
<td>(0.1)</td>
<td>(0.1)</td>
<td>(53)</td>
</tr>
<tr>
<td>Right Turn 1</td>
<td></td>
<td>(0.5)</td>
<td>(0.1)</td>
<td>(0.4)</td>
<td>(0.1)</td>
<td>(0.1)</td>
<td>(2.7)</td>
</tr>
<tr>
<td>%</td>
<td>(1.7)</td>
<td>(0.4)</td>
<td>(0.4)</td>
<td>(0.4)</td>
<td>(0.4)</td>
<td>(0.4)</td>
<td>(8)</td>
</tr>
<tr>
<td>U-Turn</td>
<td></td>
<td>(0.4)</td>
<td>(0.1)</td>
<td>(0.4)</td>
<td>(0.1)</td>
<td>(0.1)</td>
<td>(22)</td>
</tr>
<tr>
<td>%</td>
<td>(0.6)</td>
<td>(0.2)</td>
<td>(0.1)</td>
<td>(0.1)</td>
<td>(0.1)</td>
<td>(1.1)</td>
<td>(0.4)</td>
</tr>
<tr>
<td>Lane Change</td>
<td></td>
<td>(0.6)</td>
<td>(0.1)</td>
<td>(0.2)</td>
<td>(0.1)</td>
<td>(0.1)</td>
<td>(0.4)</td>
</tr>
<tr>
<td>%</td>
<td>(0.6)</td>
<td>(0.2)</td>
<td>(0.2)</td>
<td>(0.1)</td>
<td>(0.1)</td>
<td>(0.1)</td>
<td>(8)</td>
</tr>
<tr>
<td>Merge</td>
<td></td>
<td>(0.5)</td>
<td>(0.1)</td>
<td>(0.5)</td>
<td>(0.1)</td>
<td>(0.6)</td>
<td>(11)</td>
</tr>
<tr>
<td>%</td>
<td>(2.9)</td>
<td>(0.3)</td>
<td>(0.1)</td>
<td>(0.3)</td>
<td>(0.1)</td>
<td>(3.5)</td>
<td>(0.6)</td>
</tr>
<tr>
<td>Reverse</td>
<td></td>
<td>(0.5)</td>
<td>(0.1)</td>
<td>(0.2)</td>
<td>(0.1)</td>
<td>(0.1)</td>
<td>(0.4)</td>
</tr>
<tr>
<td>%</td>
<td>(2.9)</td>
<td>(0.3)</td>
<td>(0.1)</td>
<td>(0.2)</td>
<td>(0.1)</td>
<td>(0.1)</td>
<td>(8)</td>
</tr>
<tr>
<td>Stopped</td>
<td></td>
<td>(0.5)</td>
<td>(0.1)</td>
<td>(0.5)</td>
<td>(0.1)</td>
<td>(0.6)</td>
<td>(12)</td>
</tr>
<tr>
<td>%</td>
<td>(0.6)</td>
<td>(0.6)</td>
<td>(0.6)</td>
<td>(0.6)</td>
<td>(0.6)</td>
<td>(0.6)</td>
<td>(1981)</td>
</tr>
<tr>
<td>Pulling Away From Curb</td>
<td></td>
<td>(0.2)</td>
<td>(0.2)</td>
<td>(0.2)</td>
<td>(0.2)</td>
<td>(0.2)</td>
<td>(100.0)</td>
</tr>
<tr>
<td>%</td>
<td>(45.0)</td>
<td>(3.7)</td>
<td>(25.4)</td>
<td>(4.7)</td>
<td>(0.9)</td>
<td>(2.6)</td>
<td>(4.1)</td>
</tr>
</tbody>
</table>

Note: 1. Canadian study, vehicles travel on right side of roadway.
Figure 2.3. Motorcycle impact point distribution for selected accident types (White, 1978).
<table>
<thead>
<tr>
<th>CULPABILITY</th>
<th>TYPE 1 URBAN/INT</th>
<th>TYPE 2 URBAN/NON-INT</th>
<th>TYPE 3 RURAL/INT</th>
<th>TYPE 4 RURAL/NON-INT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MDAI</strong></td>
<td>O/V OPER= 100%</td>
<td>O/V OPER= 40%</td>
<td>O/V OPER= 0%</td>
<td>O/V OPER= 29%</td>
</tr>
<tr>
<td></td>
<td>M/C OPER= 0%</td>
<td>M/C OPER= 60%</td>
<td>M/C OPER= 100%</td>
<td>M/C OPER= 71%</td>
</tr>
<tr>
<td></td>
<td>(N= 10)</td>
<td>(N= 5)</td>
<td>(N= 1)</td>
<td>(N= 1)</td>
</tr>
<tr>
<td><strong>MD</strong></td>
<td>O/V OPER= 0%</td>
<td>O/V OPER= 49%</td>
<td>O/V OPER= 72%</td>
<td>O/V OPER= 45%</td>
</tr>
<tr>
<td></td>
<td>M/C OPER= 29%</td>
<td>M/C OPER= 45%</td>
<td>M/C OPER= 21%</td>
<td>M/C OPER= 43%</td>
</tr>
<tr>
<td></td>
<td>JOINT 2%</td>
<td>ENVIROM= 1%</td>
<td>M/C DEFECTS= 1%</td>
<td>ENVIRON= 11%</td>
</tr>
<tr>
<td></td>
<td>(N= 100)</td>
<td>M/C DEFECTS= 1%</td>
<td>(N= 100)</td>
<td>JOINT (M/C O/V) 3%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(N= 100)</td>
</tr>
</tbody>
</table>

**MDAI** = Multi-Disciplinary Accident Investigation data  
**MD** = Maryland Accident Data (U.S.A.)  
**O/V OPER** = Other Vehicle Operator  
**M/C OPER** = Motorcycle Operator

Figure 2.4 Comparison of accident culpability (Reiss, Berger and Vallette, 1974)
investigated by an on-the-spot investigation team in the U.K. occurred when the road was wet. They concluded that as roads are wet for one day in five (20%), the motorcycle is more accident-prone when the road is wet.

2.2.2 Braking Behaviour and Accidents

A motorcycle is very sensitive to the braking procedures employed by the rider. An erroneous braking manoeuvre can result in loss of control and consequently a spill. If the rider locks the rear wheel, the machine can slide out sideways, and unless the motorcyclist is skilled in handling this situation, a fall will result. A front wheel lock up will almost always result in the motorcycle capsizing, even in the hands of a skilled operator.

Table 2.3, from Watson and Lander (1974), shows that in dry conditions motorcycles are 1.22 times more liable to skid prior to an accident than other vehicles, and 1.69 times more liable in wet conditions. Under ice and snow conditions skidding is a problem with all vehicles, as the friction coefficient is then very low.

Inayoshi (1973) reported that in accidents where a motorcycle collided with another vehicle, the rider used the front and rear brakes together on 39.9% of occasions, front brake alone on 3.2%, and rear brake alone on 18.2%. He further stated that for single-vehicle accidents, the rider used front and rear brakes 28.8% of times, front brake alone 4.2%, and rear brake alone 13.4%. Table 2.4, reproduced from Hurt (1979), shows similar proportions for brake usage. It is seen that in accidents the front and rear brakes were used together in 24.8% of cases, front brake alone in 0.9%, and rear brake alone in 26.7% of cases.

McLean et al. (1979) found that front and rear brakes were applied in 19% of accidents studied, 6% used front only and 20% used the rear brake alone. Furthermore, experienced riders were
### TABLE 2.3 SKIDDING IN PERSONAL-INJURY ACCIDENTS IN GREAT BRITAIN ~ 1972 (Watson and Lander, 1973).

<table>
<thead>
<tr>
<th>Category</th>
<th>DD</th>
<th>WE</th>
<th>TP</th>
<th>SKMED</th>
<th>TP</th>
<th>TP</th>
<th>SKMED</th>
<th>TP</th>
<th>SKMED</th>
<th>TP</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Motorcycles</strong></td>
<td>4</td>
<td>147</td>
<td>11</td>
<td>3</td>
<td>18</td>
<td>12</td>
<td>957</td>
<td>27</td>
<td>568</td>
<td>1</td>
</tr>
<tr>
<td><strong>Other Vehicles</strong></td>
<td>20</td>
<td>423</td>
<td>9</td>
<td>1</td>
<td>18</td>
<td>11</td>
<td>721</td>
<td>16</td>
<td>8</td>
<td>531</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>24</td>
<td>570</td>
<td>20</td>
<td>1</td>
<td>18</td>
<td>1</td>
<td>684</td>
<td>43</td>
<td>58</td>
<td>1</td>
</tr>
</tbody>
</table>

### TABLE 2.4 COMPARISON OF FRONT AND REAR BRAKE USE IN COLLISION AVOIDANCE (Hurt, 1979).

<table>
<thead>
<tr>
<th>(rear Brake)</th>
<th>Not Equipped</th>
<th>Equipped</th>
<th>In At Accident</th>
<th>% Rear Determed</th>
<th>PN</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Motorcycles</strong></td>
<td>4</td>
<td>147</td>
<td>11</td>
<td>3</td>
<td>18</td>
</tr>
<tr>
<td><strong>Other Vehicles</strong></td>
<td>20</td>
<td>423</td>
<td>9</td>
<td>1</td>
<td>18</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>24</td>
<td>570</td>
<td>20</td>
<td>1</td>
<td>18</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(front Brake)</th>
<th>Not Equipped</th>
<th>Equipped</th>
<th>In At Accident</th>
<th>% Rear Determed</th>
<th>PN</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Motorcycles</strong></td>
<td>4</td>
<td>147</td>
<td>11</td>
<td>3</td>
<td>18</td>
</tr>
<tr>
<td><strong>Other Vehicles</strong></td>
<td>20</td>
<td>423</td>
<td>9</td>
<td>1</td>
<td>18</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>24</td>
<td>570</td>
<td>20</td>
<td>1</td>
<td>18</td>
</tr>
</tbody>
</table>
just as likely to fail to make full use of the braking potential of their machine (by using the rear brake only) as those who were relatively inexperienced. It should be noted that using the rear brake only significantly degrades the collision-avoidance performance of a motorcycle.

Wilkins (1969) estimated that in 5% of 140 accidents studied, the rider was thrown off as a result of wheel locking due to braking. Wilkins also stated that a further 50% would possibly not have occurred if the motorcycle brakes had been more efficient or had been applied earlier.

2.2.3 Stability and Motorcycle Accidents

A motorcycle has only two wheels and may be inherently unstable. In the absence of rider input and corrections the machine may ultimately capsize. A motorcycle under certain conditions will exhibit uncontrollable vibration behaviour. The characteristic modes of these vibrations are well documented. There are three dominant modes: (i) wobble, a high speed phenomenon consisting primarily of an oscillation of the steering assembly, (ii) weave, a coupled yaw, roll, steer oscillation which is usually well damped at medium speeds and lightly damped at low and high speeds, and (iii) capsize, an aperiodic motion, which is usually stable at low speed, and slightly unstable at medium and high speeds (Eaton, 1973; Roe and Thorp, 1976; Sharp, 1971; Weir, Zellner and Teper, 1978, Koenen and Pacejka, 1980).

(a) Loss of control

There is little evidence of stability problems in the accident literature. The relationship between motorcycle dynamic behaviour and accidents has still to be established. Identifying the contributing characteristics in accident causation would be a very difficult task. The greater proportion of accidents occur in urban areas with speed
TABLE 2.5 LOSS OF CONTROL MADE IN A MOTORCYCLE ACCIDENT STUDY (Hurt, 1979).

<table>
<thead>
<tr>
<th>Category Label</th>
<th>Absolute</th>
<th>Relative Freq.</th>
<th>Adjusted Freq.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capsize</td>
<td>2</td>
<td>0.2</td>
<td>0.6</td>
</tr>
<tr>
<td>Wobble</td>
<td>42</td>
<td>4.7</td>
<td>11.7</td>
</tr>
<tr>
<td>Weave</td>
<td>5</td>
<td>0.6</td>
<td>1.4</td>
</tr>
<tr>
<td>Lost Wheelie</td>
<td>2</td>
<td>0.2</td>
<td>0.8</td>
</tr>
<tr>
<td>Slide Out</td>
<td>9</td>
<td>1.0</td>
<td>2.8</td>
</tr>
<tr>
<td>High Side</td>
<td>202</td>
<td>22.3</td>
<td>56.2</td>
</tr>
<tr>
<td>Side in Turn</td>
<td>19</td>
<td>2.1</td>
<td>5.3</td>
</tr>
<tr>
<td>End Over</td>
<td>77</td>
<td>8.3</td>
<td>21.4</td>
</tr>
<tr>
<td>Unknown</td>
<td>4</td>
<td>0.4</td>
<td>MISSING</td>
</tr>
<tr>
<td>TOTAL</td>
<td>899</td>
<td>100.0</td>
<td>100.0</td>
</tr>
</tbody>
</table>

TABLE 2.6 RELATIVE INVOLVEMENT OF PILLION PASSENGERS IN MOTORCYCLE ACCIDENTS (Vaughan, Pettigrew and Lukin, 1977).

<table>
<thead>
<tr>
<th>Road Users riding motorcycles, by class</th>
<th>Motorcycles in the Sydney Metropolitan Area - Level Two Study</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed in Surveys (%)</td>
</tr>
<tr>
<td></td>
<td>Total</td>
</tr>
<tr>
<td>Riders</td>
<td>1305 (19.4%)</td>
</tr>
<tr>
<td>Pillion passengers</td>
<td>76 (6%)</td>
</tr>
<tr>
<td>TOTAL</td>
<td>1381 (100%)</td>
</tr>
</tbody>
</table>
TABLE 2.7 TYRE QUESTIONNAIRE RESPONSES (House of Representatives Standing Committee on Road Safety, 2 October 1979).

<table>
<thead>
<tr>
<th>Questions</th>
<th>Yes</th>
<th>No</th>
<th>Unsure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Have you had an accident because of a tyre/tyres?</td>
<td>33%</td>
<td>67%</td>
<td></td>
</tr>
<tr>
<td>Are you satisfied with the standard tyres as fitted to new motorcycles?</td>
<td>20%</td>
<td>69%</td>
<td>11%</td>
</tr>
<tr>
<td>Should there be standards for tyres?</td>
<td>81%</td>
<td>14%</td>
<td>5%</td>
</tr>
<tr>
<td>Is there enough information readily available to enable you to choose correctly the tyres for your bike?</td>
<td>21%</td>
<td>78%</td>
<td>1%</td>
</tr>
<tr>
<td>Where does most of your information on tyres come from e.g., friends, magazines, bike shops etc?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Do you feel you know enough to choose a tyre correctly?</td>
<td>63%</td>
<td>33%</td>
<td>4%</td>
</tr>
<tr>
<td>Do you think there are sub-standard tyres available?</td>
<td>90%</td>
<td>1%</td>
<td>6%</td>
</tr>
<tr>
<td>Do you think tyres are too expensive?</td>
<td>78%</td>
<td>18%</td>
<td>4%</td>
</tr>
<tr>
<td>Do you think tyres last long enough?</td>
<td>47%</td>
<td>48%</td>
<td>5%</td>
</tr>
</tbody>
</table>

The above questions were put to people at random, visiting motorcycle retailers in Brisbane on the 16th June, 1979.
limits less than 60 km/h, whereas the unstable weave and wobble modes are not normally excited at speeds less than 100 km/h. However there are a few cases reported. For example, Herbert and Corben (1977) and Herbert and Humphries (1978 a and b, 1979) reported that in 3 of 100 accidents studied, wobble was a casual factor. Table 2.5 gives a breakdown of the types of loss of control in motorcycle accidents (Hurt, 1979). Loss of control due to the motorcycle instabilities capsizes, wobble and weave together account for 5% of the accidents studied. Newman (1976) reported general loss of control in 8% of accidents (without further clarification).

(b) Pillion passengers

Waller (1972) said that pillion passengers figured more heavily in single-vehicle accidents than in multi-vehicle accidents (15% compared with 11%). Such passengers were also present in 60% of accidents caused by blowouts. Table 2.6, extracted from Vaughan, Pettigrew and Lukin (1977), indicates that a motorcycle is at 1.66 times the average risk of being involved in an accident when carrying a pillion passenger. Hurt et al. (1981) however, found that whereas passengers were involved in 17.1% of the 899 accidents analyzed, and in 14.8% of 3622 cases examined from traffic accident reports, exposure data showed that passenger-carrying motorcycles were 18.3% of the population at risk. This implies that there was no increase in risk due to the presence of a passenger.

(c) Tyres

Table 2.7 shows the results of a questionnaire organized by the Motorcycle Riders' Association, Queensland (House of Representatives Standing Committee on Road Safety, 1979). Thirty-three percent of respondents (sample size not known)
### TABLE 2.8 CONTRIBUTORY TYRE CONDITIONS (Hurt, 1979).

<table>
<thead>
<tr>
<th>CATEGORY LAST</th>
<th>CODE</th>
<th>ABSOLUTE FREQ.</th>
<th>RELATIVE FREQ.</th>
<th>ADJUSTED FREQ.</th>
<th>CUMULATIVE FREQ.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contributory Front Tire Condition</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>None</td>
<td>855</td>
<td>95.1</td>
<td>95.1</td>
<td>95.1</td>
<td></td>
</tr>
<tr>
<td>Puncture Flat</td>
<td>3</td>
<td>0.3</td>
<td>0.3</td>
<td>95.4</td>
<td></td>
</tr>
<tr>
<td>Blowout</td>
<td>1</td>
<td>0.1</td>
<td>0.1</td>
<td>95.6</td>
<td></td>
</tr>
<tr>
<td>Worn Smooth</td>
<td>4</td>
<td>0.4</td>
<td>0.4</td>
<td>96.0</td>
<td></td>
</tr>
<tr>
<td>Low Pressure</td>
<td>22</td>
<td>2.4</td>
<td>2.4</td>
<td>98.4</td>
<td></td>
</tr>
<tr>
<td>High Pressure</td>
<td>9</td>
<td>1.0</td>
<td>1.0</td>
<td>99.4</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>2</td>
<td>0.2</td>
<td>0.2</td>
<td>99.7</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>1</td>
<td>0.1</td>
<td>0.1</td>
<td>100.0</td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td>899</td>
<td>100.0</td>
<td>100.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Contributory Rear Tire Condition | | | | | |
| None | 834 | 92.3 | 92.9 | 92.8 |
| Puncture Flat | 12 | 1.3 | 1.3 | 94.1 |
| Blowout | 1 | 0.1 | 0.1 | 94.2 |
| Worn Smooth | 11 | 1.2 | 1.2 | 95.4 |
| Low Pressure | 22 | 2.4 | 2.4 | 97.9 |
| High Pressure | 12 | 1.3 | 1.3 | 99.2 |
| Valve Failure | 1 | 0.1 | 0.1 | 99.3 |
| Other | 5 | 0.6 | 0.6 | 99.9 |
| Other | 1 | 0.1 | 0.1 | 100.0 |
| TOTAL | 899 | 100.0 | 100.0 |
indicated they had had an accident because of tyre problems. Table 2.8 from Hurt (1979) displays the contribution to accidents caused by the condition of the front and rear tyres. The most common fault was low pressure in the front (2.4%) and rear tyres (2.4%). However these figures are meaningless without proper exposure data. Furthermore the effect of low pressure on the dynamic behaviour needs to be quantified. Hurt also found puncture flats totalled 1.3% of accidents for the rear tyre and 0.3% for the front tyre. Puncture flats for the rear tyre were most common when the motorcycle was carrying a passenger. Godley (1972) in an analysis of burst tyres prior to injury accidents on the M1 and M4 motorways in the U.K. found that motorcycles had the highest proportion of burst tyre, being 36% (the smallest proportion was lorries at 0.3%). Figure 2.5, drawn from an in-depth analysis of accidents (Herbert and Corben, 1977, Herbert and Humphries, 1978 a and b, 1979), shows that the lack of proper maintenance of tyres was considered to be the main contributing factor in only 2 of 100 cases (2%) and of secondary influence in 7% of cases. (66 accidents only are represented by the causal factors shown in Figure 2.5)

2.2.4 Handling and Accidents

The role of motorcycle handling in accidents is little understood. Suitable parameters to quantify desirable handling characteristics have yet to be determined, though some preliminary work has been done in this direction (Weir, Zellner and Teper, 1978; Chennahna and Koch, 1979). The influence of handling characteristics on accidents cannot be ascertained until they are well defined and measurable.

(a) Running wide on a turn

The most common accident in which handling may be directly involved is running wide on a turn. Honda (1977) reported
that running off roads in single-vehicle accidents occurred in about 9% of cases. The typical rider error in single-vehicle accidents is running wide on a corner due to excess speed or undercornering (Hurt, 1979).

Handling may play a greater role in high speed non-urban accidents. However few data are available on this type of accident.

(b) Familiarity with the motorcycle

White (1978) found that non-owners were over-represented in single-vehicle accidents, as is seen in Table 2.9.

In single-vehicle accidents, a disproportionate number of borrowers were involved in turning manoeuvres. The data indicated that 18% of the borrower’s single-vehicle crashes occurred in this manner (Barry, 1970). This difference is thought to reflect the borrower’s relative lack of skill with the vehicle, or his unfamiliarity with the handling behaviour of the machine.

(c) Machine modifications

A motorcycle’s dynamic behaviour is sensitive to the mechanical condition of the wheel bearings, steering head bearings, wheel alignment, tyre pressure, condition and design, amount of luggage carried and the presence of a windshield or fairing. It might be expected that modified motorcycles would be over-represented in motorcycle accidents. Hurt, Ouellet and Thom (1981) collected data on machine modifications for accident-involved motorcycles, and for the total motorcycle population. These results are presented in Table 2.10, together with calculated 'relative risks'. Relative risk (RR) is the proportion of motorcycles in the accident sample with a given modification divided by
Figure 2.5 Causal factors in accidents (source: Herbert and Corben, 1977, Herbert and Humphries, 1978a and b, 1979).
### TABLE 2.9 ACCIDENT-INVOLVED MOTORCYCLE OWNERSHIP (drawn from White, 1978)

<table>
<thead>
<tr>
<th>Accident type</th>
<th>Owner of motorcycle</th>
<th>Total</th>
<th>% total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Driver</td>
<td>Other Person</td>
<td>Company</td>
</tr>
<tr>
<td>Single-vehicle</td>
<td>710</td>
<td>159</td>
<td>47</td>
</tr>
<tr>
<td>% col total</td>
<td>24</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>Vehicle-vehicle</td>
<td>1961</td>
<td>315</td>
<td>59</td>
</tr>
<tr>
<td>% col total</td>
<td>65</td>
<td>59</td>
<td>50</td>
</tr>
<tr>
<td>Other</td>
<td>330</td>
<td>58</td>
<td>12</td>
</tr>
<tr>
<td>% col total</td>
<td>11</td>
<td>11</td>
<td>10</td>
</tr>
<tr>
<td>Totals</td>
<td>3001</td>
<td>532</td>
<td>118</td>
</tr>
</tbody>
</table>
### Table 2.10: Comparison of Motorcycle Modifications for Accident and Exposure Data (drawn from Hurt et al., 1981)

<table>
<thead>
<tr>
<th>Motorcycle Modification</th>
<th>Exposure Data %</th>
<th>Accident Data %</th>
<th>Relative Risk</th>
<th>Std. Dev. of estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front Suspension</td>
<td>10.6</td>
<td>10.2</td>
<td>0.96</td>
<td>0.11</td>
</tr>
<tr>
<td>Rear Suspension</td>
<td>14.1</td>
<td>19.1</td>
<td>1.35</td>
<td>0.12</td>
</tr>
<tr>
<td>Crash Bars</td>
<td>18.1</td>
<td>18.1</td>
<td>1.0</td>
<td>0.08</td>
</tr>
<tr>
<td>Sissy Bars</td>
<td>29.8</td>
<td>27.1</td>
<td>0.91</td>
<td>0.06</td>
</tr>
<tr>
<td>Seat</td>
<td>23.1</td>
<td>24.8</td>
<td>1.07</td>
<td>0.07</td>
</tr>
<tr>
<td>Windshield (with or without fairing)</td>
<td>19.5</td>
<td>12.0</td>
<td>0.62</td>
<td>0.06</td>
</tr>
<tr>
<td>Fairing</td>
<td>12.3</td>
<td>8.7</td>
<td>0.71</td>
<td>0.09</td>
</tr>
<tr>
<td>Handlebars</td>
<td>24.8</td>
<td>16.3</td>
<td>0.66</td>
<td>0.06</td>
</tr>
<tr>
<td>Exhaust System</td>
<td>27.3</td>
<td>30.1</td>
<td>1.10</td>
<td>0.07</td>
</tr>
</tbody>
</table>

Relative Risk = relative risk of being involved in an accident given that motorcycle modification
the proportion of the total population with that modification. RR thus measures the average risk associated with a given modification relative to the average risk for all motorcycles in the population (for which RR = 1). An RR of unity means that the motorcycle has an 'average' probability of being involved in an accident; an RR greater than unity implies above average accident probability; less than unity, below average (Fox, Good and Joubert, 1979 presented a useful discussion of the use of the relative risk concept). Table 2.10 also shows the standard deviation of the estimate of RR. The range RR ± SD represents approximately the 68% confidence interval for the calculated RR. From Table 2.10 it is seen that front suspension modifications (which include extended front forks) have little effect on accident involvement. However rear suspension modifications (stated as including installation of a large rear tyre and modified shock absorbers; but unfortunately no further details are given) resulted in the motorcycle having a relative risk of 1.35 ± 0.12, a significant (p<0.001) departure from the average value of 1.

The addition of a windshield and a fairing reduced the relative risk to 0.62 ± 0.06 and 0.71 ± 0.09 respectively. This modification is known in some cases to degrade the handling characteristics, particularly if the windshield is mounted directly to the forks of the motorcycle (Weir et al., 1978). The reduction of accident involvement may be related to the increased frontal area which improves conspicuity of the machine. McLean et al. (1979) found that alterations to the front suspension and to the handlebars were the most common modifications in their accident sample. They reported there were no accidents in which a rider was obviously disadvantaged by either extended forks or modified handlebars. Table 2.11 (Kraus, Riggins, Drysdale and Franti, 1973) shows an accident sample and a comparison group sample for vehicle modifications together with their relative risks, as defined above. There appears to be no significant change in risk resulting from the modifications.
### TABLE 2.11 RELATIVE RISK OF MOTORCYCLES WITH MODIFICATIONS
(drawn from Kraus et al., 1973)

<table>
<thead>
<tr>
<th>Type of Motorcycle Modification</th>
<th>Case Group</th>
<th>Comparison Group</th>
<th>Relative Risk</th>
<th>Std. Dev. of estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No.</td>
<td>%</td>
<td>No.</td>
<td>%</td>
</tr>
<tr>
<td>Modified engine</td>
<td>73</td>
<td>9.7</td>
<td>55</td>
<td>12.6</td>
</tr>
<tr>
<td>Front fork extended (250 mm)</td>
<td>39</td>
<td>5.2</td>
<td>19</td>
<td>4.3</td>
</tr>
<tr>
<td>Front fork extended (250 mm +)</td>
<td>20</td>
<td>2.7</td>
<td>13</td>
<td>3.0</td>
</tr>
<tr>
<td>Raised foot rests</td>
<td>31</td>
<td>4.1</td>
<td>23</td>
<td>5.3</td>
</tr>
<tr>
<td>Lowered seat</td>
<td>38</td>
<td>5.1</td>
<td>27</td>
<td>6.2</td>
</tr>
<tr>
<td>Modified handlebars</td>
<td>66</td>
<td>8.8</td>
<td>41</td>
<td>9.4</td>
</tr>
<tr>
<td>Sissy bar</td>
<td>38</td>
<td>5.1</td>
<td>37</td>
<td>8.5</td>
</tr>
<tr>
<td>Other modifications</td>
<td>42</td>
<td>5.6</td>
<td>52</td>
<td>11.9</td>
</tr>
<tr>
<td>No modifications</td>
<td>546</td>
<td>72.6</td>
<td>312</td>
<td>71.4</td>
</tr>
<tr>
<td>No. of respondents</td>
<td>752</td>
<td>100.0</td>
<td>437</td>
<td>100.0</td>
</tr>
</tbody>
</table>

Relative Risk = relative risk of being involved in an accident given that motorcycle modification.
2.3 CONCLUSIONS

(i) Approximately 75% of motorcycle accidents, and 70% of casualty accidents occur in the urban/suburban area where the speed limit is 60 km/h.

(ii) The most common motorcycle accident involves a collision with another motor vehicle (70% of cases)

(iii) With motorcycle-vehicle collisions, the other vehicle typically turns across the path of the motorcycle. This accident type is represented in about 30% of motorcycle-vehicle collisions.

(iv) When blame is apportioned for motorcycle-vehicle collisions, the driver of the other vehicle is usually responsible (60% of cases).

(v) When a motorcyclist brakes to avoid a collision the full braking potential of the machine is typically not realized. Front and rear brakes were used together in only about 25% of the accidents studied by Hurt (1979). If one brake alone is used, the deceleration of the motorcycle is reduced considerably, resulting in a higher impact speed and increased crash severity than if both brakes had been used.

(vi) Motorcycles that are on the road in wet weather have an increased chance of being involved in an accident. However wet weather does not appear to be a problem as between 91% to 97% of accidents occur on dry roads. Apparently motorcycle traffic essentially disappears in wet weather.
(vii) There is little evidence of stability problems in
accidents. This is probably due to the low speed at which
most accidents occur (less than 60 kn/h). There have been
some isolated cases reported in which the motorcycle
instabilities capsize, weave and wobble were involved
(3% to 5%).

(viii) The literature relating to pillion passengers and accident
involvement offer conflicting views. Vaughan et al.
(1977) found that a motorcycle with a pillion passenger
had 1.66 times the average risk of being in an accident.
On the other hand, the study by Hurt et al. (1981) shows
no increase in risk due to the presence of a passenger.
Barry (1972) found that pillion passengers figured more
heavily in single-vehicle accidents than multi-vehicle
accidents.

(ix) With regard to motorcycle tyres, one study found that
motorcycles had the highest proportion of burst tyres
prior to an injury accident on the M1 and M4 motorways in
the U.K. Apart from this work there was little evidence
to suggest that tyre pressures, condition and design were
important accident causation factors.

(x) In single-vehicle accidents, the most common handling
problem found in the accident literature was running wide
on a turn.

(xi) Borrowers are more involved in single-vehicle accidents
than in multi-vehicle accidents. This may be due to
unfamiliarity with the borrowed motorcycle's handling
behaviour.
(xii) Modifications to motorcycles do not have a great influence on accident involvement. In one study, however, rear suspension modifications were found to result in a relative risk of 1.35 ± 0.12.
3. MOTORCYCLE BRAKING

3.1 INTRODUCTION

A conclusion from Chapter 2 is that there is evidence of braking problems in accidents. Such problems were related to rider strategy in decelerating the motorcycle when trying to avoid an accident. In-depth accident studies revealed that motorcyclists used both brakes together in only half of the accidents in which braking was attempted. Inability to use both brakes means that the motorcycle does not decelerate at its maximum rate. If both brakes were used, some accidents might have been avoided, and the severity of others could have been reduced.

Following is a review of the literature specific to motorcycle brakes and associated problems.

3.2 MOTORCYCLE BRAKES AND PROBLEM AREAS

3.2.1 Disc Brake Performance In Wet Weather

Motorcycles today are almost universally fitted with disc brakes as original equipment. Disc brakes give the motorcycle the potential to stop rapidly in dry conditions. Furthermore, it is only under race conditions that disc brakes will exhibit fade problems (temperature induced loss of effectiveness). Their response to rider input is both predictable and controllable, which could explain motorcyclists' preference for this system. They are a low maintenance device and their appearance is aesthetically pleasing. However, their performance suffers considerably in wet conditions. The House of Representatives Standing Committee on Road Safety (HoR, 1978) said in paragraphs 65 and 67 of their report:
65. The deterioration in braking performance of disc brakes in wet weather is of concern and the Committee was informed that Japanese manufacturers are researching various ways to solve the problem. Research has indicated that mechanical sources of improving wet weather braking performance are the material of the disc and the pad.

67. Several witnesses referred to long delays in effective braking with several makes of front disc brakes in wet conditions... 

Irving (1978) referred to the increased response time of a wet disc brake after traversing a deep water splash. Initially on application of the brake lever, very little braking effect is felt, as a film of water exists between the disc and the pad. Then due to centrifugal effects of the rotating disc and the scraping action of the pads, the disc dries, and suddenly a large braking torque appears with possible disastrous results.

The Transport and Road Research Laboratory (TRRL, 1978 a) indicated that riders experience significant and inconsistent reductions in wet braking efficiency. Their research has shown that the reduction in braking efficiency is caused by the presence of a laminar layer of water on the surface area of the disc acted on by the pads. Any excess water beyond that necessary to form the laminar layer is in the form of a turbulent layer. This layer does not affect the brake performance directly, but acts as a reservoir to maintain the laminar sublayer. Robinson (1978 a and b) using an experimental laboratory disc brake dynamometer confirmed the increase in stopping time attributable to a wet disc. Using the same brake line pressures, the wet disc took between two and three times as long to stop as a dry disc.
As well as an increased response time for a wet disc, the level of force input from the rider to obtain a brake torque similar to that for a dry disc is increased by a factor of approximately two. Work at Honda Research and Development, Japan, reported by Wigan (1977) has shown that the rider needs to apply double the pressure on the disc brake lever in wet conditions – a reaction which many experienced motorcyclists find very difficult as a result of their trained reactions linked to dry conditions. Figure 3.1 shows these disc brake characteristics schematically. TRRL leaflet LF697 (1978 a) stated that riders are not able to judge the amount of brake application pressure required to provide a desired level of deceleration and because the road surface is also wet, overbraking can lead to wheel locking and loss of control.

It would appear that a solution to wet weather disc brake performance might be available, based on experimental work at TRRL with sintered metal disc pads. The performance of such pads in dry conditions is equal to that of organic pads. They give adequate wear rates, and the stopping distances when the discs are wet are little different from that when dry, as is indicated by Figure 3.2. However problems have been encountered with boiling brake fluid, and crazing of hard-chromed cast iron discs. These problems can be overcome by using a special hydraulic fluid, insulating the sintered pads from the wheel cylinder piston, and using stainless steel discs. These factors will make it difficult for sintered pads to be generally available as a change-over item for existing motorcycles, but manufacturers could be encouraged to market them on new machines.

3.2.2 Australian Design Rule Number 33 - Motorcycle and Moped Braking Systems

The Australian Transport Advisory Council has recommended to Commonwealth and State Governments that all motorcycles and mopeds manufactured on and after 1 March 1976 should comply with
Australian Design Rule No. 33 - Motorcycle and Moped Braking Systems. (Department of Transport, 1980). Aspects of the testing procedure in this design rule are considered to be inadequate as discussed below. ADR 33 is closely modelled on the American Federal Motor Vehicle Safety Standard (FMVSS) No. 122 (U.S. D.O.T., 1977-78) and some of the FMVSS 122 revisions have been included in ADR 33.

Ervin et al. (1977) developed a test methodology for the measurement of motorcycle braking performance. They employed a technique whereby the motorcycle was towed behind a utility truck with a torsionally-stiff tow coupling, as shown in Figure 3.3.

They began with the premise that FMVSS 122 was fundamentally inadequate in areas relating to the measurement of motorcycle braking performance, and furthermore the test rider was exposed to a potentially hazardous situation. It was demonstrated that the tow method adequately evaluates the performance of a motorcycle brake system including effectiveness, burnish, thermally induced fade and wet brake performance.

Wigan (1978) indicated two additional inadequacies of ADR 33, namely:

(i) lack of specification of road surface condition during testing (FMVSS 122 has been amended to this end)

(ii) the water conditioning procedure for wet brake testing does not model the real world situation accurately. ADR 33 calls for submerging the complete brake assembly in water for two minutes.

The wetting procedure makes it virtually impossible for zero-pressure-gradient seals on some drum brakes to pass the wetted brake test even though they may perform satisfactorily in
Figure 3.1. Response characteristics of disc brakes (Wigan, 1977).
Figure 3.2. Sintered pad performance (Transport Road Research Laboratory, 1978 a).
service. Moreover this procedure favours disc brakes, as after submerging the brake, the test requires that the motorcycle be accelerated at the maximum rate to the specified test speed. During this interval the water on the disc is flung off, and testing experience has shown the disc performance to be virtually unaffected (VIPAC, 1979). With road conditions in wet weather, the disc is continuously saturated with rain, spray from the tyres and spray from the mudguards. It is under these conditions that disc brake performance rapidly deteriorates.

3.2.3 Linked Braking Systems

Irving (1978) is of the opinion that many modern motorcycles are overbraked and points out that there has been a trend towards very large brakes, the control of which requires only finger tip pressure. In an emergency situation, an inexperienced rider is likely to grab the brake lever with all his power thus causing the front wheel to lock and the machine to lose stability. Furthermore Irving shows that to obtain the minimum stopping distance both front and rear brakes must be used together. It is interesting to note that Irving mentions a brake system employed on a Rudge-Whitworth motorcycle in the late 1920s called 'proportionate braking'. Both the front and rear brakes were applied via a single pedal control. A control lever was also supplied for the front brake. A similar system has recently been reintroduced by the Italian motorcycle manufacturer 'Moto Guzzi' (Manicardi, 1979). This system was designed in conjunction with the brake manufacturer 'Brembo'. Motorcycles fitted with it have two front discs and one rear disc. The left side front disc and the rear disc are hydraulically linked together and are operated by a foot lever. The other front disc is operated by a handlebar lever. Figure 3.4 shows a publicity pamphlet (Moto Guzzi, 1979) which displays expected performance using the integral braking system. However this represents a subjective evaluation, and is not the result of appropriate testing.
Figure 3.3. Tow-test apparatus (Ervin, MacAdam and Watanabe, 1977).

Figure 3.4. Traditional braking compared to integral braking (Moto Guzzi, 1979).
Figure 3.5. Brake force distribution of simple linked brake system (Manicardi, 1979).

Figure 3.6. Pressure distribution of fixed shear rate pressure regulator valve (Manicardi, 1979)
Distribution of the braking force in an integral system with variable load regulator

Braking force on front wheel

Figure 3.7 Brake force distribution with variable proportion linked braking system (Manicardi, 1979).
Ervin, MacAdam and Watanabe (1977) conducted a study to evaluate FMVSS 122, and as a part of this work motorcycle manufacturers were requested to give their views on the evolution of brake technology. Moto Guzzi's contribution consisted of engineering calculations in support of their integral brake system. Two errors were made in the computations which to a certain extent compensated for each other (Ervin et al. 1977). The Moto Guzzi integral braking system has been modified twice since it originally appeared in 1973. The system which Ervin et al. analyzed was the first version, in which proportioning of hydraulic pressure was fixed at 1:1 to front and rear disc. The differing brake torque requirements were accomplished via wheel radius, disc radius and pad friction coefficient variations. The braking force distribution is shown in Figure 3.5. This system suffered from wheel locking problems. Moto Guzzi have modified the simple system and included a fixed shear rate valve, the behaviour of which is illustrated in Figure 3.6. Manicardi (1979) published a paper on this system in which the errors made in the submission to Ervin et al. were corrected. Manicardi includes information about, and the brake force distribution for, an integral system with a variable load regulator. The distribution characteristics are shown in Figure 3.7. This system would appear to have ideal characteristics. Moto Guzzi motorcycles sold in Australia do not have this variable load regulator fitted to them. At the time of writing, no further information was available on this system.

The House of Representatives Standing Committee on Road Safety (1978) recommended in paragraph 68:

68. Operation of front and rear brakes together by applying the correct proportion of braking effort to each wheel is a skilled operation of particular concern even to experienced riders. Skidding is a particularly hazardous situation to be avoided on a motorcycle as directional control of the vehicle is
lost and a spill is extremely likely. Many experienced riders are consequently frightened to use their front brake and are thereby more than doubling their braking distance in an emergency by using only the rear wheel brake. The Committee therefore recommends that:

* a requirement for licensing be a demonstration of the effective use of all brakes fitted to the motorcycle particularly the front brakes; and

* the Commonwealth Department of Transport develop advisory performance specifications for this test.

The report recommends in paragraph 70:

* experiments be undertaken to assess the physical performance of, and the ability of riders to make better practical use of, coupled braking systems as exemplified by Moto Guzzi with a view to encouraging wide use of this type of system if shown to demonstrate an added margin of safety.

3.2.4 Antilock Braking Systems

Watson and Lander (1974) established that motorcycles are more accident prone than other motor vehicles while the road is wet, and that skidding is a significant factor in these accidents. This work prompted TRRL to investigate antilock braking for motorcycles. Watson, Lander and Miles (1976) said that in 1974 a total of some 7000 motorcycle accidents involving personal injury in the United Kingdom involved skidding on both dry and wet roads. They adapted an experimental antilock brake system originally designed for cars by Mullard Ltd. for motorcycle use. Their research showed that, on a range of surfaces with friction coefficients down to 0.3, motorcycles between 90-225 kg can be
stopped using front wheel braking only without wheel locking, provided they are fitted with the antilock system, and that the performance on good surfaces is not impaired. Some measure of cornering could also be undertaken at the same time as braking on the most slippery surfaces. The improvement that could be expected by the use of an antilock brake system is indicated in the braking distance diagram, Figure 3.8.

Wilkins (1969) investigated in detail 140 accidents involving motorcycles and found that in about 50% of cases the rider was thrown off as a result of wheel locking due to brake application. It was estimated that a further 50% of accidents studied would possibly not have occurred if the motorcycle brakes had either been more efficient or had been applied earlier. Wilkins established that 10% of motorcycle accidents might be prevented through fitting antilock brakes.

Antilock brake systems suitable for motorcycles have now been at the prototype development stage for about 10 years. There are three fundamental types of antilock brake systems:

(i) slip ratio control — whereby the wheel velocity and vehicle velocity are monitored to allow a predetermined amount of slip between the two.

(ii) wheel deceleration control — the system measures the wheel deceleration and compares it to a preset maximum allowable level.

(iii) jerk control — when the rate of change of deceleration approaches zero, the braking force is a maximum.

The Mullard system investigated by TRRL measured wheel deceleration, and Miemert (1974) applied a similar system to a heavy motorcycle. He reported the system to be an extremely
Figure 3.8 Antilock brake performance (Transport Road Research Laboratory, 1978,b).
desirable motorcycle component. However this contention was apparently not supported by exhaustive experimental testing. The only results presented in his report were a comparison between the antilock system and the braking performance of a locked wheel.

Manion and Tenny (1975) presented results of a feasibility analysis using jerk to control the brake lock-unlock sequence, and cited advantages as:

(i) yields consistent indication of the maximum friction coefficient, which is a function of wheel slip ratio. Peak friction coefficient occurs when the rate of change of deceleration (jerk) is zero

(ii) does not compromise system performance for varying road conditions

(iii) control system is simpler

(iv) levels of jerk are high; axis crossing is easy to discriminate

However to implement the proposed system, a suitable sensor to measure jerk still had to be developed.

Aoki (1975) investigated a deceleration-sensing antiskid braking system fitted to a Honda CB 350. His test results show that the antilock system significantly improved stopping distance compared to a locked wheel. However the stopping distances are similar to the no-antiskid device, no-locked wheel condition. This system was apparently in early development stages in 1975.

Weir, Zellner and Teper (1978) conducted experimental work to evaluate the Mullard antilock system as fitted to a Norton 850 motorcycle by TRRL. A series of straight line and cornering/braking tests were undertaken using this system and a
conventional system. Two different road surfaces were used, being dry brushed concrete, and a wet sealed black top surface. The performance of the antilock system was generally superior. On the dry brushed concrete, it gave results nearly the same as those achieved by an expert rider with a motorcycle fitted with a conventional system. An 'open-loop' testing procedure was also used. Pressure limiters were installed in the brake lines, which could be pre-set to give theoretical maximum performance. On the low-coefficient wet surfaces, performance with the antilock system was significantly better than that which could be achieved by either an expert rider or suitably tuned open-loop procedures.

Figure 3.9 shows the results from these experiments. The major advantage of the antilock system is seen to be on low skid number surfaces. Motorcycles are seldom ridden when these conditions exist (Hurt et al., 1981). However they are very dangerous when encountered.

3.2.5 Brake System Modulability

Motorcycle brakes are a dynamic system which have response characteristics characterized by a rider input force-deceleration hysteresis loop (Zellner, 1980). These properties vary from machine to machine. The force/displacement or 'stiffness' properties of the brake system measured at the control lever define its 'feel' properties. Zellner (1980) observed:

'Feel properties are the primary means by which the rider senses and controls the activity by his limbs on the manipulators ... So, manipulator feel properties which interface with the limb are of interest'.

It is the combination of feel properties and dynamic response characteristics of a brake system that will influence a riders'
Figure 3.9 Wheel lockup and capsize in braking manoeuvres (Weir Zellner & Teper, 1978).
impression or rating of it, and moreover his ability to modulate and control deceleration.

Motorcycle magazine road tests publish stopping distance figures as a measure of brake system performance. The variations of brake dynamic response characteristics and rider ratings are not reflected in stopping distance tests. The following information extracted from 23 road tests from the Australian magazine TWO WHEELS supports this contention:

Initial speed 100 km/h, mean stopping distance = 36.4 m, std. dev. = 2.75 m
Initial speed 60 km/h, mean stopping distance = 12.14 m, std. dev. = 1.43 m

The standard deviation for both speeds is small when experimental errors and variations due to different tyres and road surfaces are considered. The data suggest that the motorcycles tested all had similar maximum deceleration capabilities despite the wide variations in subjective ratings of the brakes given for these machines (cf., Figure 4.20). The average deceleration represented by the mean stopping distance is 1.08 g for 100 km/h and 1.17 g for 60 km/h initial speed.

The derivation of simple equations to predict motorcycle deceleration is given in Appendix A. It is shown that when both front and rear brakes are used together up to the limit of the available tyre-road friction coefficient (μ), the maximum attainable deceleration is μg m/s². When only one of the brakes is used, up to the friction limit, the maximum deceleration is reduced considerably. A plot of percentage of available deceleration versus μ (using the data for six motorcycles from Rice, Davis and Kunkell, 1976) is shown in Figure 3.10. With surfaces of characteristically high μ (dry bitumen μ = 1), using the rear brake alone will realize approximately 45% of an average motorcycles' braking potential. The situation is generally
Figure 3.10 Percentage of available deceleration versus friction coefficient (see Appendix E)
slightly worse with large machines and better with small machines, due to differing geometrical configurations. On the basis of a brake reaction time of one second (Johansson and Rumar, 1971), then typically only one second will be available for effective deceleration, given that on average a motorcyclist has two seconds for collision avoidance (Hurt, 1979). Further, if the initial speed is assumed to be the urban/suburban limit of 60 km/h (where most accidents occur), then using both brakes will result in an impact speed of 25 km/h; if using the rear brake only, 44 km/h. The kinetic energy of the vehicle at 44 km/h is about three times that at 25 km/h, which would result in a collision of much greater severity than if both brakes had been used. It was concluded in Chapter 2 that many motorcyclists do not use both brakes in an accident situation. The reasons for this are not known; it could be due to a fear of locking the front wheel, or due to a poor understanding of the correct procedure for efficient stopping.

As yet the dynamic behaviour and transfer characteristics of the motorcycle brake control system have not been identified. Furthermore, the ergonomic capabilities of the human operator for this control task are not yet known. There is a pressing need to obtain such data so that brake systems may be designed to maximize the rider's ability to control deceleration and minimize wheel locking. These requirements apply equally to the linked braking system. The linked system has an inherent advantage in that it forces the motorcyclist to use both front and rear brakes simultaneously, with obvious advantage in an accident situation.

3.3 CONCLUSIONS

(1) Motorcycle disc brake performance in wet weather is not satisfactory due to slow response, the high input force levels required and variable and unpredictable responses. Sintered metal pads appear to offer considerably improved
performance. However only one manufacturer as yet incorporates them as original equipment, and they are not available as retro-fit items in Australia.

(ii) *Australian Design Rule 33 'Motorcycle and Moped Braking Systems' has areas which are inadequate in relation to measuring brake performance in wet conditions. This design rule is in need of modification so as to more accurately model actual wet weather braking conditions.*

(iii) Linked braking systems appear to offer considerably better braking performances for unskilled operators. The variable proportioning system ( mooted by Moto Guzzi but not currently available in Australia) appears to have ideal characteristics. However, there is a lack of published information on experimental or in-service performance of linked brake systems.

(iv) Antilock brakes offer excellent braking performance in wet, slippery conditions, virtually independent of the operator's skill level. They are still in developmental stages, and are not yet commercially available.

(v) Motorcycle brake 'feel' and response behaviour has not yet been properly quantified. Furthermore, the ergonomic capabilities of the rider are still to be understood. Work in this area is urgently required in order that brake systems may be designed which will give most riders the confidence and ability to realize the full deceleration capacity of their machines.
4. STABILITY AND HANDLING CHARACTERISTICS

4.1 MATHEMATICAL MODELS OF RIDER/MOTORCYCLE SYSTEM

The modelling of the rider/motorcycle system has developed from the analysis of bicycle-alone dynamics. This knowledge was extended and applied to motorcycle-alone motions and, more recently the rider has been included as an active part of the dynamic system.

4.1.1 Motorcycle-alone Dynamics

The first significant work on the stability of the motion of a bicycle was that of Whipple (1899). He discussed the general motion of a bicycle with circular wheels making point contact with the ground, and he was able to identify dynamic instabilities with the model. Pearsall (1922) and Kondo, Nagaoka, and Yoshimura (1963) made further contributions to the analysis of the stability of bicycle.

Wilson-Jones (1951) made the earliest significant contribution towards understanding the dynamics of a motorcycle. He described roll and steering wobble instabilities, and recognized that the generation of cornering forces resulted primarily from camber rather than slip angle for single-track vehicles. As well, he proposed that it was necessary to supply a negative steer torque to initiate a turn, a view which was very controversial at the time but is now well recognized.

The first complete and concise mathematical model of lateral motorcycle dynamics is due to Sharp (1971). His model consisted of a vehicle with two rigid frames joined at the steering axis, with the wheels being represented by rigid discs each making point contact with the road. Tyre forces were represented as linear functions of wheel camber and slip angle. The rider was considered to be a rigid mass lumped with the rear frame. The
Figure 4.1 Effect of forward speed on weave and wobble modes
(Weir, Zellner and Teper, 1978)

Figure 4.2 Roll mode divergence (Weir Zellner and Teper, 1978)
machine moved at constant speed with degrees of freedom in side-slip, yaw and roll. The equations of motion were linearized and the eigenvalue problem was solved with a digital computer. The model showed that the motorcycle had three physically significant modes. These modes are illustrated in Figure 4.1 by way of root loci, with motorcycle forward speed as a parameter (Weir, Zellner and Teper, 1978). The mode for which the steer angle is the most significant component of the eigenvector is called the wobble mode, and becomes unstable at high speeds for this particular machine. The weave mode consists of a coupled roll, steer and yaw oscillation and with this machine is seen to be unstable at both very low and very high speed. The frequencies of these modes are such as to put them beyond the control abilities of a rider, should they become unstable. The capsize mode is aperiodic. At low speeds it is usually stable. At higher speeds it becomes mildly divergent, thus requiring continuous control by the rider. The inverse time constant for this mode is illustrated in Figure 4.2.

Sharp (1974) extended his original model to investigate frame flexibility effects. He also investigated the effect of acceleration and deceleration on stability (Sharp, 1976 a) and the influence of the suspension system on weave mode oscillations (Sharp, 1976 b). Sharp and Alstead (1980) looked at the influence of structural flexibilities on straight running stability. There have been investigations of motorcycle dynamics by many other workers (Eaton, 1973; Ellis and Hayhoe, 1973; Segel and Wilson, 1977; Verma, 1978; Watanabe and Segel, 1980; Koenen and Pacejka, 1980). It can be concluded that motorcycle-alone dynamics are now reasonably well understood. However the main uncertainty with this work would appear to rest with accurate representation of tyre dynamics and the lack of empirical data to describe motorcycle tyres. Furthermore there have been only a few attempts to experimentally validate the motorcycle dynamic models. These areas still require further attention.
The following practically significant implications for motorcycle frame design can be drawn from the motorcycle-alone dynamic studies:

* **Wobble mode is most sensitive to steering damping** (Sharp, 1971)
* a high speed motorcycle frame should have the rear frame centre of gravity low and as far forward as possible, and the front frame centre of gravity as far back as possible (Sharp, 1971)
* an increase of torsional flexibility in the rear forks reduces the weave damping at medium and high speeds (Sharp, 1974)
* acceleration has a significant stabilising influence on the capsize mode (Sharp, 1976 a)
* the pitch mode natural frequency should be kept away from the weave mode frequency to prevent coupling of these two modes during cornering manoeuvres (Sharp, 1976 b)
* for large motorcycles, the torsional stiffness of the rear swinging arm suspension member should be of the order of at least 1.2 kNm/rad to minimise weave mode oscillations (Sharp, 1974)
* for a machine of conventional frame geometry, the optimum rear frame torsional stiffness will lie in the region of 80 kNm/rad, provided the front forks are stiff laterally (greater than 200 kN/m) This value should make wobble mode damping constant throughout the speed range of the motorcycle and of an adequate level (Sharp and Alstead, 1980)

4.1.2 Modelling of Rider/Motorcycle System

The first published analysis of rider/motorcycle dynamics was that of Weir (1972). At all but very low speeds, Sharp (1971) predicted that the roll mode will be unstable so that without rider control inputs, the motorcycle will fall over. Weir argued
Figure 4.3 Motorcycle rider control model (Weir, Zellner and Teper, 1978).
that the inclusion of the rider and his actions in the analysis of motorcycle dynamics is essential to a complete understanding of the system behaviour. The rider's control action, aimed at stabilising the roll behaviour, modifies the vehicle's effective stability and disturbance response characteristics.

Weir stated that for the manual vehicular guidance and control task, the requirements are to follow the desired path and reduce any path errors to zero in a stable, rapid and well-damped manner. He found that rider upper-body lean angle could be used for 'outer' loop control of heading and lateral position. To control roll angle, the rider's best strategy was to use steer torque. The 'inner' loop of roll angle is therefore central to the handling qualities of the vehicle. Figure 4.3 shows the rider control model developed by Weir.

Rice, Davis and Kunkel (1976) used a non-linear model of the motorcycle/rider system with eight degrees of freedom to simulate motion in straight line running, constant speed turns and lane-change manoeuvres. An instrumented motorcycle was used to obtain experimental data. The simulated rider required more time and distance to execute a lane change than did the actual rider. They concluded that further modifications to the simulation were necessary to include suspension effects, braking and acceleration capability, rider model improvements, and a more sophisticated tyre model.

Rice and Kunkel (1976) performed supplementary investigations to those of Rice et al. (1976) using the lane change manoeuvre, including both simulation and experimental work. They attempted to cover rider influences to a greater depth, and to complete the investigation of several motorcycles in a simulated lane change manoeuvre. A plan view of the path used for lane change is shown in Figure 4.4. Figure 4.5 gives a direct comparison of the simulated performance of the different motorcycles with respect
Figure 4.4 Lane change manoeuvre, plan view (Rice and Kunkel, 1976).

Figure 4.5 Path comparisons and speed effects in lane change manoeuvre (Rice and Kunkel, 1976).
to the lane change path. It can be seen that the paths are very similar (results for smallest and largest motorcycles only have been shown).

Weir, Zellner and Teper (1978) used a non-linear motorcycle/rider model in analyzing handling response and performance. The simulation program provides for all-axis, large amplitude motions of the vehicle. These include lateral directional motions, longitudinal motions, coupled lateral and longitudinal motions, and coupled lateral and longitudinal response. Structural compliances in the front fork assembly and the rear swing arm are represented. Provision is also made for open and closed-loop rider control actions, involving handlebar steer torque and rider upper body lean. The model is intended for analysis of wobble, cornering weave, roll over, incipient spins, braking in a turn, and evasive manoeuvres.

Figure 4.6 shows results of a simulated entry into a steady turn for a Honda CB 360 motorcycle and rider. Figure 4.7 shows the rider model used in the simulation. The command input was a ramp of roll angle $\gamma_c$ as shown in Figure 4.6. The steady state roll angle of 0.05 rad corresponds to a lateral acceleration of only 0.05 g. This is a mild manoeuvre which does not test the non-linear features of the simulation.

At present the non-linear simulation has very limited application, as all but one of the gains in the rider model are unquantified. Extensive analysis is required to put values to these gains, and then further experimental work would be required to validate them. However, a validated rider/cycle simulation would be an extremely valuable tool for safe and economical testing of the influence of a variety of machine and rider skill variables on handling performance.
Figure 4.6 Non-linear rider/motorcycle simulation during transition to steady turn (Weir, Zellner and Tepet, 1978).
Figure 4.7 Rider model used in non-linear simulation (Weir, Zellner, and Teper, 1978).
Wilson-Jones (1951) conducted an experimental investigation into rider behaviour in a turn, and identified rider strategies. The rider first steered away from the intended turn in order to set up the appropriate roll angle. This understanding was controversial at that time, as evidenced by the published discussion at the conclusion of the paper. Hurt (1973) experimentally established that Wilson-Jones' understanding of the cornering manoeuvre was correct. Hurt pointed out that very few riders were aware of how they made a turn, and that in an accident situation the rider may well turn his machine into the obstacle as he tries to steer away from it.

Watanahe and Yoshida (1973) investigated evasive handling performance and braking of motorcycles. The test method employed involved the rider heading towards an obstacle. At a measured distance from the obstacle a signal lamp indicated to the rider to veer left or right, as shown in Figure 4.8. The tests were conducted at 50 km/h, 80 km/h and 100 km/h using three different motorcycles (small, medium and large) with riders of varying experience (and skill). Figure 4.9 shows the required evasion distance versus speed for all riders and all motorcycles. The distance required for avoidance increases roughly in proportion to the increase in velocity. Rider skill is a more significant factor than motorcycle size in determining emergency handling performance. Low skilled riders required 15-20% greater distance to avoid the test obstacle than skilled riders.

Watanahe and Yoshida (1973) defined an 'avoidance ability coefficient' as the quotient of the distance required for evasion and the test velocity. Avoidance ability coefficient was used to compare the performance of different riders and motorcycles. On this basis the 125 ml machine had the lowest performance of the three motorcycles, while the 350 ml and the 750 ml machines behaved similarly. It was therefore concluded that it could not
Figure 4.8 Plan of obstacle avoidance manoeuvre (Watanabe and Yoshida, 1973).

Figure 4.9 Required evasion distance versus speed in the obstacle avoidance manoeuvre (Watanabe and Yoshida, 1973).

Figure 4.10 Effects of machine and rider skill on avoidance ability coefficient (Watanabe and Yoshida, 1973).
Figure 4.11 Comparison of evasive handling and braking manoeuvres

Figure 4.12 Evasive paths of an automobile and a motorcycle (Watanabe and Yoshida, 1973).
be assumed that a large and heavy motorcycle would be inferior to a small light motorcycle in emergency handling performance. These effects, along with rider skill, are shown in Figure 4.10.

Tests were also conducted to determine straight-line stopping distance when using the brakes. This enabled the comparison of evasive handling and braking shown in Figure 4.11. Braking distance increases in proportion to the square of the velocity. The tests showed that at 30 km/h, braking and avoidance required the same distance. At higher speeds, the braking distance is longer. It was concluded that, at speeds encountered in normal traffic conditions, evasion may be a better strategy than braking to avoid obstacles.

Motorcycles are generally considered to be more manoeuvrable than automobiles. Figure 4.12 shows the avoidance paths taken by a motorcycle and an automobile. From these tests Watanabe and Yoshida concluded that a motorcycle should not be considered more manoeuvrable than an automobile, because of the relatively long distance required by the motorcycle to establish the roll angle for a turn.

Weir, Zellner and Teper (1978) conducted analytical and experimental studies of the handling responses and performance of five different motorcycles. Five test riders were used in the experiments. They had a wide range of experience, skill and age. The machines used for this work were a Honda 125, a Kawasaki 250, a Honda 360, a Norton 850 and a Harley Davidson 1200. Steady turn single lane change, cornering and braking, and cornering and accelerating tests were performed. Data collected included rider inputs, vehicle motions, and rider subjective evaluation of motorcycle performance.

The steady turn test was used to measure motorcycle control gains under a variety of operating conditions.
The performance measures evaluated included the ratio of steer torque to cycle roll angle and the ratio of steer torque to yaw velocity (which both relate to the rider providing roll stability and damping); the ratio of yaw velocity to steer angle (with its variation in forward speed providing the 'under/over-steer' characteristic as commonly used with automobiles); and the ratio of steer torque to steer angle (measuring the steering 'feel' properties).

The small Honda 125 showed substantial oversteer, and the large Harley Davidson 1200 exhibited large understeer. The motorcycles with neutral to modest oversteer properties were rated more highly by the test riders. Correlations were also made between rider ratings and total directional damping, defined as:

$$\text{Total Damping} = 2\xi_1 \omega_1 + 1/T_c$$

where $\xi_1$ = weave mode damping ratio
$\omega_1$ = weave mode natural frequency
$T_c$ = capsize mode time constant

This factor is said to be a measure of the low and mid-frequency damping which is important to rider control, and therefore does not include the wobble mode and other high frequency effects. It appeared that riders preferred more total damping in the mid-speed range. Vehicles with total damping that decreased too much at high speed were not favoured. This corresponds to the weave mode destabilising at high speed.

Path performance of the motorcycle was also evaluated. The measure used was the root-mean-square (r.m.s.) displacement of the motorcycle from a prescribed circular track, measured with a downward-pointing movie camera attached to the motorcycle. This r.m.s. path deviation showed no variation with speed or with motorcycles for a given level of lateral acceleration, which
illustrates riders' abilities to adapt to changes in vehicle
dynamic behaviour. Path performance worsened as lateral
acceleration was increased.

There was a lack of simple correlation between path
performance and stability factor, total directional damping or
capsize mode inverse time constant across motorcycles. Further
analytical work and experimental investigation was recommended.

The single lane change test was used to study the maneuvring
performance of the motorcycles and the rider/cycle system because
it emphasises the transient response of the vehicle. The path
was defined by a painted line on the roadway. In order to
establish rider control strategy during a transient manoeuvre,
tests were conducted with the rider instructed to complete the
lane change without steering torque input, using only lean for
control. The vehicle response was slow and less precise than
with steer torque, showing the importance of rider steer torque
as the major directional control input.

Weir et al. (1978) said that from an analytical viewpoint the
weave mode frequency and damping should have an influence on the
riders' ability to control the motorcycle in a transient
manoeuvre. The higher the weave mode natural frequency, the
greater the potential bandwidth of the rider/cycle system. As
speed decreases, so does the weave mode natural frequency,
although to some extent this is offset by an increase in capsize
mode inverse time constant. Weir et al. also showed that heavier
motorcycles have a lower weave mode natural frequency suggesting
that their performance may be poor at low speed. However, the
relationship between mid-frequency vehicle dynamics and the
actual motorcycle performance in the lane change tests was not
clearly established, and the authors suggest further
investigation.
The high-frequency cycle response properties, obtained from computation with a linear simulation of motorcycle dynamics, were related to subjective measures from the lane change experiments. Figure 4.13 shows rider rating versus roll-acceleration/steer-torque gain at high frequencies. A rapid turning manoeuvre is made by rolling the motorcycle via a torque input, and this parameter was expected to be important. However little correlation was found. Figure 4.14 shows rider rating versus yaw-acceleration/steer-torque gain and a definite trend is discernable. The riders preferred a motorcycle which began to yaw initially, rather than the first response being a change of roll angle. It was suggested that better correlation would be obtained if experimental gains were used rather than the calculated gains from the linear simulation, as the latter suffered from uncertainties.

The study by Weir et al. (1978) represents the most comprehensive attempt yet made to determine the most significant motorcycle handling response parameters. The inconclusive results obtained attest to the difficulties in this area and the fact that the study of motorcycle handling is still in its infancy.

Cornering-whilst-braking tests were also conducted by Weir et al. (1978) using the Honda 360 motorcycle. Pressure limiters were used in the brakelines to control braking levels. The results indicated that the maximum deceleration obtainable is reduced when a motorcycle is negotiating a turn. The addition of rear braking caused the motorcycle to go from slightly understeering to more neutral steering, with little variation as speed was reduced. With front wheel braking a similar transition was noted. On heavy application of the front brakes, the motorcycle oversteered to a greater extent as speed decreased. Rider subjective ratings were lower under high levels of deceleration, indicating the increased workload. Cornering and accelerating tests were conducted, and the results differed little from the
Figure 4.13 Rider ratings versus roll angle per steer torque sensitivity in the single lane change manoeuvre (Weir Zellner and Teper, 1978).
Rider: JBR
Single Lane Change
Basic Configurations
40 mph Ratings
$\Delta x = 80$ ft

Figure 4.14 Rider ratings versus yaw acceleration per steer torque sensitivity in the single lane change manoeuvre (Weir, Zellner and Teper, 1978).
steady turn cases, except at very low speeds where the motorcycle understeered to a greater extent.

Weir and Zellner (1979) published further analysis of the data collected from the experimental program of Weir et al. (1978), concentrating on the transient behaviour of the Honda 125, the Honda 360 and the Harley Davidson 1200. They found that addition of a rear load of 10% gross vehicle weight can lead to weave oscillations in near-limit steady turns. Good damping properties of the rear shock absorbers are important to limit this behaviour. Addition of weight in front of the steering head on the front fork assembly decreased the weave damping and natural frequency. A fork-mounted fairing lowered the wobble mode frequency, and aerodynamic disturbances from the fairing excited wobble oscillations at high speed. Furthermore it was found that a cornering weave occurred in high lateral acceleration steady turns due to coupling of the pitch mode and the weave mode. The coupling occurs as a result of the large roll angles in such turns (Sharp, 1976 b). They were able to predict a critical speed region for this phenomenon, where the weave and pitch mode natural frequencies coincide. This range was from 95 km/h to maximum speed for the Honda 360 (with 45 kg rear load) as shown in Figure 4.15. Also the limiting roll angle was found to be due to ground clearance rather than tyre side force limits.

Chenchanna and Koch (1979) analysed the stability and handling characteristics of motorcycles using both analytical and experimental techniques. A linear model of the rider/motorcycle system was developed. It incorporated a rider model which had rider lean resulting from motorcycle roll angle, rider steer torque resulting from yaw rate and rider steer torque resulting from steer angle. Experimental values for these feedback gains were obtained using a laboratory motorcycle simulator. The equations were solved using a digital computer to obtain eigen-
Figure 4.15 Lateral-longitudinal coupling in high acceleration turns (Weir and Zellner, 1979).
values. The capsize mode, weave mode and wobble mode were identified.

A motorcycle with a data acquisition system on board was used to obtain data to validate the simulation. Straight line running tests with speeds from 20 km/h to 160 km/h were conducted. To stimulate weave oscillations a lateral force disturbance was applied via a sudden expansion of compressed air from a nozzle mounted on the motorcycle. Experimental and theoretical weave mode natural frequency and damping ratio as a function of speed were plotted as shown in Figure 4.16. Good correlation is noted at speeds greater than 100 km/h. Discrepancies at lower speeds were said to be due to more intense rider control activity. Higher speed operation was said to be more nearly 'open loop'.

To analyze the handling behaviour, Chenchanna and Koch (1979) conducted a series of tests using entry to and exit from 90° of a 50 m radius curve. They proposed use of a 'Handling Index' (H.I.) to characterize handling as defined below:

\[ H.I. = \frac{\hat{M}}{\hat{v}} \]

where \( \hat{M} \) = peak value of steer torque  
\( \hat{v} \) = forward velocity  
\( \hat{\phi} \) = peak value of roll velocity

For speeds greater than 50 km/h, H.I. = \( \frac{I_3}{R_v} \)

where \( I_3 \) = front wheel moment of inertia  
\( R_v \) = rolling radius of front wheel

Apparently the H.I. was chosen to characterize handling on the basis that the rider has a limited capacity to apply steer torque.

Figure 4.17 shows H.I. as a function of speed. Figure 4.18 gives maximum curve-negotiating speeds for various values of H.I.
Figure 4.16 Experimental and theoretical weave mode natural frequency and damping ratio as a function of speed (Chenchanna and Koch, 1979).
Figure 4.17 Handling Index (HI) as a function of speed (Chenchanna and Koch, 1979).
Figure 4.12 Maximum curve negotiating speed versus Handling Index (HI) (Cheninna and Koch, 1979).
based on a constant peak torque. A low H.I. gives a higher curve negotiating speed. However, no real justification for this particular choice of a handling index was presented.

The experimental investigations of rider/motorcycle performance reviewed here have made attempts at defining appropriate handling parameters to describe motorcycles. However motorcycle behaviour and rider/motorcycle interactions are still not well understood, and further research is required. Handling characteristics need to be defined so that what constitutes a 'good' handling motorcycle is known. This would then allow the interaction of handling behaviour and accident involvement to be investigated, and the assessment of the effects on handling qualities of various motorcycle modifications.

4.3 ANECDOTAL EVIDENCE OF BRAKING STABILITY AND HANDLING PROBLEMS WITH CURRENT MOTORCYCLES

Motorcycle magazines from Australia, Great Britain and U.S.A. were reviewed in order to further investigate braking, stability and handling problems encountered with currently available machines. The information obtained primarily originated from road test reports.

To assess braking, stability and handling performance of a particular motorcycle, the road tester typically covers 1000 to 2000 km through all types of terrain and conditions; i.e. commuting in heavy traffic, touring over long distances, and race track limit manoeuvres. The handling of the motorcycle is then subjectively rated on its performance in lane changing, negotiation of S-bends, low speed manoeuvring ability in traffic situations, and high speed stability.

The British magazine *Motor Cycle Mechanics* and the American magazine *Cycle World* report the results of this testing by way of verbal description. Problematical behaviour is usually described
in journalistic and jargon terms which can make interpretation difficult, e.g.:

'At speeds reasonably attainable on the street, the machine feels much lighter than it is and is surprisingly neutral in handling.'
(Anon, Cycle World, Vol. 18, No. 1)

'Handling through fairly fast country roads felt good, too. Apart from a tendency for the steering head to nod from side to side on some corners, the machine was stable and predictable.'
(Anon, Motor Cycle Mechanics, Sept. 1979)

The Australian magazine Two Wheels presents, in tabulated form, the subjective ratings given under various handling and braking headings; two examples are shown in Figure 4.19. The ratings range from poor through to outstanding with a total of eight increments. Unfortunately the headings used are not easily interpreted; e.g. what does 'steering' actually mean, and how is this quantity assessed? Furthermore it is not clear what constitutes an 'average' rating. An analysis of twenty-three of these report summaries, published over a period of 18 months, indicated that the mean subjective rating in each category was 'above average'.

The distributions of the ratings of handling and braking qualities are shown in Figure 4.20. It can be seen that there is a fairly wide range of ratings for each attribute. The most severe judgement was generally 'below average', with some bikes bordering on 'poor.' The (low speed) manoeuvring quality was the only one to attract ratings of 'poor.' At the other end of the scale, motorcycles were rated as 'outstanding' in every category except braking in corners.
It is of interest that the ratings of the various handling attributes of a given machine were generally highly correlated. This would suggest either a 'halo effect' in the raters' assessments, or that 'outstanding' top speed stability, for example, can be achieved without compromising manoeuvrability. The latter interpretation suggests that it should be possible to design a motorcycle which is 'outstanding' in all respects. According to one reviewer, the machine rated in Figure 4.19 (b) comes close to this ideal.

The most serious problems encountered by road testers were high speed weaves, high speed wobbles, slow response at low speed, self steering and roll limits imposed by foot pegs, mufflers and stand brackets. It is emphasized that these problems are not common to all motorcycles, nor do they necessarily all occur with a particular motorcycle. Furthermore, some only become obvious when speeds far in excess of the legal limit are attempted. However they do exist with some machines. An example of weaving and wobbling behaviour:

'Setting the shocks up to a maximum preload helped, but the machine still wallowed and wobbled in turns at speeds above 160 km/h and was particularly upset by bumps and road irregularities after a few laps at that speed. The rider had to be very careful with the throttle exiting turns, especially bumpy turns, or else a combination of inadequate shock damping and losing and regaining rear tyre traction threatened to send the machine into tank slappers.'

(Anon, Cycle World, Vol. 18, No. 1, 1979)

An example of slow low-speed steering response:

'Along with the superb high-speed handling buyers will have to put up with this maker's traditionally heavy low-speed steering and slow low-speed responses
Figure 4.19 Subjective ratings of motorcycle performance (*No Wheels* June 1977, March 1979).
Figure 4.20 Distribution of ratings given for handling and braking qualities (source: Two Wheels, June, 1974 to December 1979).
as well as the usual annoying lack of steering lock (because maker mounts its forks in very narrow triple clamps they come back and touch the tank quite early).

(Anon, Two Wheels, January, 1979)

The following report is of a motorcycle with inadequate ground clearance for roll angle limits:

'Handling and steering, while heavy, were firm and positive. The only time the 1200 ml machine got upset was when I let it ground by going through a bumpy bend faster than I should've. Then it leapt up and twitched across the road. It would ground easily, many degrees before most other machines...'

(Anon, Motor Cycle Mechanics, August 1978)

A further example of a handling problem is in a report of a road test on an 1100 ml machine. The variation of steering characteristics with different tyres is noted:

'The steering of the machine was affected considerably by the tyres fitted. With the Metzeler on the front the machine was a huge self-steerer (more so than any other bike we've ridden), but with the Avon on the front the self-steering tendencies were much reduced. The bike could be more accurately manoeuvred at low to medium speeds so the Roadrunner tyres certainly suited the bike more. It was surprising a front tyre alone could make such a difference.'

(Anon, Two Wheels, November, 1978)

The preceding text serves to give an indication of some of the stability and handling problems test riders have reported with new motorcycles. It would appear that most riders find the
stability and handling behaviour of a new motorcycle to be satisfactory under normal riding conditions. However it seems the behaviour of the machine deteriorates with age and distance covered. An important contribution towards elucidating some of these problems has been made by the Australian importing agent for Metzeler tyres (Anon, 1979). Unfortunately the 'problems' are not specified or defined, so it can only be assumed that weaving, wobbling and change of steering behaviour are implied. The report is as follows:

'After monitoring some 200 motorcycles over the past few months whose owners complained of some type of handling difficulties, we collated some rather terrifying statistics, 90% of machines had out of balance wheels, 85% had inadequate tyre pressures for operating conditions and 94% of wheels were out of alignment.

These figures closely approximate figures obtained in recent surveys conducted in the U.S.

Eliminating these three major faults, corrected the handling problems in 95% of the machines. The balance of handling complaints were traced to faulty suspension action, worn steering head and swing arm bearings, and bushes and bent frames.

The point is loud and clear. Any motorcycle, but particularly those operated at high speed, should have these areas thoroughly checked at regular intervals.

Every motorcycle manufacturer issues details of correct tyre pressures for their machines. Wheels should be balanced, obviously, whenever a new tyre is
fitted and subsequently every 3000 kms.
Wheel alignment should be carried out every time a wheel is replaced on the motorcycle.

A further source of evidence of the existence of stability and handling problems is the user correspondence published by motorcycle magazines. As an example a letter published in Motor Cycle Mechanics, February, 1978 said:

'I am writing to you in the hope that my experience may help by warning others. In mid-September I bought a top half sports fairing with pouches to extend over the handlebars...With fairing fitted properly I set off to work as usual but noticed a little instability about the handlebars and front wheel at around 110 km/h, but this disappeared when I leaned forward. Coming home at 120 km/h the wobble returned. It was as if the front wheel was being lifted and the handlebars being shaken from side to side. I shut the throttle and the bars went onto full lock and threw me up the road, breaking bones in my wrists and hands and resulting in stitches in the knee and hand. I was lucky I wasn't run over.

Although my bike... also has a top box fitted, it has never before shown the slightest handling problem, and the police could find nothing wrong with it when they examined it after the accident. While I appreciate that the accident could have been caused by some unknown factor I believe the fairing was to blame.'

This letter resulted in Motor Cycle Mechanics being flooded with reader complaints of a similar nature, particularly from those who had fitted handlebar fairings. The magazine conducted an experimental program aimed at identifying the problems. The
### TABLE 4.1  PERFORMANCE OF MACHINES WITH VARIOUS LOADS CARRIED (Motor Cycle Mechanics, June 1978)

<table>
<thead>
<tr>
<th>Yamaha RD250</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>Kawasaki Z650</th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Test</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>11</td>
<td>12</td>
<td>13</td>
<td>14</td>
<td>15</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>Weight carried</td>
<td>Empty</td>
<td>10lb</td>
<td>30lb</td>
<td>60lb</td>
<td>75lb</td>
<td>80lb</td>
<td>85lb</td>
<td>106lb</td>
<td>162lb</td>
<td>Empty</td>
<td>40lb</td>
<td>Parts off</td>
<td>Empty</td>
<td>70lb</td>
<td>70lb</td>
<td>Parts off</td>
<td></td>
</tr>
<tr>
<td>Lap time (all + 1min)</td>
<td>37.5s</td>
<td>30.8s</td>
<td>29.9s</td>
<td>33.3s</td>
<td>32.5s</td>
<td>31.7s</td>
<td>34s</td>
<td>34.5s</td>
<td>54s</td>
<td>30.4s</td>
<td>33.1s</td>
<td>31.3s</td>
<td>29.5s</td>
<td>31s</td>
<td>—</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>Top speed mph</td>
<td>85</td>
<td>85</td>
<td>85</td>
<td>85</td>
<td>83</td>
<td>83</td>
<td>83</td>
<td>83</td>
<td>79</td>
<td>85</td>
<td>85</td>
<td>85</td>
<td>107</td>
<td>106</td>
<td>—</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

### TABLE 4.2  PERFORMANCE OF MACHINES WITH DIFFERENT FAIRINGS (Motor Cycle Mechanics, August 1978)

### MAXIMUM SPEEDS (MPH)

<table>
<thead>
<tr>
<th>MACHINE</th>
<th>Unfaired</th>
<th>OF Sports</th>
<th>OF Touring</th>
<th>HoW Monza</th>
<th>HoW Tourer</th>
<th>HoW Stingray</th>
<th>HoW Hawk</th>
<th>GP Sports</th>
<th>GP Tourer</th>
</tr>
</thead>
<tbody>
<tr>
<td>KAWASAKI 400</td>
<td>98</td>
<td>93.5</td>
<td>87.8</td>
<td>98</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HONDA 400-4</td>
<td>106</td>
<td></td>
<td>87.5</td>
<td>97</td>
<td>103</td>
<td>104</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>YAMAHA 250</td>
<td>89.5</td>
<td>81</td>
<td>88.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
first tests were done on top boxes and panniers, and they found that almost any amount of weight could be carried without seriously degrading handling behaviour. Test results are shown in Table 4.1. The second investigation was of the influence of fairings on stability. It was found that handlebar fairings had little effect on the stability of the motorcycles during the experiments. The results are given in Table 4.2. These apparently unexpected results are possibly more a reflection of the method of analysis used rather than conclusive evidence of no effects.

Magazine road test reports also serve to highlight braking problems with current motorcycles. Many different problems are encountered, including: brakes that are too powerful, enabling wheels to be easily locked; brakes that are under-powered; lack of stopping power for disc brakes in wet conditions; slow response of disc brakes when wet; and control gains of the braking system not appropriate to the task. Following are three extracts from road test reports. These are examples that have been selected to be representative of brake problem areas.

First, from a road test of a 750 ml machines:

'While the front and rear brakes were quite well balanced for heavy braking, the machine wasn't so good under less strenuous conditions when more use was made of the rear brake. It's often convenient to drag the rear brake to scrub off speed while the bike is banked over, or while manoeuvring through traffic and in these conditions the drum brake could have done with more power. Towards the end of the test the front discs started to squeal under light braking but they kept up their performance and apart from a slight lag at very low speed worked well in the rain.'

(Anon, Motorcycle Mechanics, July, 1979)
The second extract comes from a road test report for a 400 ml machine:

'Braking is a mixed bag. The numbers aren't too bad; 11 m from 50 km/h and 48 m from 100 km/h. But under hard braking the rear of the bike hops easily when the brake locks, making control difficult. The front brake provides good control but it is not powerful for a disc. In wet weather only the rear brake slows the bike, the front washing out completely and being slow to recover.'


The final extract is from a road test of a 650 ml machine:

'To be frank, the braking system...is an overkill. Triple disc brakes on a machine of this weight and performance...? Not only does the bike stop quickly it also locks up wheels easily, especially the front one. That's unnecessary and potentially hazardous...

The biggest problem with a pure disc brake arrangement is the wet weather performance and the (machine) stopped as expected in rainy conditions - badly. At some stages it felt like it had no brakes at all...'

(Anon, *Two Wheels*, January 1979)

4.4 CONCLUSIONS

(i) The study of motorcycle-alone lateral dynamics has received considerable attention in the literature over the past decade. The models developed appear to give reasonable correlation with actual behaviour, but further experimental validation is required. Useful design conclusions have been drawn from these studies.
The lack of empirical data for motorcycle tyres, and oversimplified modelling of tyres, is thought to be the main cause of discrepancies between theoretical and experimental lateral dynamic behaviour.

Three physically significant natural modes have been identified from linear mathematical models of the lateral dynamics of the motorcycle. These have been designated as the wobble, weave and capsize modes. For some design configurations and forward speeds the weave and wobble modes may become unstable, and their natural frequencies are too high to allow the rider to control them. For most machines the capsize mode is unstable at normal traffic speeds, thus requiring continuous control activity by the rider.

The dynamics of the closed loop rider/cycle system are much less well understood than the cycle-alone dynamics. Motorcycle/rider simulations are available which include non-linear representation of the motorcycle dynamics so as to allow for the large roll angles experienced in various manoeuvres. Considerable further work, however, is required to establish appropriate rider control strategies and parameters.

Experimental studies have shown that, contrary to some popular belief, motorcycles are no more 'manoeuvrable' than automobiles in obstacle avoidance situations.

Motorcycle size, as such, does not appear to have an important influence on the obstacle avoidance performance of the rider/cycle system. On the other hand, rider skill variations lead to substantial differences in evasion distances required to successfully avoid obstacles in the motorcycle's path.
(vii) At normal traffic speeds, evasive manoeuvring appears to be a better accident-avoidance strategy than braking.

(viii) Little progress has been made in identifying the important features of a motorcycle's dynamic response which determines its 'handling quality'.

(ix) There is a considerable amount of anecdotal evidence suggestive of braking, stability and handling problems in the popular motorcycling press. Examples cited include high speed weaves and wobbles, poor brakes in both wet and dry conditions, slow steering response at low speeds, tyres influencing motorcycle behaviour to a large extent, and fairings upsetting high speed stability. There is a need for further research to improve the level of understanding of motorcycle-rider interactions so that such problems can be reduced and so that desirable handling properties can be quantitively specified.