

Bicycle Accidents Caused By Steering Instability

Report for The Federal Office of Road Safety

by

**Dr Frank Bullen, B.Sc(Met), B.E(Civil)(Hons), ME, PhD, FIE.Aust., CPEng.
Principal Researcher, Physical Infrastructure Centre
Associate Professor, School of Civil Engineering
Queensland University of Technology.**

**Sean Wilkinson B.Eng.(Civil)(Hons.), MEng
Researcher, Physical Infrastructure Centre
Lecturer, School of Civil Engineering
Queensland University of Technology.**

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EXECUTIVE SUMMARY

Recently the community has been made aware that certain bicycles in use in the general community possess a potential steering instability. The issue has gained increased exposure in Queensland and Australia after the death of a 12 year old girl in 1994. In this report, the stability of bicycles is investigated. A review of the present methods of accessing bicycle instability is presented and the effect of trail on the stability of bicycles is examined by testing a variety of commonly available bicycles. While trail is shown to be indicative of bicycle stability it is recommended that it not be used in isolation as other factors can negate the benefits of large trails.

1. INTRODUCTION.

Recently the community has been made aware that certain bicycles in use by the general community possess a potential steering instability. This issue has gained increased exposure in Queensland and Australia after the death of a 12 year old Brisbane girl in 1994. It was perceived by investigators that the death occurred as a result of the girl's bicycle steering becoming unstable, causing her to lose control and crash at an unknown critical speed. Since the death and the ensuing publicity, other cases of serious injury have come to light through the involvement of Queensland Office of Consumer Affairs and the Police Accident Investigation Unit.

Preliminary work carried out by the Queensland Police Accident Investigation Unit and the School of Civil Engineering at QUT, has identified some criteria that may be used to identify bicycles that could exhibit instability under certain operating conditions.

2. LITERATURE REVIEW.

There are many variables that can affect the behaviour of bicycles. Since the "stability" of a bicycle is also related to the ability of the rider (Lewis, 1973), most papers have concentrated on obtaining quantitative information on stability by removing rider variability.

Review of the literature has indicated that the following factors may affect stability:

1. Trail (defined as the distance between the point of intersection of the line of rotation of the steering axle and the ground, and the point of contact of the wheel and the ground - see Figure 1)
2. Wheelbase
3. Steering geometry
4. Gyroscopic forces
5. Handlebar configuration
6. Front wheel brakes
7. Wheel diameter

Some researchers have argued that trail is relatively unimportant, and that factors such as the effects of the steering weight, the weight on the front tyre and the gyroscopic forces are the primary reasons for stability (Wilson-Jones, 1951-1952). Others however, have indicated that trail is one of the most important characteristics and added that there is a limited area of inherent stability that is dependent on the gyroscopic forces. Other parameters are only important in so much as they define this region of stability (Franke, Duhr & Rieb, 1990).

In a study conducted on the stability of the bicycle (Jones, 1970), a number of bicycles were modified to investigate the effects of the gyroscopic forces and the steering geometry. It was found that the gyroscopic forces were insignificant in bicycle stability, and that the steering geometry played an important part in the behaviour of the bicycle. It was concluded that there is an "intimate connection" between trail and stability.

Jones also developed a Steering Stability Factor (SSF) given by the equation:

$$u = \frac{1}{4} \left[109.1 \left(\frac{y}{d} \right) - (90 - H)(\sin H) \right] \quad \text{eq 1}$$

where

u = Steering Stability Factor,
y = fork rake, or offset,
d = wheel diameter and
H = the steering head angle.

Style	Steering Head Angle, H (degrees)	Offset, y (mm)	Wheel Diameter (mm)	Wheelbase (mm)	Trail (mm)	SSF
Dragster	72.15	35	490	960	42	-2.3
U-Frame	71.9	48	496	910	30	-1.67
Racing	74	45	664	1045	48	-1.99
BMX	76.05	50	514	930	12	-0.73

The "U Frame" Bicycle was tested at only two trails. At each of these trails the "knocking" and "no-knocking" tests were performed. The "Racing" bicycle was also tested at two trails with "knocking" and "no-knocking" tests being performed. The "Dragster" was tested at two trails and was found to be unstable during the "no-knocking" test therefore it was deemed unnecessary to perform the "knocking" test as little useful data would be obtained.

3.2 Trail Measurement.

As mentioned previously, the trail is defined as the distance between the point of intersection of the line of rotation of the steering axle and the ground, and the point of contact of the wheel and the ground (Figure 1). It is a characteristic of every bicycle and has been incorporated into the ISO standard ISO 4210 (1989) (E).

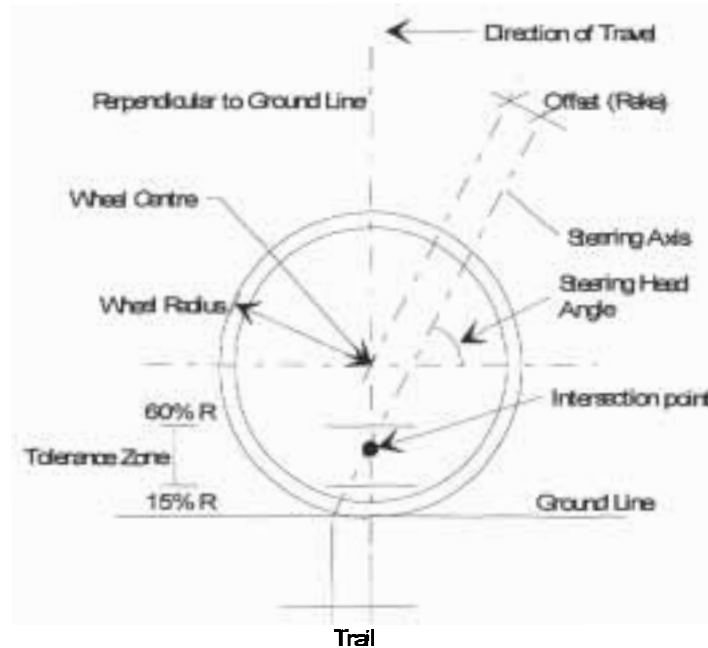


Figure 1 Steering Geometry

The trail-height difference relationship for the BMX style bicycle is presented in Graph 1. Relationships for other bicycles are shown in Appendix A.

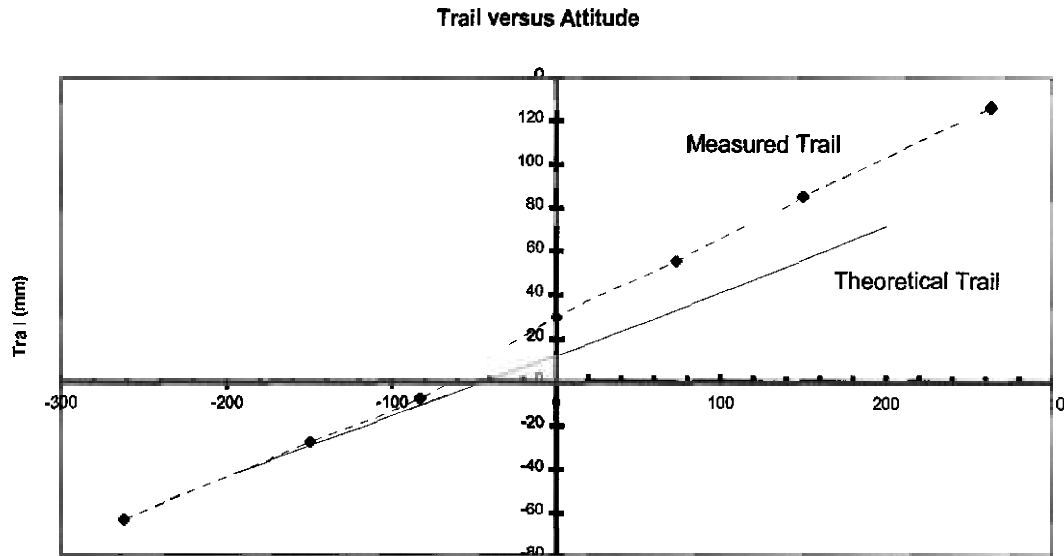
A theoretical relationship between trail and front and rear wheel elevation difference was developed and is shown in equation 2:

$$t = \frac{r}{\tan\left(H - \sin^{-1}\left(\frac{fwh - rwh}{wb}\right)\right)} - \frac{y}{\cos\left(90 - \left(H - \sin^{-1}\left(\frac{fwh - rwh}{wb}\right)\right)\right)} \quad \text{eq 2.}$$

where

t = trail,
r = wheel radius,
H = steering head angle,
fwh = front wheel elevation,
rwh = rear wheel elevation,
wb = wheelbase and
y = fork rake or offset.

The relationship is a simple function of bicycle geometry and was used to determine the "theoretical" trails shown in Graph 1 and Appendix A.



It should be noted that the minor discrepancies between the theoretical and measured trails are due to the inaccuracy in the measurement of the steering head angle and the offset. It is these two measurements that produce the largest inaccuracies. Alignment of the measuring rod with the steering column (measuring the steering angle) relies upon subjective judgement. When the steering angle is low, these inaccuracies are magnified. The measurement of the offset also relies upon subjective judgement and successive measurements yielded up to 10 % variations. This is important when placing a conservative limit on trails as it may be difficult to accurately measure trail to within 10 %.

3.3 Testing Apparatus.

A bicycle testing unit was designed and constructed and the assembly test rig is shown in Plate 8. The test rig is capable of speeds between 0 and 60 km/hr. Higher speeds are possible however, overheating occurs due to the friction between the belt and the riding surface and only short duration tests are possible above this speed.

The test rig consists of a belt running between two pulleys (Plate 9), powered by a 3 phase 7.5 kW, AC motor (Plate 10). The speed of the motor is controlled by an AC speed controller unit (Plate 11). This controller unit is also calibrated and can measure the speed of the motor.

The bicycle is attached to the rig by a shackle and two rod ends, as shown in Plate 12. This has the effect of restraining the bicycle in the forward direction only and allows the bicycle to move in the other five degrees of freedom (i.e. sideways, up/down, pitch, roll and yaw). Only sideways, roll and yaw movement are relevant in the test.

To allow the rear wheel to move from side to side it was placed on a bearing surface (see Plate 13). By allowing the rear wheel to move sideways it is possible to simulate turning of the bicycle. As the handlebars are turned, the bicycle leans over and the rear wheel moves sideways. The leaning of the bicycle keeps the front wheel in the direction of the belt and the rear wheel finishes at an angle to the front wheel.

To simulate a 6 - 8 year child riding the bicycle, a mass of 40 kg was placed on the frame, located at the same position as the centre of gravity of a child. The loading arrangement can be seen in Plate 14.

The bicycle was steered by an operator located alongside the handlebars. This has the disadvantage of making the test somewhat dependant on the operator. As the operator was an adult with reasonable co-ordination, test results could be considered to be conservative. However, no other procedure for steering the bike was found to be suitable. All methods of passively steering the handlebars failed. They either did not restrain the handlebars enough or restrained them so much that the front wheel could not turn laterally, and thus would remain "stable". Only interactive methods of control are suitable. Mechanical feedback control was found to be too expensive for this project, and human control was the most realistic approach.

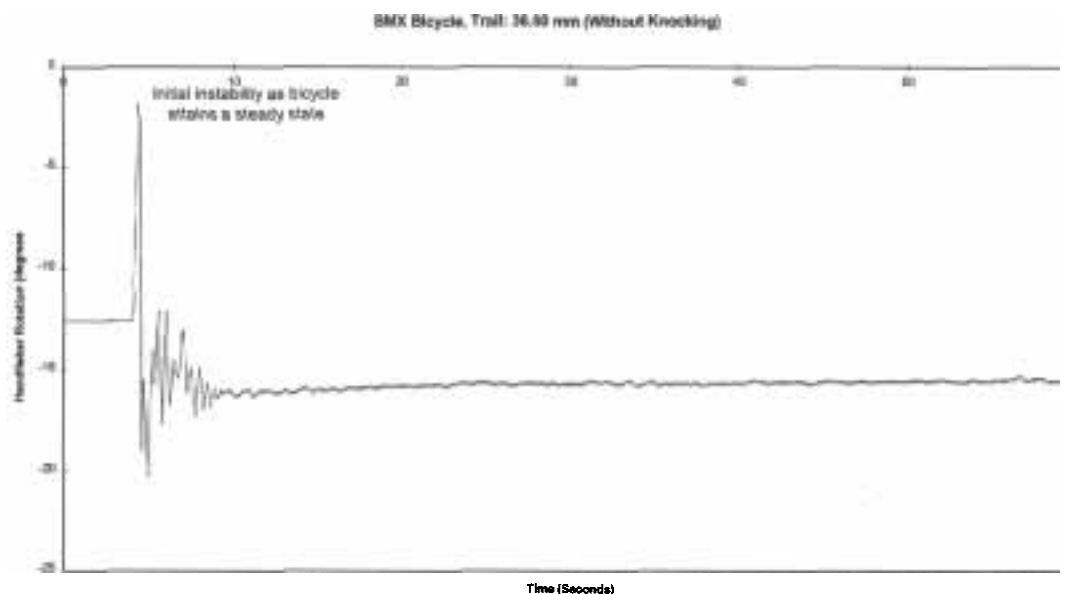
3.4 Test Procedure.

Although much of the preliminary work was carried out over a wide range of speeds, all the test data presented in this report was taken at a speed of 30 km/hr. It is at this and higher speeds that serious accidents may occur.

The bicycle was placed on the testing apparatus and the wheels were aligned in the direction of travel. The rear platform was adjusted for height to obtain the required trail. Data recording commenced followed by the activation of the belt drive. The seat column was hand-held initially and the bike was manually guided into a free running stable condition. It should be noted that for some tests, where the bike was inherently unstable, the handlebars were used to reach a stable condition but at no stage after were the handlebars used to intentionally guide the front wheel and maintain an "artificial" stability. After this stable condition had been reached only slight balance adjustments were made to stop the bicycle from toppling.

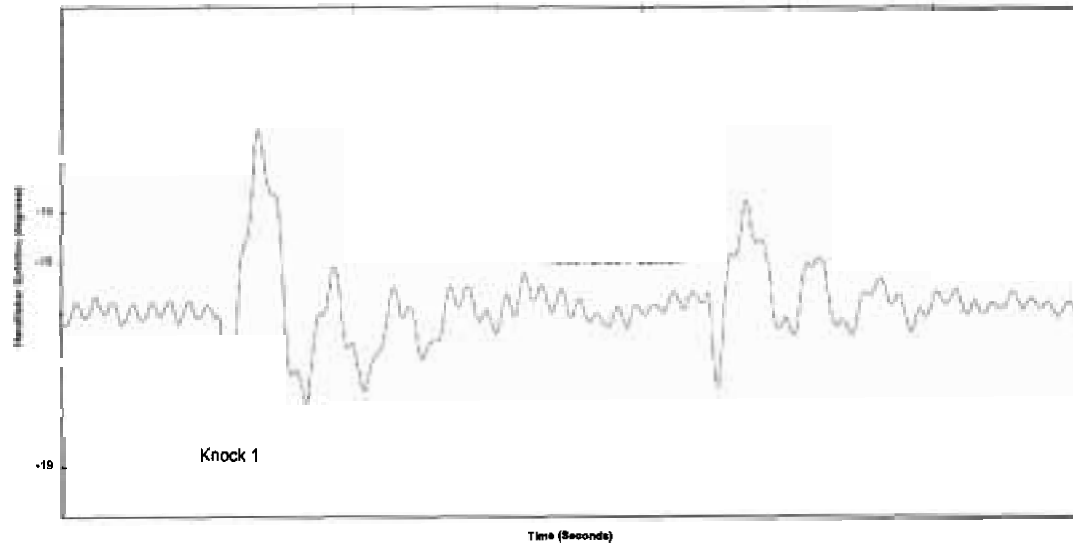
4. RESULTS.

For each trial, the rotational displacements were recorded for a duration of one minute using a rotational displacement transducer and a data acquisition system. The results of a test where the handlebars were not knocked is shown in Graph 2. The standard response was for little rotational displacement after the free running condition was reached. Small fluctuations are to be expected due to such factors as the small irregularities in the belt and deformations in the tyre and wheel. Initial fluctuations were recorded as the bicycle accelerated to a steady state.



Graph 2 Typical Response for Stable, No-Knocking Test.

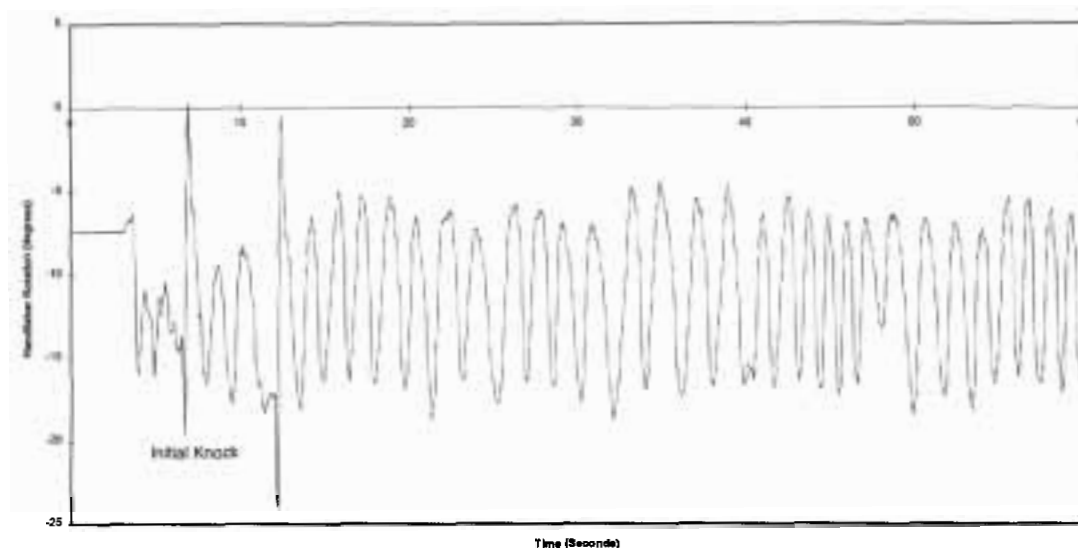
For those tests where the handlebars were knocked, there were two typical outcomes. Firstly, if the bicycle configuration was inherently stable, then a number of oscillations of reducing magnitude were noticed before a relatively complete recovery was made and the bicycle resumed a stable free



Graph 3 Typical Response for Stable, Knocking Test.

However, when the bicycle was unstable, the oscillation continued and fluctuated wildly, before failure occurred or manual intervention was required for safety. Failure was identified as the time when the bicycle swung laterally to an extent that it left the test track. Such a failure can be seen in Graph 4. This test had just one knock applied at the start of the test and the bicycle never recovered to a steady state.

BMX Bicycle, Trail: -8.48 mm (Knocking)

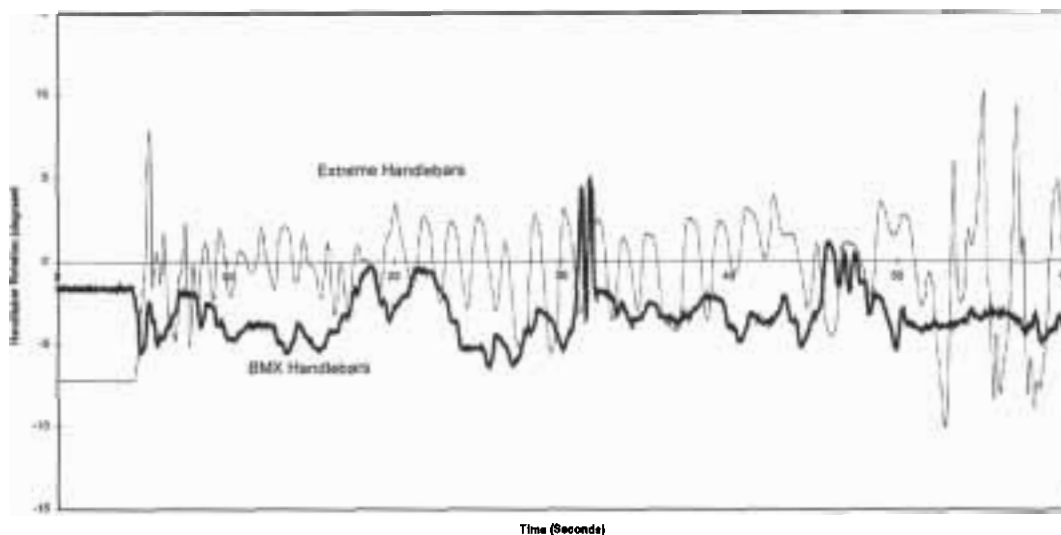
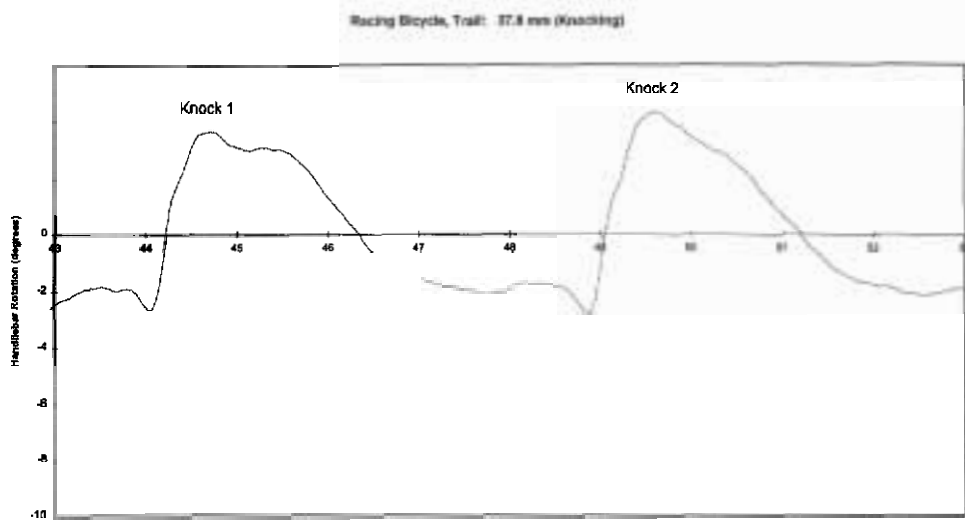


Graph 4 Typical Response for Unstable, Knocking Test

4.1 Performance of Racing Bicycles.

It was observed that the behaviour of the Racing style bicycle at both trails tested was highly stable whether the handlebars were knocked or not. When knocked, the front wheel did not oscillate as other bicycles, but instead gradually returned to in line motion in one sweeping movement (Graph 5). Its SSF is relatively low and considered to be outside the recommended range of -2.0 to -2.8.

Therefore its inherent stability is due to the large trail associated with this bicycle, and the high wheel diameter that provides greater contact area with the ground in the intended direction of travel.



Graph 6 Effect of Different Handlebar Configurations on the Performance of the Dragster

4.3 Performance of U-Frame Bicycles

The U-Frame Bicycle tested is known to have been involved in an accident at high speed. Like the Dragster it has swept-back handlebars and a relatively small wheel radius. It also had a low trail, and an SSF that was outside the accepted range. While relatively unstable, it had better handling characteristics than the Dragster. When subject to the knocking test, however, it was unsatisfactory in its ability to recover.

5. DISCUSSION OF RESULTS.

5.1 Analysis of Jones' Steering Stability Factor SSF.

Each bicycle was measured and analysed for the Steering Stability Factor, SSF as given in equation 1. For each wheel diameter, this equation was used to produce Graphs 7, 8, 9, and 10 in Appendix C. As indicated earlier, Jones (1970) considered that for optimum performance, SSF values lie between -2.0 and -2.8. It was observed that the SSF for the BMX (-0.73) was very low and thus indicates high manoeuvrability, but also possibly low stability. It was shown that this bike was reasonably stable at a speed of 30 km/hr, but at higher speeds, shimmying of the front wheel may occur, producing a subsequent loss of steering control.

The U-Frame bicycle, while having a higher SSF (-1.67) was still outside the suggested limits and was observed to be more unstable than the BMX. This could be due to the swept-back handlebars, which decreases the bicycle handling ability.

The Dragster had an SSF (-2.3) well within the design limits, yet appeared to have the poorest handling characteristics. As with the U-Frame bike, it had an extreme handlebar configuration as well as the smallest wheel diameter, which could contribute to the instability observed.

The Racing bicycle (SSF of -1.99) was the most stable configuration tested which is due to its large wheel diameter providing greater contact area with the ground in the direction of travel, and a large trail.

From this analysis, it would appear that while the SSF gives an indication of the handling properties of the bicycle, it should not be used without considering such factors as the handlebar configuration and trail.

5.2 Minimum Safe Trail.

~~Through a thorough analysis of the steering response of the BMX bicycle at various trails, the transition between steady and unsteady behaviour was observed at a trail of approximately -3.0 mm. While at this trail the bicycle was reasonably stable when tested with no handlebar interference, as can be seen in Appendix D some temporary instability was observed.~~

When the handlebars were knocked, thereby inducing a temporary rotation of the steering mechanism, it was observed that at this trail the bicycle was unable to consistently recover on its own. Tests on lower trails (-8.48 mm and -5.73 mm) showed that while it was possible for the bike to remain in line as long as the conditions were smooth when temporary displacements were introduced, the bicycle was unable to exhibit the self correcting ability noticed in the larger trail tests.

It should be mentioned that the trail of -3.0 mm is not a conservative estimate of safe trail and is rather the actual transition point between stable and unstable conditions. Adopting a trail of -3 mm would not be recommended as the bicycle was observed to spontaneously change from stable to unstable states.

5.3 ISO Standard Recommendations.

The ISO standard recommends that limitations be placed on the magnitude of the trail. For the physical characteristics of the test bicycles (Table 1) these limitations are given in Table 2.

Table 2 Comparison of Measured Trail with ISO Recommendations

Style	Upper ISO Bound (mm)	Lower ISO Bound (mm)	Actual Trail (mm)	SSF
U-Frame	48.35	12.08	30.56	-1.67
Racing	60.22	15.05	48.48	-1.99
BMX	41.32	10.33	12.3	-0.73

All bicycles are within the limits specified in the ISO standard. The BMX is however, only just within the lower bound limit, and could be considered to have very little margin for safety. Using the BMX and racing bicycles as a guide (as they do not have extreme handlebar configurations) it would appear that any recommendations for new trail guidelines should be closer to the upper bound as determined by the ISO standard for optimum stability.

6. FUTURE WORK: INDUCING UNSTABLE CONDITIONS,

In order to develop a minimum safe trail, a “modelled” hazard could be placed in front of the vehicle and the effects on the stability studied. The placement of such a hazard temporarily shifts the point of contact of the front wheel with the ground, and therefore alters the trail of the bicycle (Figure 2).

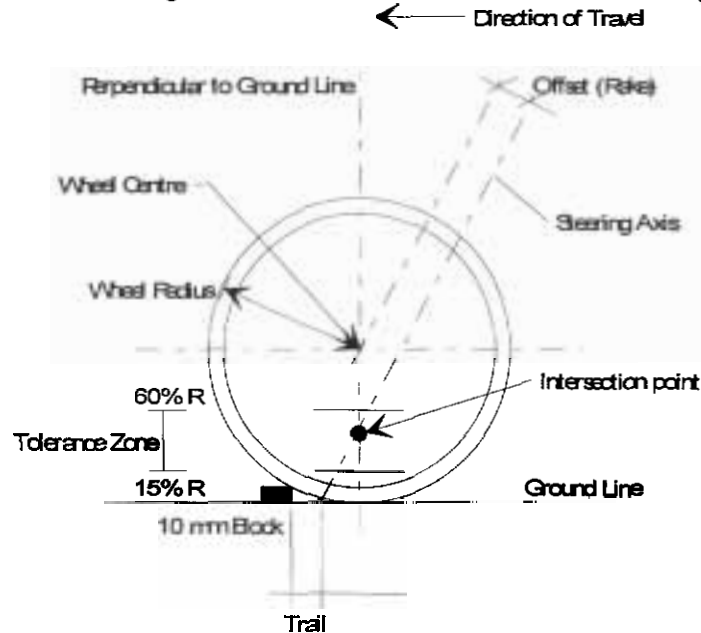


Figure 2 Change in Trail Due to 10 mm Block

For each of the bicycles' configurations this bump was included, and the resulting trail changes calculated (Table 3).

Table 3 Adjusted Trail with Inclusion of 10 mm Block Placed in Front of Leading Wheel

Style	Trail With 10 mm Intrusion (mm)
Dragster	-27
U-Frame	-39
Racing	-32
BMX	-58

As can be seen, the inclusion of a minor road hazard (such a riding over a thick stick) changes the trail dramatically. The steering capability is then compromised and instability may occur. This condition would only occur briefly as the wheel passes over the obstacle, the trail would then return to normal, allowing the bicycle to recover its stability.

7. CONCLUSIONS.

The ISO standard guidelines for trail provide a good initial guide for safe trail in bicycles. The work undertaken in this study suggests that ISO guidelines may need to be modified such that the lower limits be increased.

It should be noted that exclusive use of the trail as a measure of stability may not be appropriate as other factors can negate, the benefits of large trails. Similarly, any use of factors that consider only the simplified dimensions of the steering mechanism, such as the SSF or ISO, should be regarded as only indicative of stability. Better measures of stability should be developed, in order to allow for all factors that affect steering properties. The development of these parameters is beyond the scope of this project.

Road roughness will play an important role in inducing instability. This research should be extended to consider the effects of road macrotexture and megatexture on instability and the relevance of the ISO recommendations and SSF.

It is recommended that further investigation be made into the effect of extreme handlebar configurations on bicycle stability. Since these configurations can introduce highly unstable conditions, a modification factor should be developed which allows for increased trail to balance the effects of poor handling configuration.

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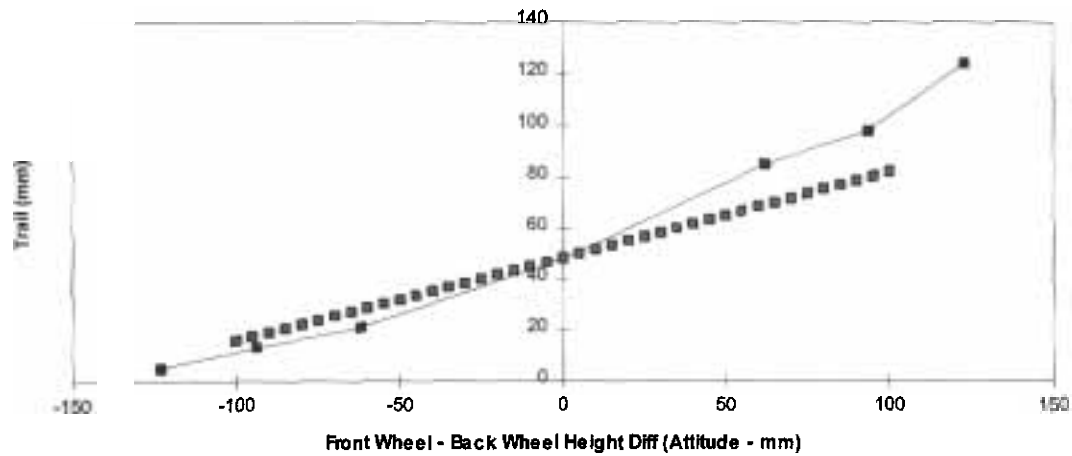
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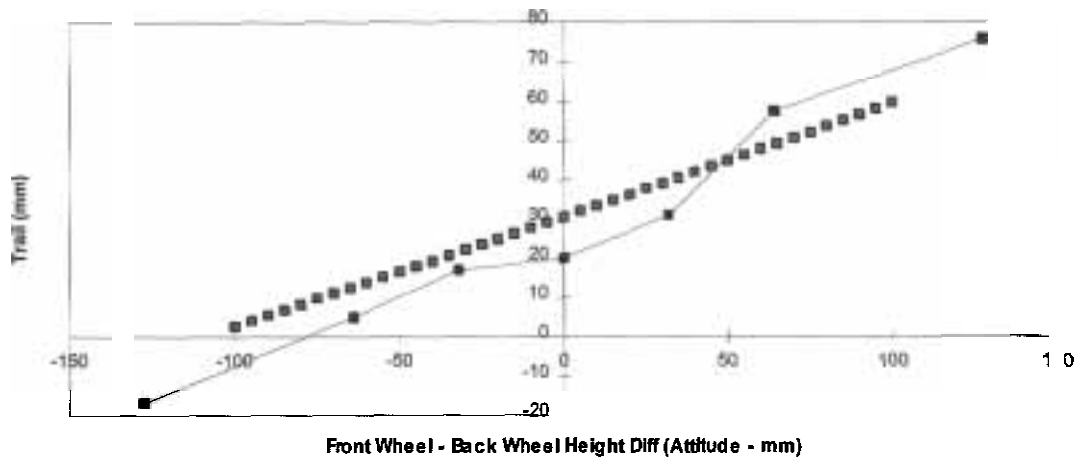
Wilson-Jones, R.A., (1951-52) **'Steering and Stability of Single-track Vehicles.'**, Proceedings, Institution of Mechanical Engineers, Automotive Division, London

APPENDIX A.

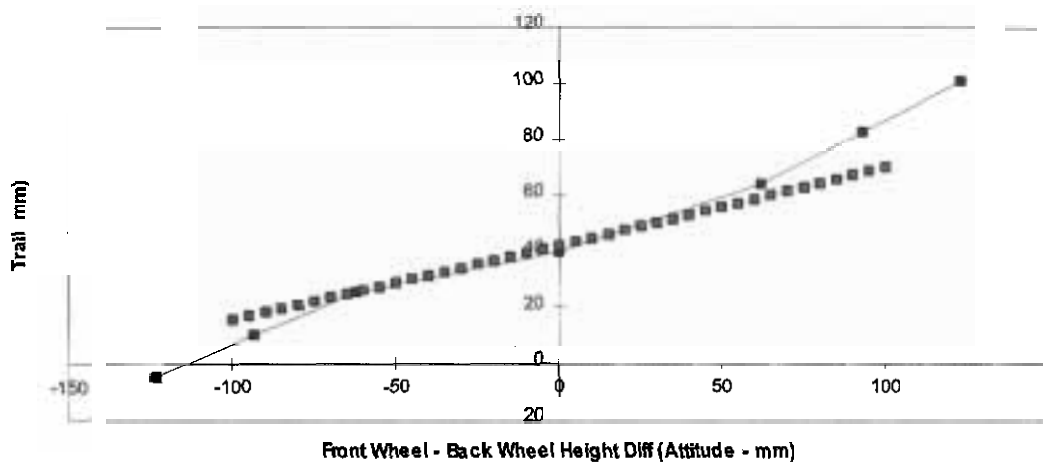
Trail versus Attitude (Racing)



Trail versus Attitude (U-Frame)



Trail versus Attitude (Dragster)



APPENDIX B.

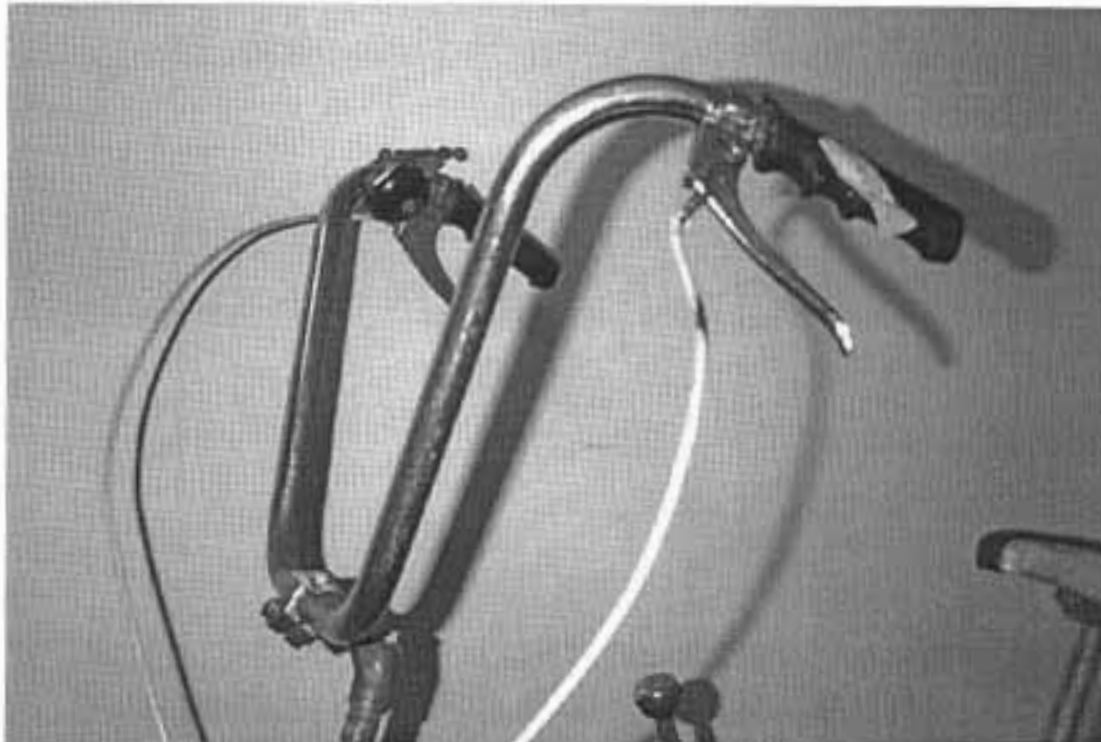


Plate 1 Extreme Handlebars: Swept-back Handlebar Configuration of the Dragster



Plate 2 Standard Handlebars: Standard Handlebars on the BMX Bicycle



Plate 3 "BMX" Style Bicycle



Plate 4 "Dragster" Style Bicycle



Plate 5 "U-Frame" Style Bicycle



Plate 6 "Racing" Style Bicycle



Plate 7 Measurement of Trail



Plate 8 Bicycle Test Rig

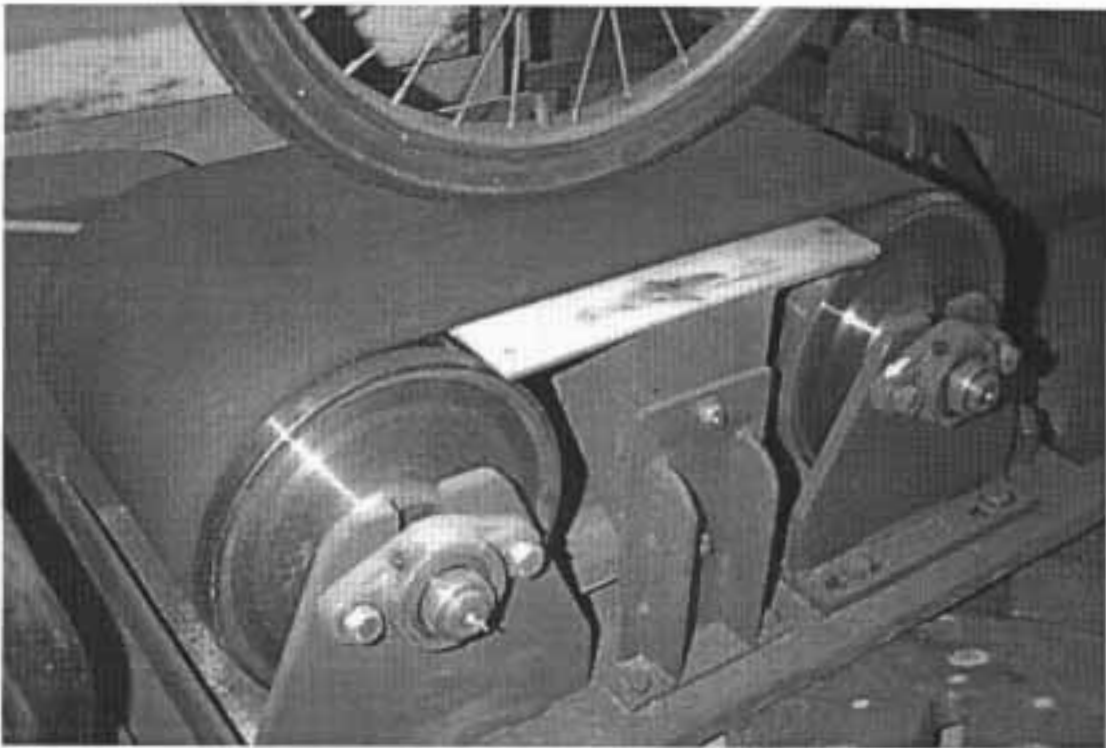


Plate 9 Belt and Pulleys

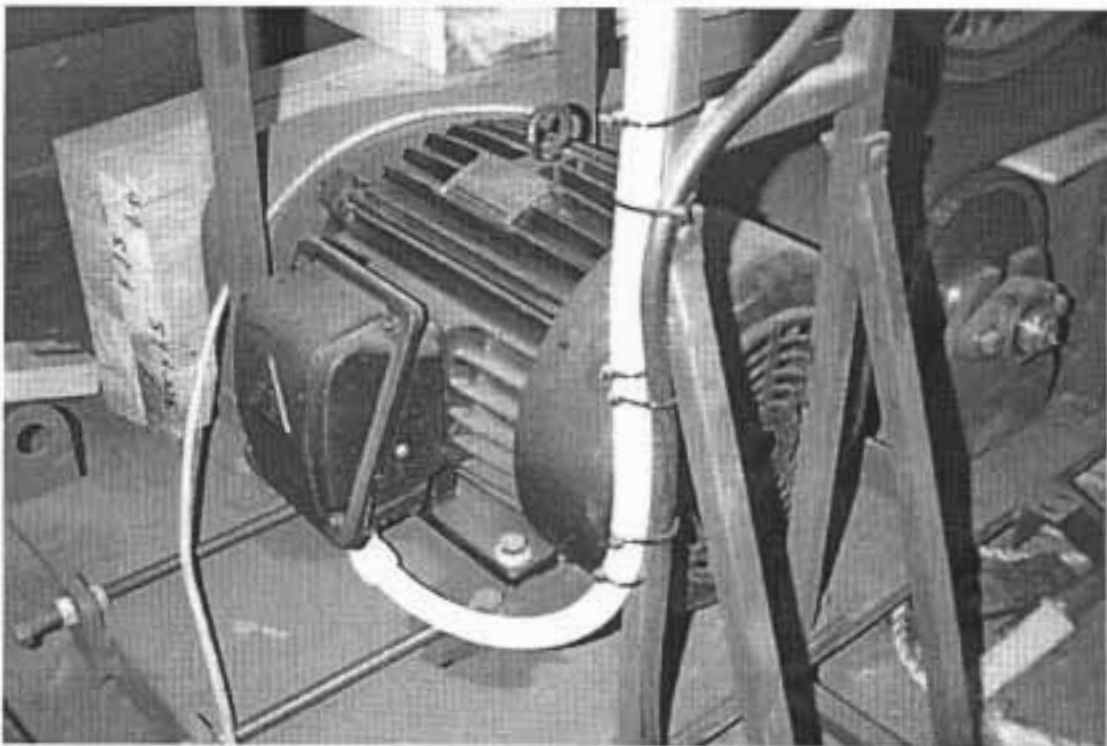


Plate 10 AC Motor



Plate 11 AC Controller Unit

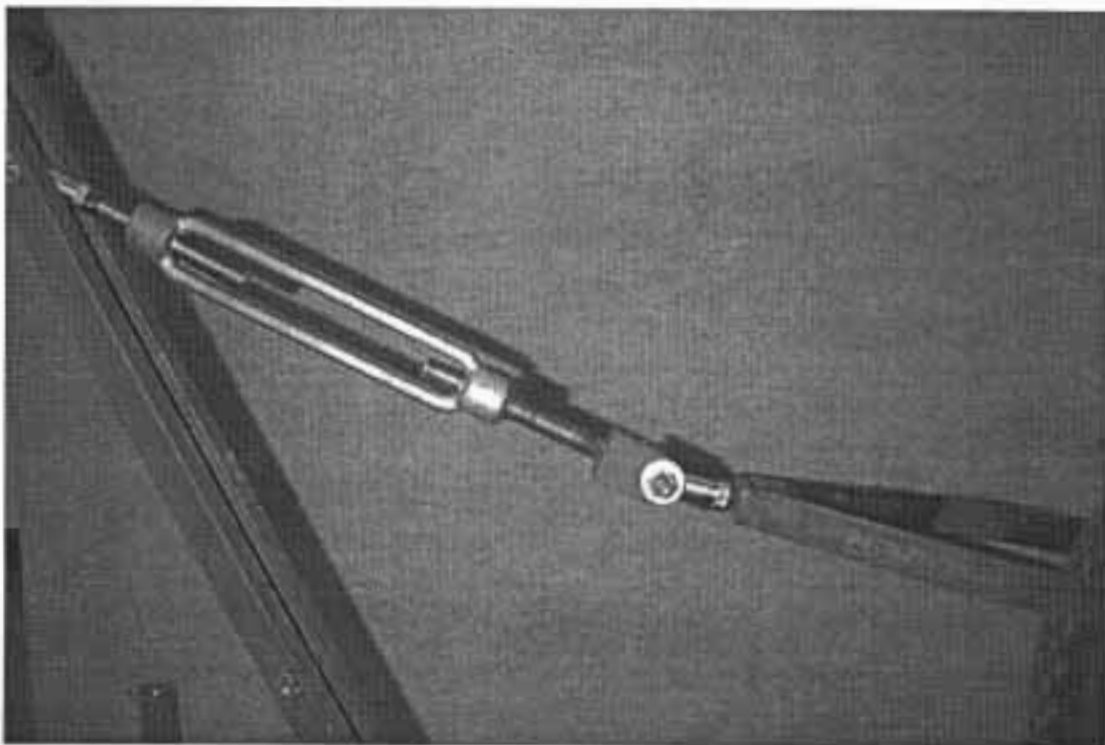


Plate 12 Shackle (restraining rear wheel in the forward direction only)

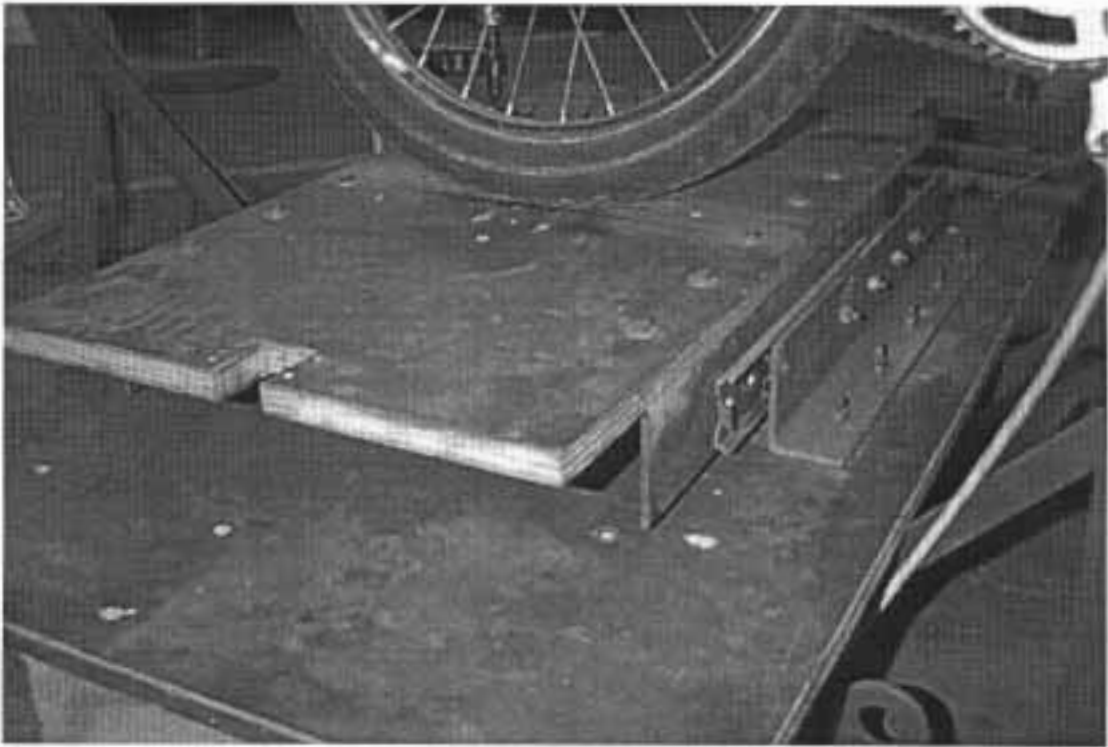


Plate 13 Rear Wheel Support

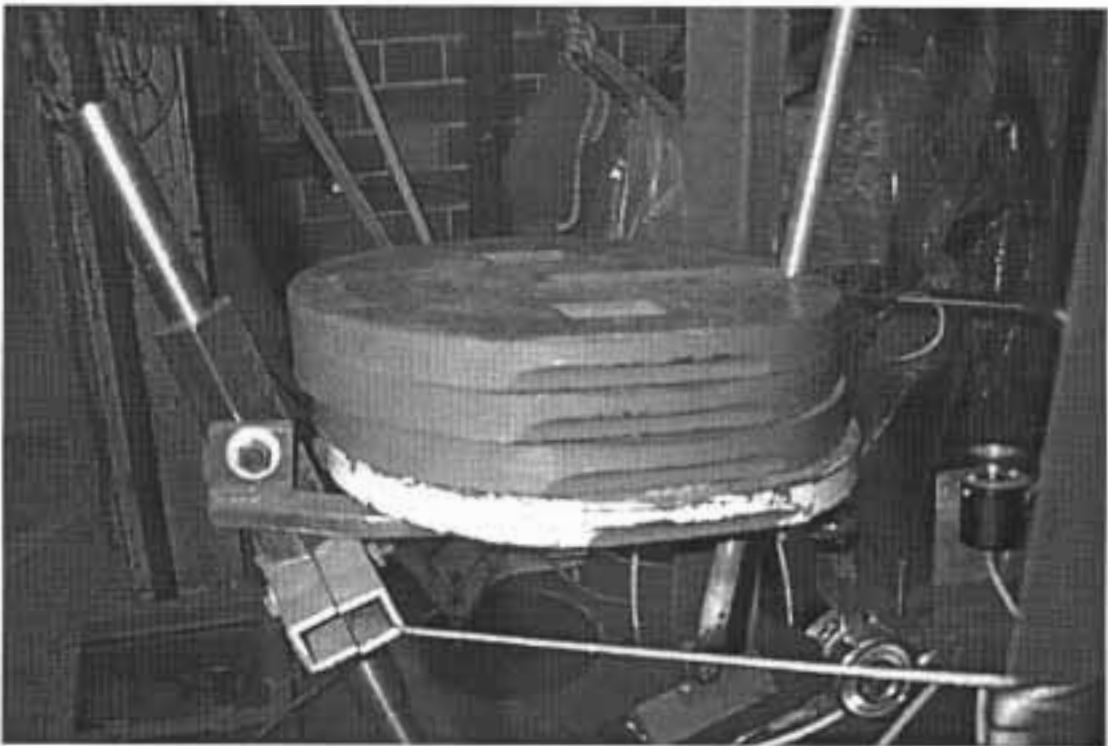
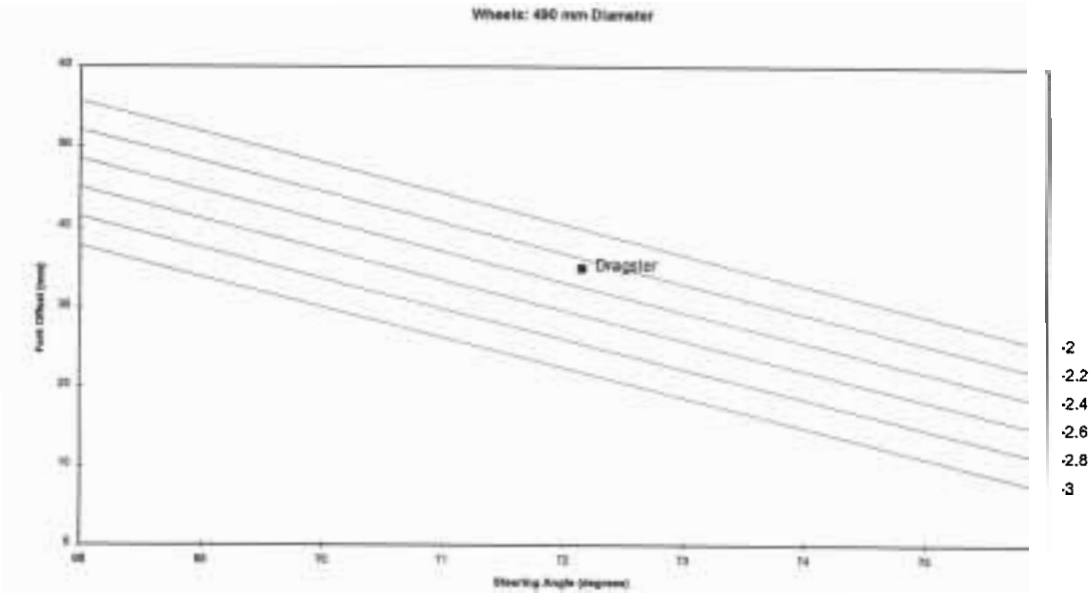
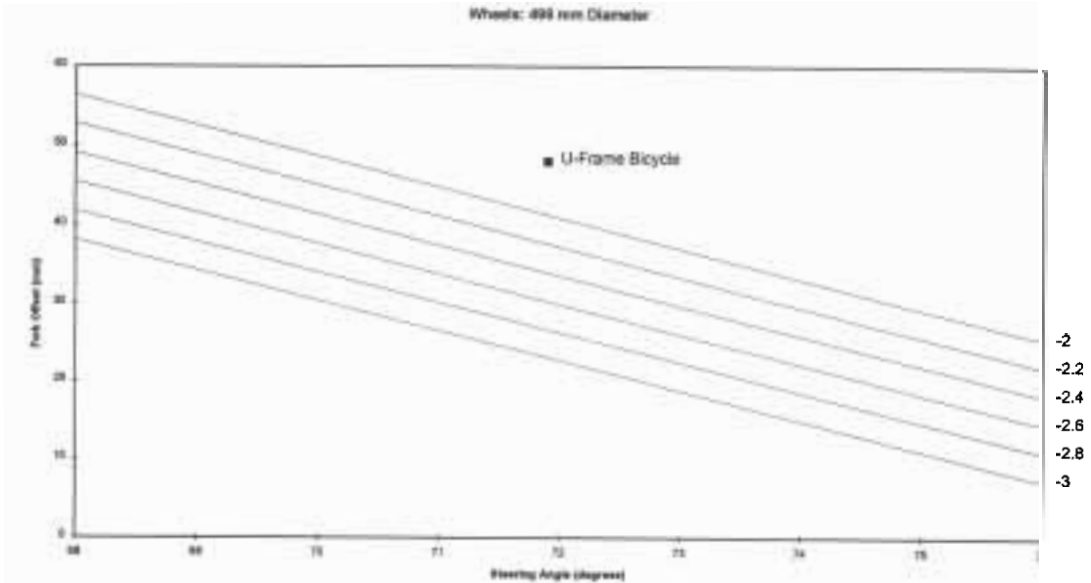


Plate 14 Weights on the Bicycle

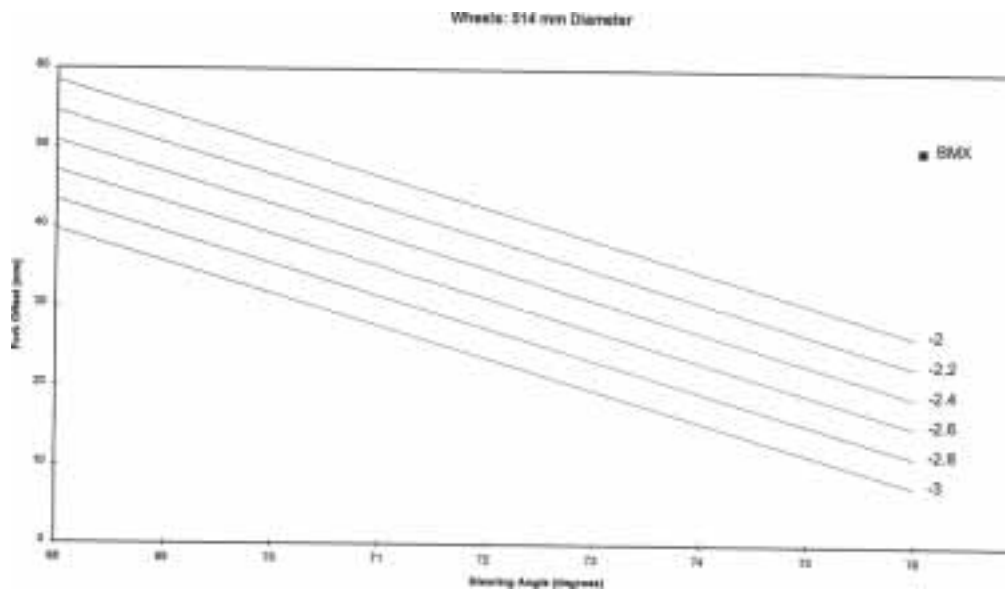
APPENDIX C.



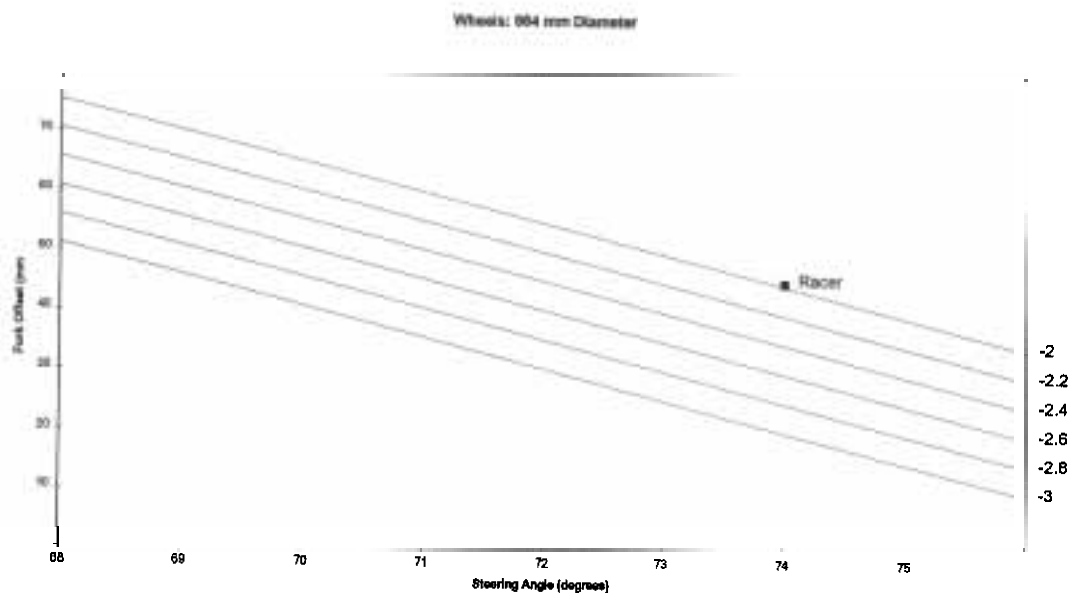
Graph 1 Steering Stability Factor for Dragster



Graph 2 Steering Stability Factor for U-Frame Bicycle



Graph 3 Steering Stability Factor for BMX



Graph 4 Steering Stability Factor for Racer

APPENDIX D.**Performance Categories:**

Highly Stable - would obtain a stable condition quickly and remain in a stable state

Stable - would obtain a stable condition after some time and remain in a stable state

Transitional - would obtain a stable condition but would sporadically jump between stable and unstable states

Unstable - would most often not obtain a stable condition and would often exhibit unstable behaviour

Highly Unstable - would not obtain stable condition and would not maintain a stable state

BMX Bicycle Testing**Test No. 1**

Front Wheel Elevation: 320 mm

Rear Wheel Elevation: 346 mm

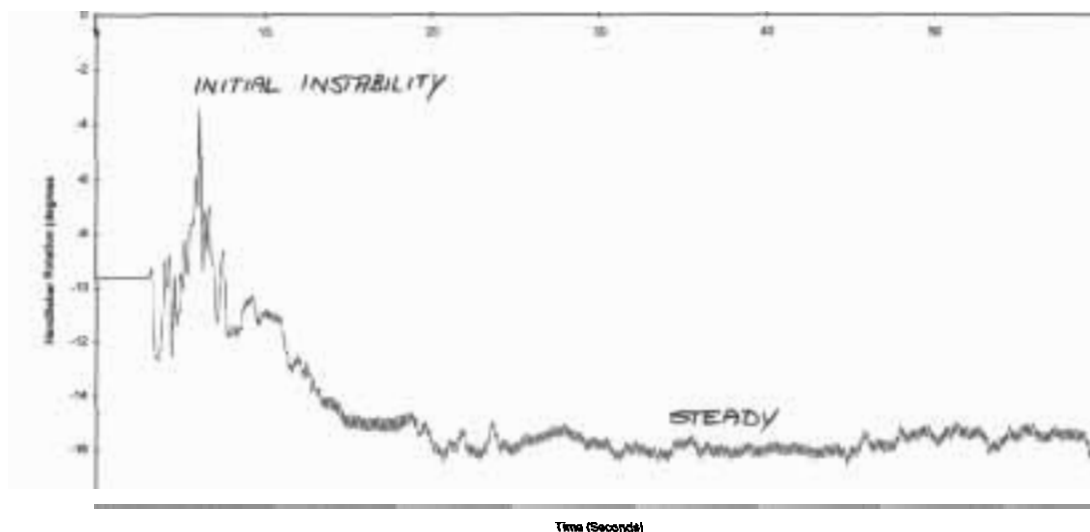
Height Difference: -26 mm

Trail: 5.34 mm

Without Knocking

Comments: Initially difficult, but became easier and steady. Category: Stable

BMX Bicycle, Trail: 5.3 mm (Without Knocking)



Test No. 2

Front Wheel Elevation: 320 mm

Rear Wheel Elevation: 346 mm

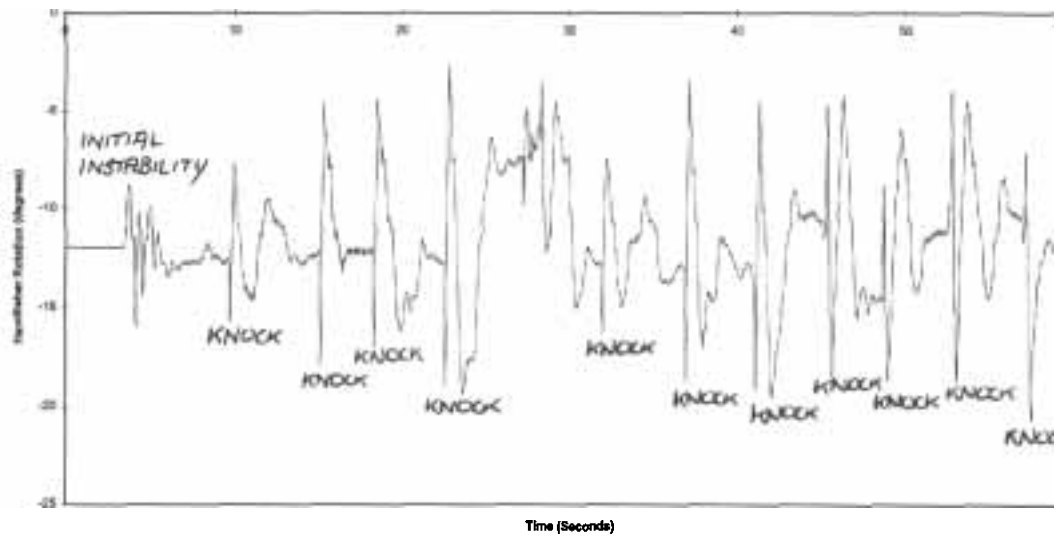
Height Difference: -26 mm

Trail: 5.34 mm

With Knocking

Comments: Recovered after each knock with little difficulty. Category: Stable

BMX Bicycle, Trail: 5.3 mm (Knocking)

**Test No. 3**

Front Wheel Elevation: 320 mm

Rear Wheel Elevation: 373 mm

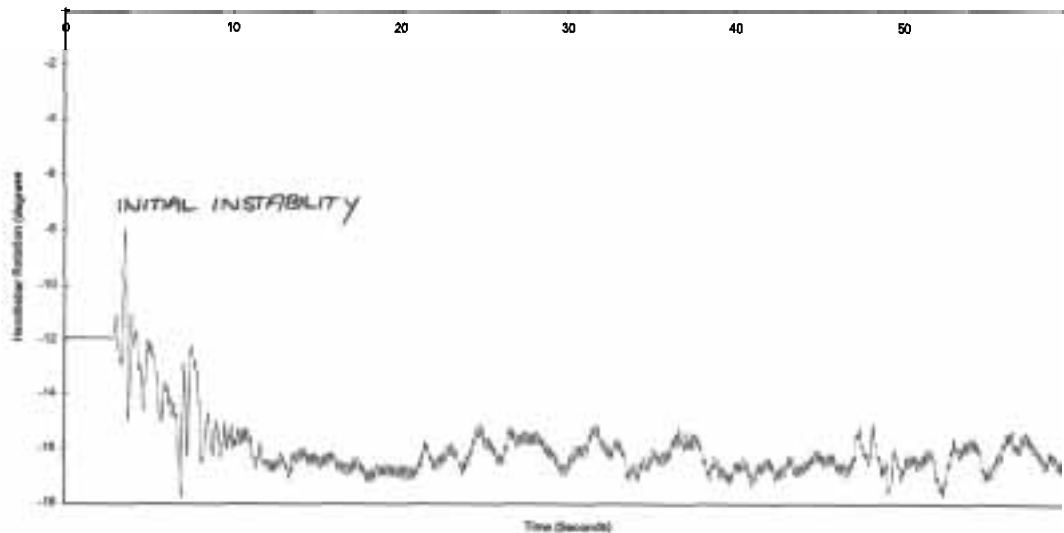
Height Difference: -53

Trail: -2.97 mm

Without Knocking

Comments: Would sometimes jump and kick. Some difficulty noticed. Category: Transitional

BMX Bicycle, Trail: -2.97 mm (Without Knocking)



Test No. 4

Front Wheel Elevation: 320 mm

Rear Wheel Elevation: 373 mm

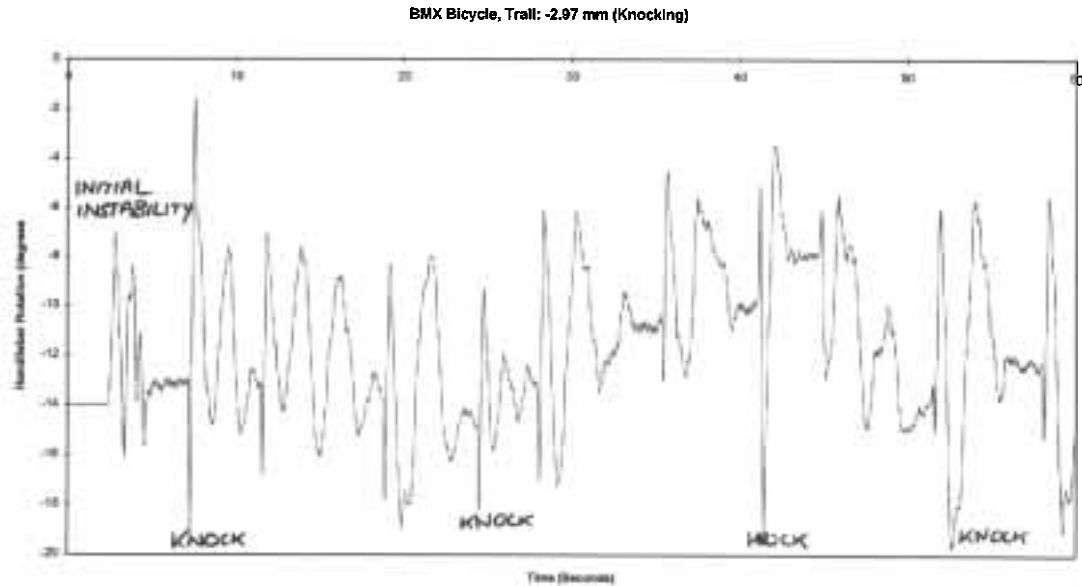
Height Difference: -53 mm

Trail: -2.97 mm

With Knocking

Comments: Unstable, would sometimes return, but spontaneously become unstable.

Category: Transitional

**Test No. 5**

Front Wheel Elevation: 320 mm

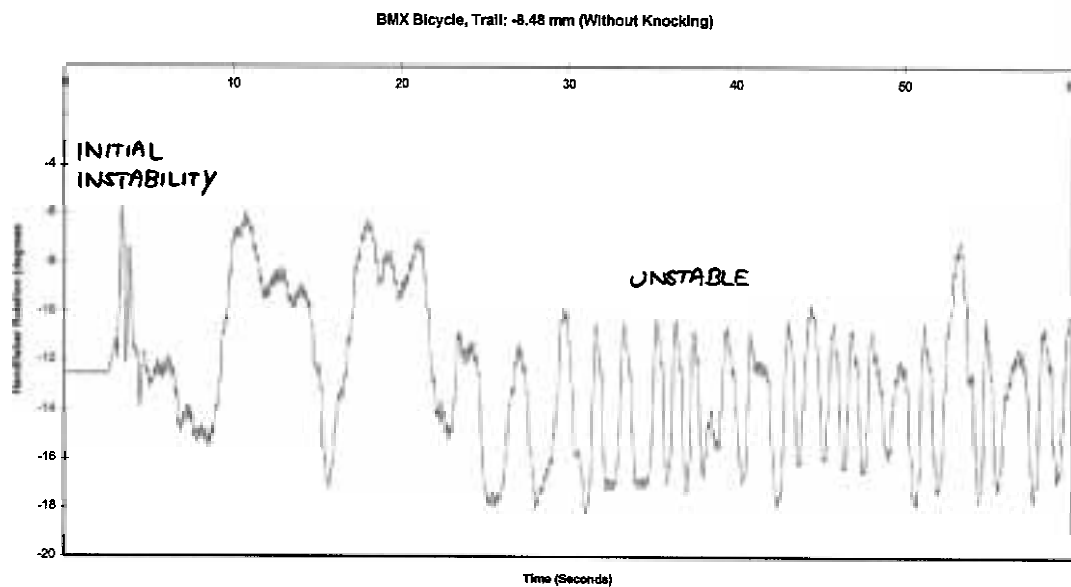
Rear Wheel Elevation: 394 mm

Height Difference: -74 mm

Trail: -8.48 mm

Without Knocking

Comments: All over the place, very unstable. Category: Highly Unstable



Test No. 6

Front Wheel Elevation: 320 mm

Rear Wheel Elevation: 394 mm

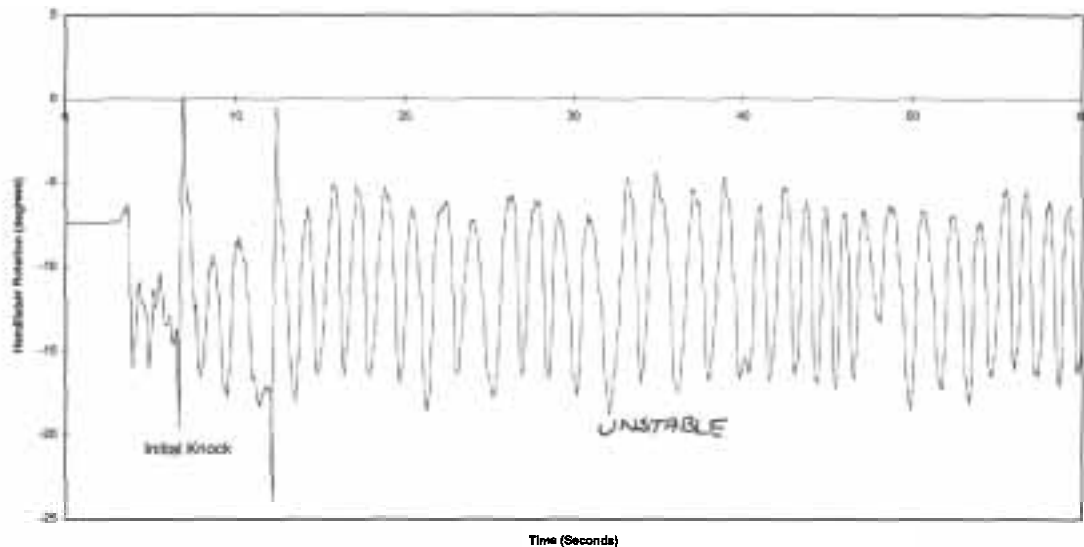
Height Difference: -74 mm

Trail: -8.48 mm

With Knocking

Comments: Never recovered from initial knock. Category: Highly Unstable

BMX Bicycle, Trail: -8.48 mm (Knocking)

**Test No. 7**

Front Wheel Elevation: 320 mm

Rear Wheel Elevation: 386 mm

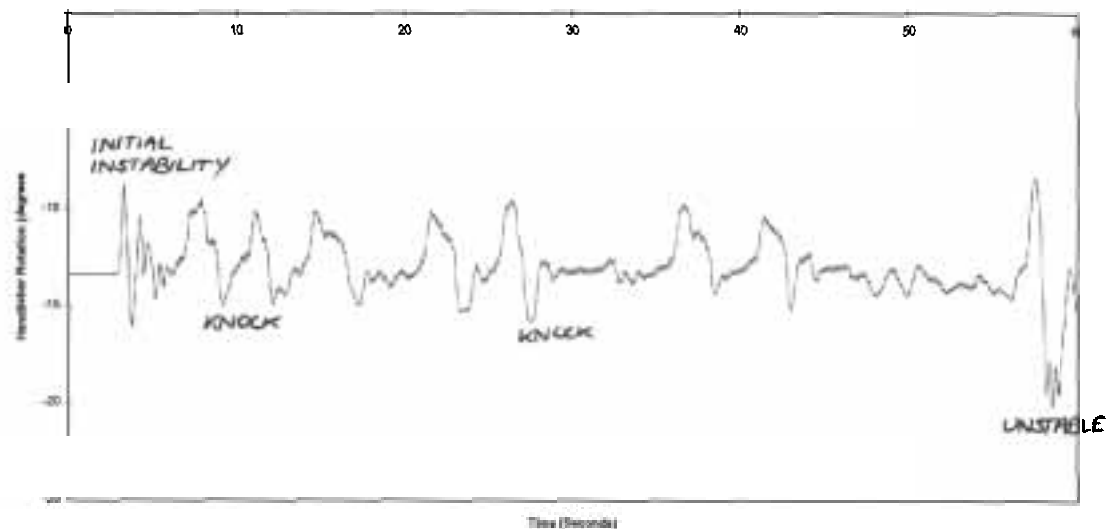
Height Difference: -66 mm

Trail: -5.73 mm

Without Knocking

Comments: Would spontaneously swish around. Category: Unstable

BMX Bicycle, Trail: -5.73 mm (Without Knocking)



Test No. 8

Front Wheel Elevation: 320 mm

Rear Wheel Elevation: 386 mm

Height Difference: -66 mm

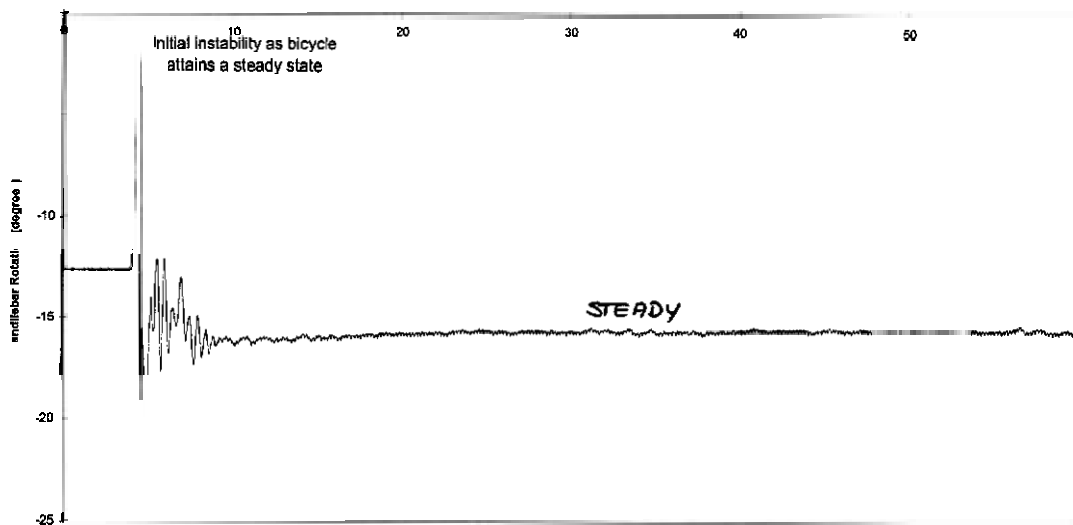
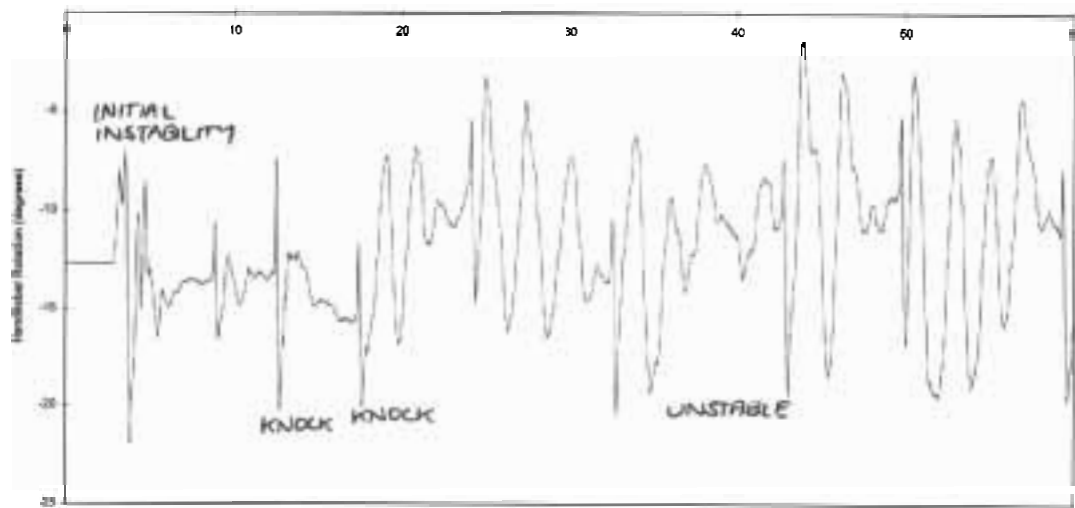
Trail: -5.73 mm

With Knocking

Comments: Would only sometimes recover. Would become unstable by itself in some cases.

Category: Unstable

BMX Bicycle, Trail: -5.73 mm (Knocking)



Test No. 10

Front Wheel Elevation: 320 mm

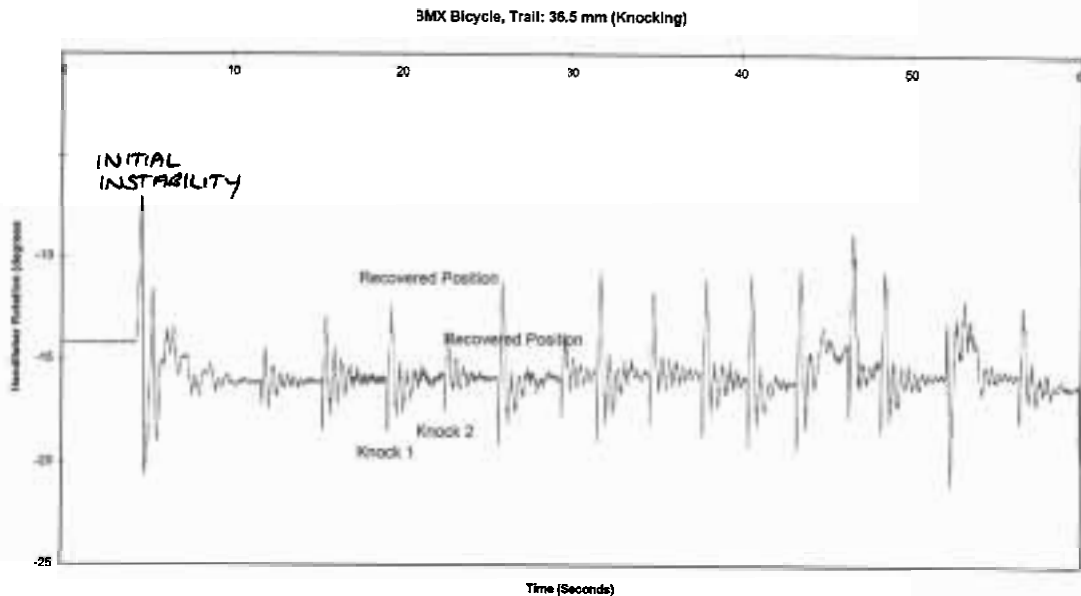
Rear Wheel Elevation: 234 mm

Height Difference: 86 mm

Trail: 36.5 mm

With Knocking

Comments: Would return to normal readily. Category: Highly Stable

**Test No. 11**

Front Wheel Elevation: 320 mm

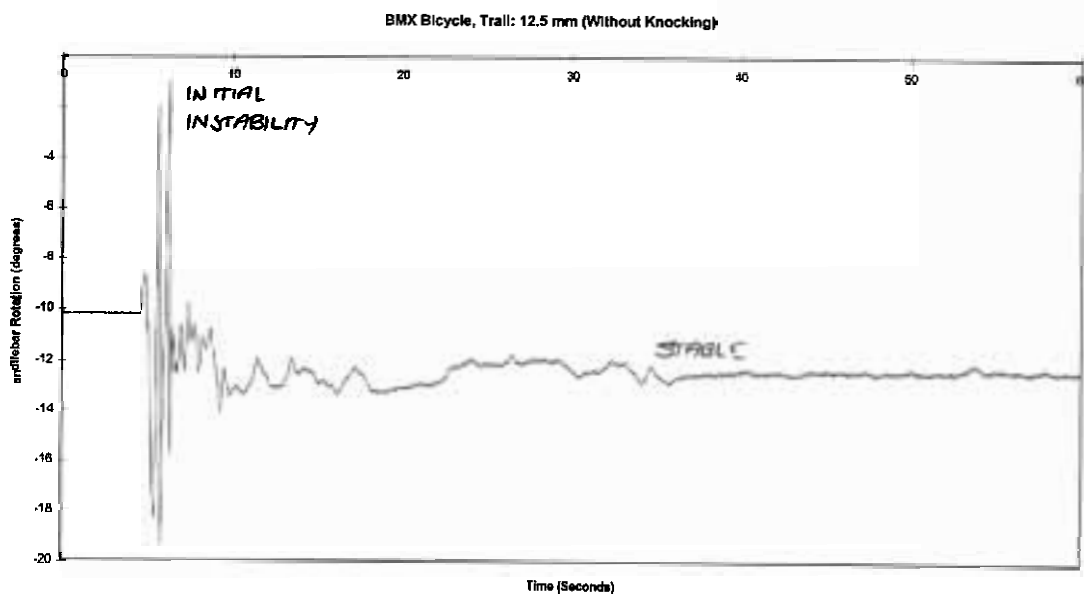
Rear Wheel Elevation: 318 mm

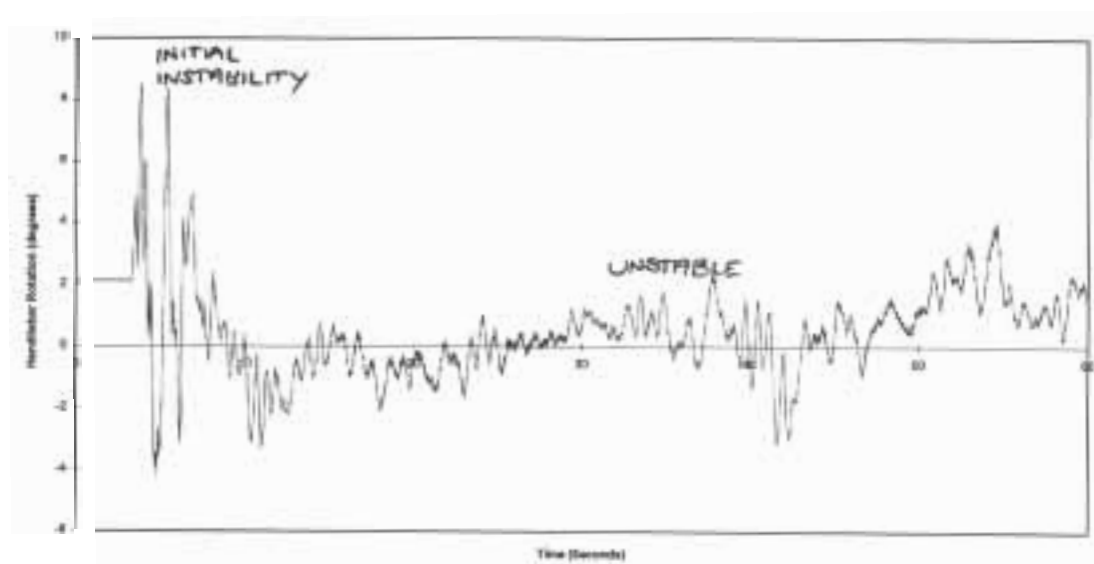
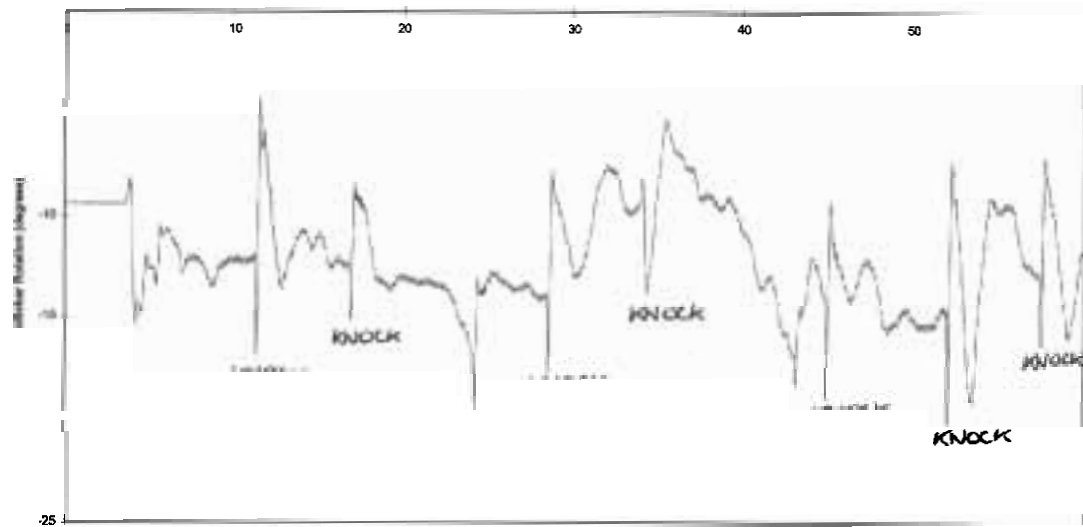
Height Difference: 2 mm

Trail: 12.5 mm

Without Knocking

Comments: Very stable. Category: Highly Stable





Test No. 2

Front Wheel Elevation: 320 mm

Rear Wheel Elevation: 347 mm

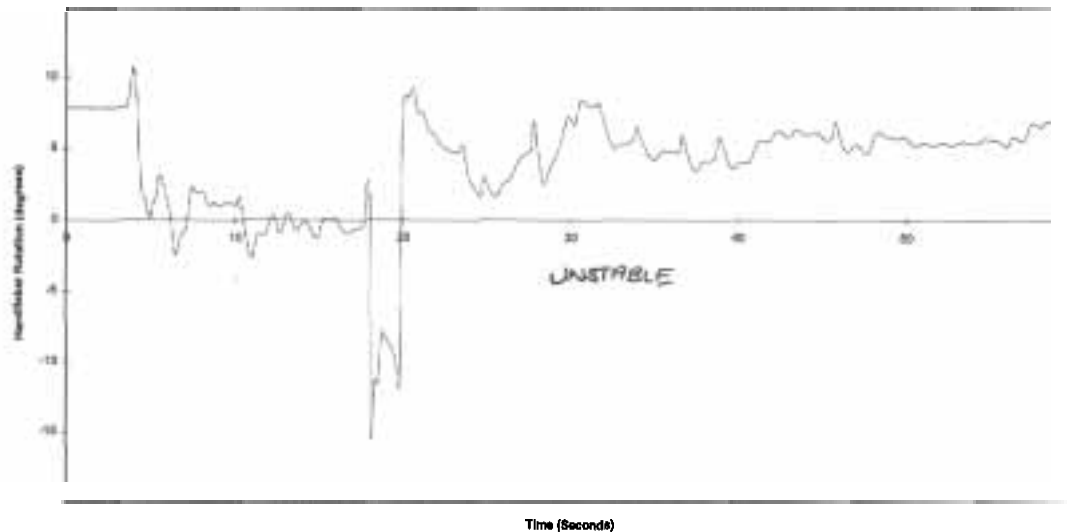
Height Difference: -27 mm

Trail: 15.27 mm

With Knocking

Comments: Would not come back under control. Handlebars had to be used to guide the bike under control as it was going to fly off the belt. Category: Highly Unstable

U Frame Bicycle, Trail: 15.27 mm (Knocking)

**Test No. 3**

Front Wheel Elevation: 320 mm

Rear Wheel Elevation: 310 mm

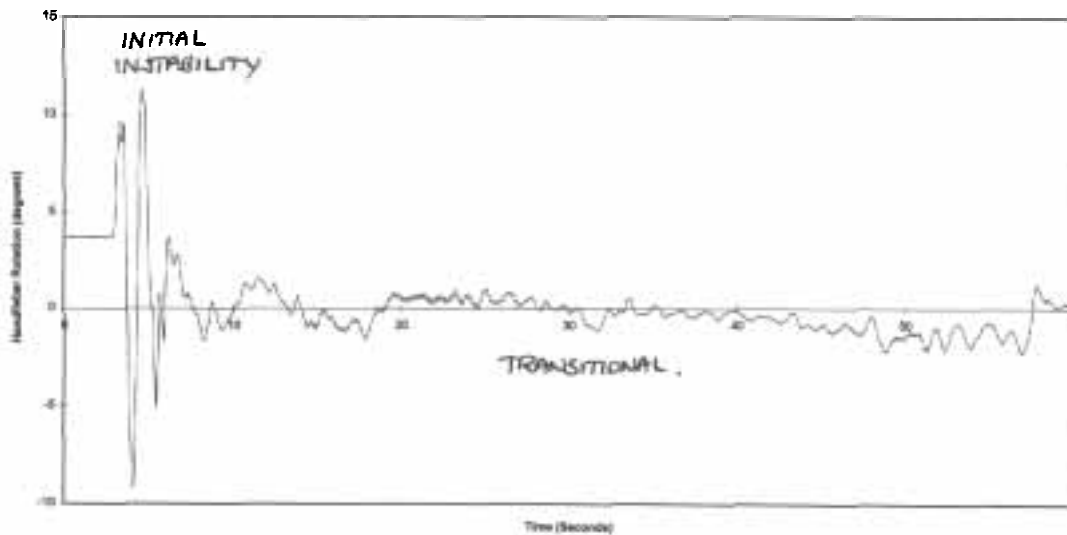
Height Difference: 10 mm

Trail: 24.7 mm

Without Knocking

Comments: Still bounced a bit. Greater control noticed. Category: Transitional

U Frame Bicycle, Trail: 24.7 mm (Without Knocking)



Test No. 4

Front Wheel Elevation: 320 mm

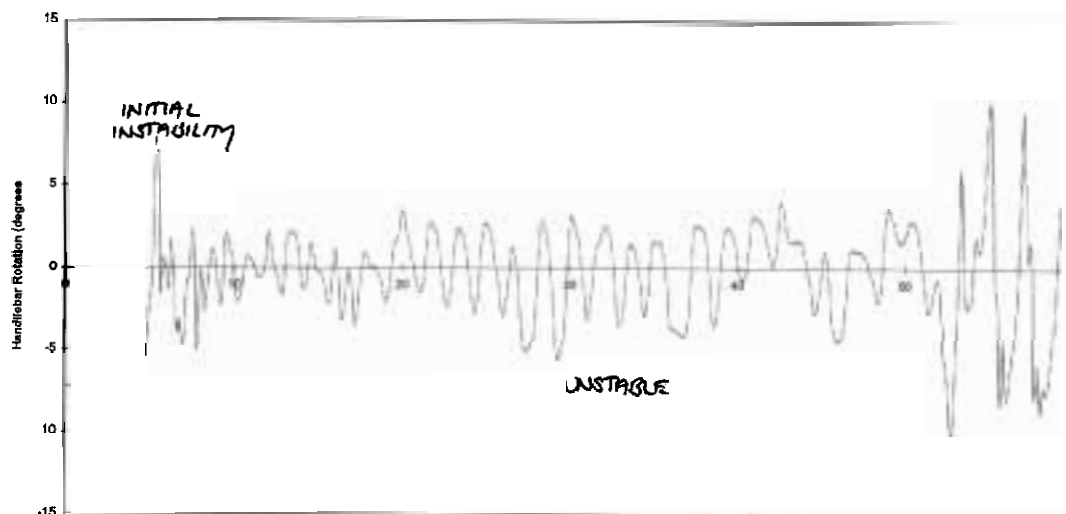
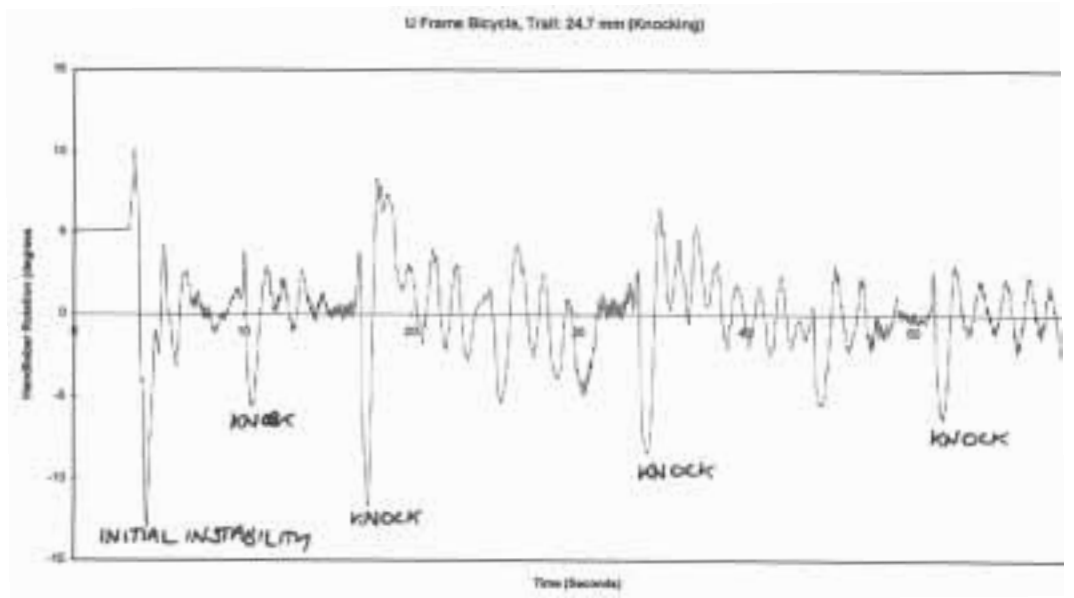
Rear Wheel Elevation: 310 mm

Height Difference: 10 mm

Trail: 24.7 mm

With Knocking

Comments: Would not recover. Category: Unstable



Test No. 2

Front Wheel Elevation: 320 mm

Rear Wheel Elevation: 347 mm

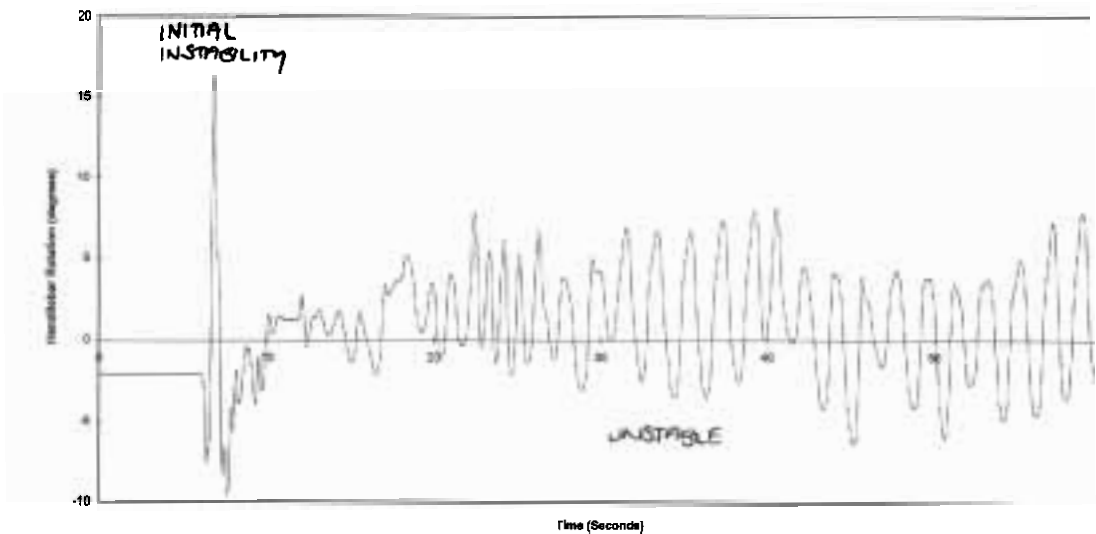
Height Difference: -27 mm

Trail: 33.6 mm

Without Knocking

Comments: Would not obtain a stable position at this speed. Category: Highly Unstable

Dragster Bicycle, Trail: 33.6 mm (Without Knocking)

**Test No. 3**

Front Wheel Elevation: 320 mm

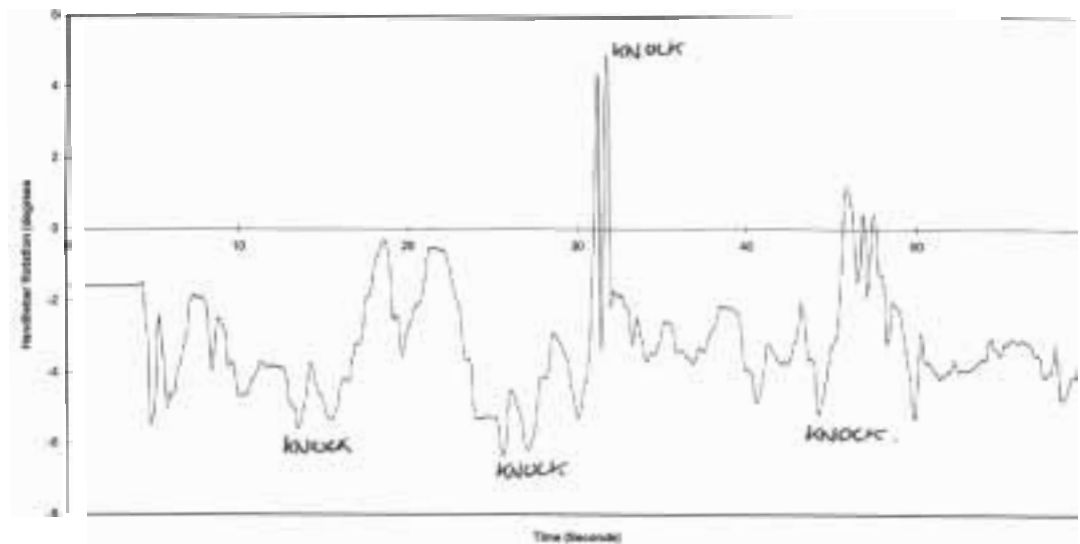
Rear Wheel Elevation: 310 mm

Trail: 43.2 mm

Without Knocking. Standard Handlebar Attached

Comments: Would move around a bit. Category: Transitional

Dragster Bicycle Standard Handlebars, Trail: 43.12 mm (Without Knocking)



Test No. 4

Front Wheel Elevation: 320 mm

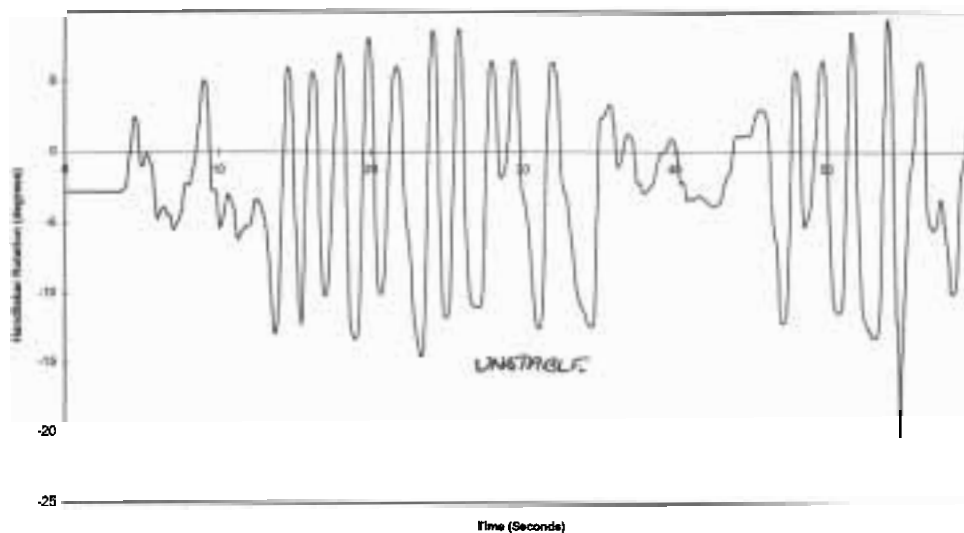
Rear Wheel Elevation: 310 mm

Trail: 43.2 mm

With Knocking. Standard Handlebar Attached

Comments: Would not recover. Category: Unstable

Dragster Bicycle Standard Handlebars, Trail: 43.2 mm (With Knocking)

**Test No. 5**

Front Wheel Elevation: 320 mm

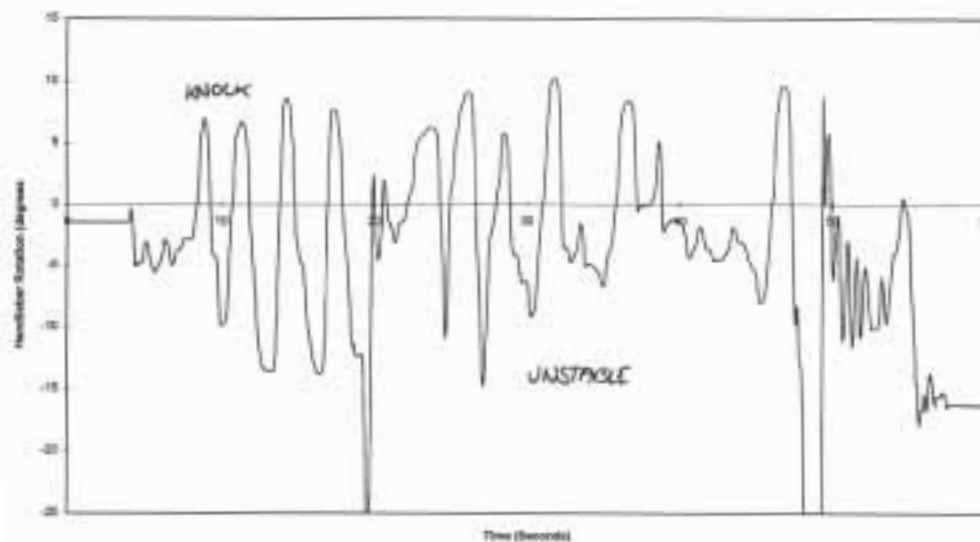
Rear Wheel Elevation: 347 mm

Trail: 33.6 mm

Without Knocking. Standard Handlebar Attached

Comments: Would not recover. Category: Unstable

Dragster Bicycle Standard Handlebars, Trail: 33.6 mm (Without Knocking)



Test No. 6

Front Wheel Elevation: 320 mm

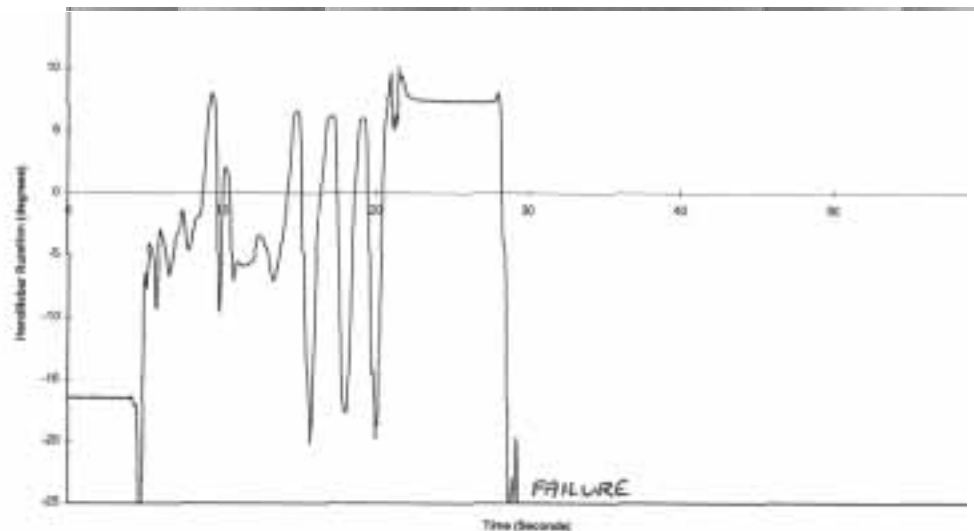
Rear Wheel Elevation: 347 mm

Trail: 33.6 mm

With Knocking. Standard Handlebar Attached

Comments: Would not recover. Category: Highly Unstable

Dragster Bicycle Standard Handlebars, Trail: 33.6 mm (With Knocking)

**Racing Style Bicycle****Test No. 1**

Front Wheel Elevation: 320 mm

Rear Wheel Elevation: 347 mm

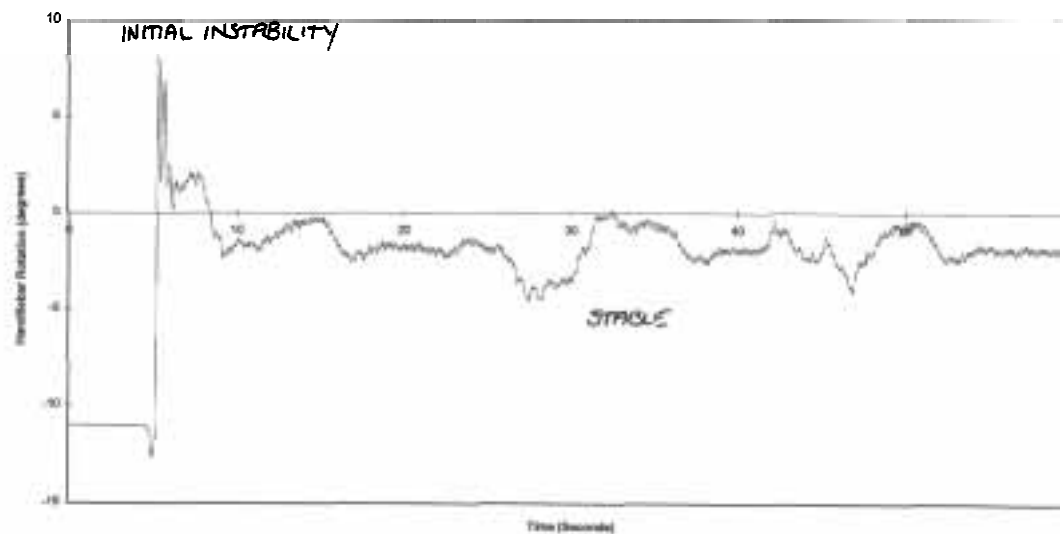
Height Difference: -27 mm

Trail: 37.8 mm

Without Knocking

Comments: No problems noticed. Category: Highly Stable

Racing Bicycle, Trail: 37.8 mm (Without Knocking)



Test No. 2

Front Wheel Elevation: 320 mm

Rear Wheel Elevation: 347 mm

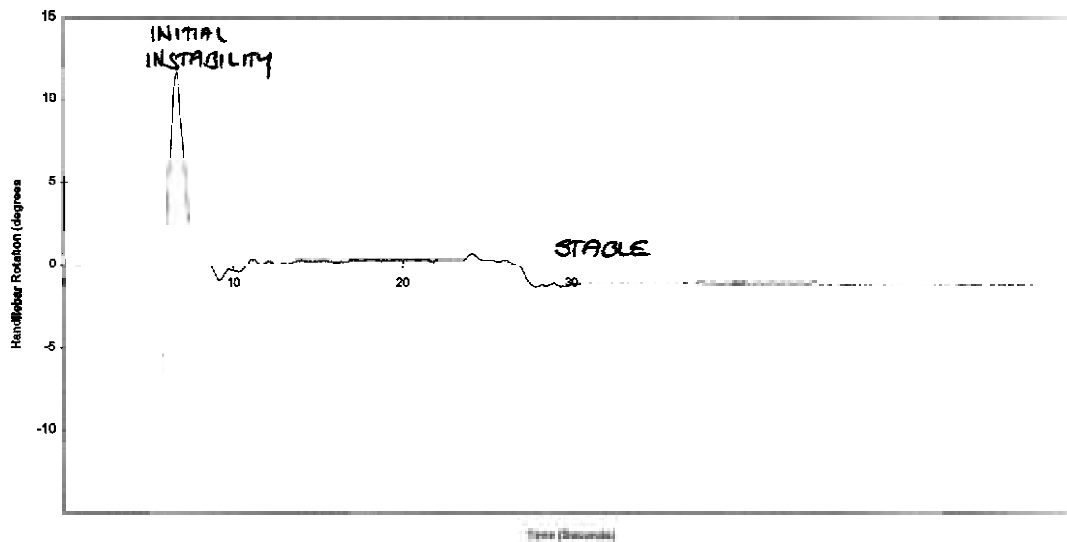
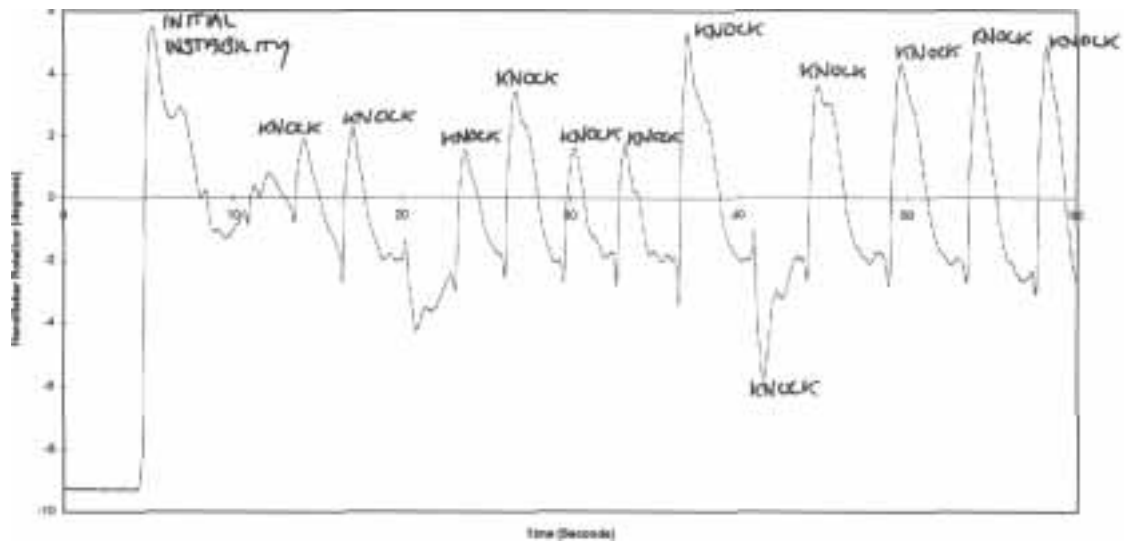
Height Difference: -27 mm

Trail: 37.8 mm

With Knocking

Comments: No problems noticed. Would recover readily. Category: Highly Stable

Racing Bicycle, Trail: 37.8 mm (Knocking)



Test No. 4

Front Wheel Elevation: 320 mm

Rear Wheel Elevation: 310 mm

Height Difference: 10 mm

Trail: 54.0 mm

With Knocking

Comments: No problems noticed. Would recover readily. Category: Highly Stable

Racing Bicycle, Trail: 54 mm (Knocking)

