Stability of motorcycles on audio tactile profiled (ATP) roadmarkings

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An important note for the reader

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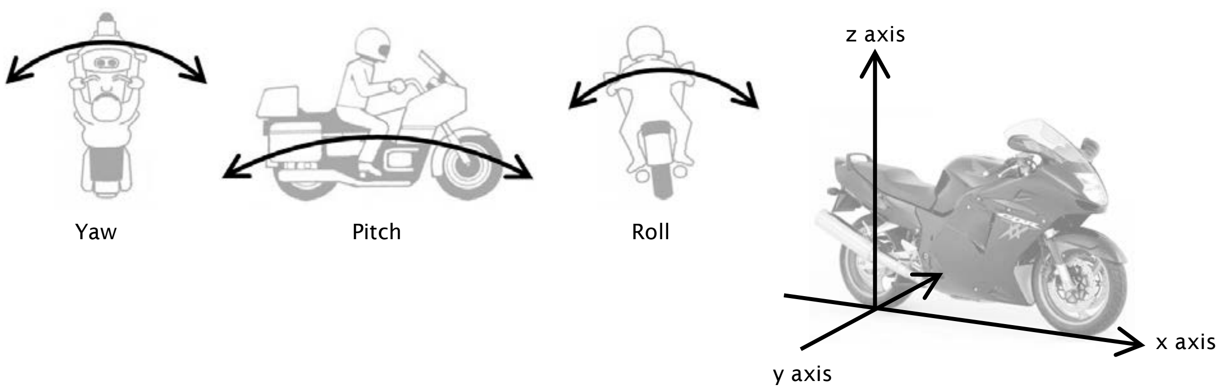
Acronyms and terms

ATP roadmarkings	Audio tactile profiled roadmarkings, also known as rumble strips, have raised ribs or mounds arranged in a line adjacent and parallel to the traffic flow
CAS	Crash Analysis System database
Heading angle	The direction the line of the motorcycle body is pointing relative to a 0° datum, usually north
Motorcycle	The range within vehicle class LC (Motorcycle) being motor vehicles that have two wheels and either an engine cylinder capacity exceeding 50ml or a maximum speed exceeding 50km/h. This includes motorcycles and motor scooters but excludes mopeds, farm bikes and all-terrain vehicles (ATVs)
MOTSAM	*Manual of traffic signs and markings*
NZTA M/24	The NZ Transport Agency specification for ATP roadmarkings
Rib	The raised block, bar, or mound of the ATP roadmarking
Rib height	The vertical distance between the top of the rib and the surface upon which the rib is installed
Rib length	The longitudinal distance of the rib measured parallel to the traffic flow
Rib spacing	The longitudinal distance between consecutive ribs measured parallel to the traffic flow, alternatively called 'pitch'
Rib width	The 'face' distance of the rib measured perpendicular to the traffic flow
Steering angle	The angle between the direction of the line of the motorcycle body and the direction the steered front wheel of the motorcycle is pointing



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Executive summary

New Zealand has adopted the use of raised-profile type of audio tactile profiled (ATP) roadmarkings. As a key initiative for addressing the issue of high-risk rural roads, the NZ Transport Agency's (NZTA's) use of ATP roadmarkings has accelerated since 2008/2009. Although the current use of ATP roadmarkings does not appear to be causing any motorcycle stability issues, the NZTA requires a better understanding of any stability issues associated with two-wheeled vehicles (particularly motorcycles) crossing ATP roadmarkings on straights, bends, edge lines and centrelines. This research project was undertaken in 2011/2012 to help to address gaps in the available international literature on the stability of two-wheeled vehicles when travelling on or across ATP roadmarkings.

In terms of operating characteristics, the range of two-wheeled vehicles likely to encounter ATP roadmarkings is broad, from bicycles through to powerful motorcycles. Bicycles have often been identified as being vulnerable to the effects of encountering ATP roadmarkings or other road surface irregularities. There is a body of literature and work that focuses on this topic, and recommendations targeted at minimising bicycle contact have been incorporated into ATP roadmarkings standards and guidelines.

The current use of ATP roadmarkings assumes that ATP roadmarkings of the dimensions used in New Zealand present no special issues for motorcycles, nor has any stability issue become apparent to date. New Zealand studies reviewing the effects of ATP roadmarkings have included analysis of statistics for all road user crashes in New Zealand and have associated the use of ATP roadmarkings with a 15–20% reduction in crashes. These studies did not highlight any anomalous effects of ATP roadmarkings for motorcycles – but nor was that the focus of those studies. It is possible that any problem of ATP roadmarkings causing instability for motorcycles may have been masked by a general trend of crash reduction.

At the time of the research, the primary use of ATP roadmarkings in New Zealand was on open highways; therefore the focus was on the stability of motorcycles at high speeds, up to 100km/h, on ATP roadmarkings.

An analysis of existing crash records was undertaken to identify if there was any existing evidence of motorcycles instability on ATP roadmarkings associated with their current use in New Zealand. The analysis inspected the details of motorcycle/moped crashes that had been reported to New Zealand Police in locations where ATP roadmarkings were likely to be present. Ninety-one motorcycle/moped qualifying crashes were identified and the traffic crash reports for those crashes were extracted and manually reviewed. None of the reports indicated evidence of the involvement of ATP roadmarkings in the crash.

To establish if there was any emerging evidence of motorcycle instability on ATP roadmarkings, associated literature was reviewed. The literature included coverage of:

- the impacts on motorcycles when they contact ATP roadmarkings
- the impacts on motorcycles when they contact other surface irregularities
- other overseas analyses of motorcycle crash records
- the likelihood of motorcycles contacting ATP roadmarkings and subsequently suffering harm.

The broad collection of associated literature contained no evidence that the current New Zealand usage and dimensions of ATP roadmarkings would cause significant instability issues to motorcycles.

Simulation of interactions of motorcycles with ATP roadmarkings was performed to examine and identify any potential instability effects of ATP roadmarkings on motorcycles. This comprised two parts:

1 validation of the computer simulation via full-scale physical tests within the limits of safe and ethical experimentation

2 extension of the computer simulation to simulate motorcycle travel over ATP roadmarkings at open road speeds.

Full-scale physical tests were undertaken with an instrumented motorcycle ridden on a range of ATP roadmarking profiles at a range of speeds on straights and low-radius corners. The motorcycle instrumentation included accelerometers, load cell, and a data acquisition system. For test-runs that included ATP roadmarking ribs, the ribs were uniform wooden blocks adhered to the road surface so there was no movement of the ribs as they were traversed by the motorcycle. The instrumented motorcycle was ridden for each test-run with the specified speed and riding-line being as consistent as possible. Data was recorded continuously at a rate of 1000Hz for each test-run.

For the simulation modelling, PC-Crash (3D Version 9) was used. PC-Crash is an internationally-recognised three-dimensional vehicle crash and trajectory simulation modelling software. Through reasonable agreement between the full-scale physical data and the computer simulation data, the PC-Crash model was verified as suitable for the ATP roadmarking simulation tasks intended.

PC-Crash was used to simulate model-runs for each of three motorcycles, at two speeds, with different braking scenarios – both *with* and *without* ATP roadmarking ribs, so the effects of the ATP roadmarkings on motorcycle stability could be produced.

The full-scale physical testing simulations and the PC-Crash simulations showed no significant stability or loss-of-control differences between the simulations with *no* ATP roadmarkings and the simulations *with* ATP roadmarkings. Some simulations included conditions that led to motorcycle instability or loss of control, and in these simulations there were also no significant differences between the simulations with *no* ATP roadmarkings and the simulations *with* ATP roadmarkings.

When trying to maintain the same vehicle path, the PC-Crash simulations showed that contacting ATP roadmarkings did effect small differences in the steering angles, and consequently the heading angles, compared with not contacting ATP roadmarkings. The differences were small.

From the existing crash records, the literature, and validated computer simulation modelling, this research found no evidence that ATP roadmarkings as currently used in New Zealand create any significant instability issues for motorcycles. Therefore, at this stage it appears there is no need to change current practice in this area.

Abstract

New Zealand has adopted the raised-profile type of audio tactile profiled (ATP) roadmarkings. This research was undertaken in 2011/2012 to help address gaps in available international literature on the stability of motorcycles when travelling on or across ATP roadmarkings.

The research investigated the stability of motorcycles when contacting ATP roadmarkings, through evidence of traffic crash reports from motorcycle crashes at locations where ATP roadmarkings were present, a review of associated international literature, and simulation of motorcycles interacting with ATP roadmarkings via full-scale physical testing and computer simulation testing.

This research found no evidence that ATP roadmarkings as currently used in New Zealand create any significant instability issues for motorcycles.

1 Introduction

New Zealand has adopted the use of raised-profile type of audio tactile profiled (ATP) roadmarkings. This is distinct from the indented-pavement type of ATP roadmarking that is used in some countries, especially the US. The raised-profile type of ATP roadmarking is used either in the form of raised ribs over a base roadmarking line, or as raised ribs beside a roadmarking line that increases the effective width of the roadmarking.

Raised-profile ATP roadmarkings have been used for many years (20+) in the UK and in Australia. They were seldom used in New Zealand until 2004 when, following successful trials within the South Waikato and Taupo treatment areas, the use of ATP roadmarkings was expanded. Since 2008/2009, the use of ATP roadmarkings in New Zealand accelerated further as their effectiveness became apparent and as more funds became available via a specific government package (NZTA 2009).

In developing its usage of ATP roadmarkings and in responding to received correspondence and parliamentary questions, the NZ Transport Agency (NZTA) has consulted representative motorcycle groups and available research and literature, but none of these have provided conclusive statements about the effects of ATP roadmarkings on motorcycle stability. Although the current use of ATP roadmarkings does not appear to be causing any motorcycle stability issues, in 2011 the NZTA commissioned the research described in this report to 'help to address gaps in available international literature on the stability of two-wheeled vehicles when travelling on or across [ATP roadmarkings]' (NZTA 2011).

In terms of operating characteristics, the range of two-wheeled vehicles likely to encounter ATP roadmarkings is broad, from bicycles through to powerful motorcycles. Bicycles have often been identified as being vulnerable to the effects of encountering ATP roadmarkings or other road surface irregularities. There is a body of literature and work that focuses on this topic, and recommendations targeted at minimising bicycle contact have been incorporated into standards and guidelines for ATP roadmarkings. The current use of ATP roadmarkings assumes that ATP roadmarkings of the dimensions used in New Zealand present no special issues for motorcycles, nor has any stability issue become apparent to date. New Zealand studies reviewing the effects of ATP roadmarkings by Charlton (2006) and James (2011) included analysis of statistics for all road user crashes in New Zealand and have associated the use of ATP roadmarkings with a 15–20% reduction in crashes. These studies did not highlight any anomalous effects of ATP roadmarkings for motorcycles – but nor was that the focus of those studies. It is possible that any problem of ATP roadmarkings causing instability for motorcycles may have been masked by a general trend of crash reduction.

At the time of the research, the primary use of ATP roadmarkings in New Zealand was on open highways; therefore the focus was on the stability of motorcycles at high speeds, up to 100km/h, on ATP roadmarkings.

1.1 Report structure

Chapter 2 of this report gives the context for ATP roadmarkings in New Zealand. Then the report format follows the sequence of the research objectives as follows:

- Chapter 3 reports on the process and results of an analysis of existing crash records that was undertaken to identify if there was any existing evidence of motorcycle instability on ATP roadmarkings associated with their current use in New Zealand.

- Chapter 4 outlines findings from a literature review that was conducted to establish if there was any emerging evidence of motorcycle instability on ATP roadmarkings in the international literature, or if any issue could be inferred from the literature regarding two-wheeled vehicle instability on other road surface irregularities.
- Chapter 5 reports further examination of any potential instability effects of ATP roadmarkings on motorcycles via the use of an existing vehicle behaviour model. This includes validation of the model via physical tests, within the limits of safe and ethical experimentation.
- Chapter 6 presents the conclusions drawn from this research and the recommendations made.

2 ATP roadmarkings in New Zealand

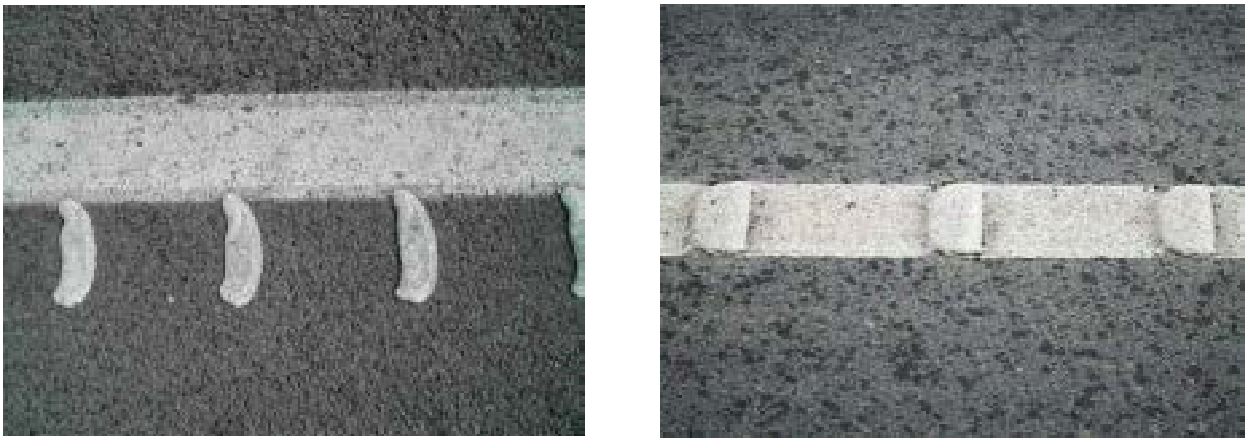
The two primary documents prescribing ATP roadmarkings in New Zealand are the *Manual of traffic signs and markings* (MOTSAM) (NZTA 2010b) and the *TNZ M/24 Specification for audio tactile profiled roadmarkings – Part 2: markings* (TNZ 2006).

In particular, section 4.08 of MOTSAM Part 2 sets out where ATP roadmarkings can be used, and notes that their predominant use is for edge lines and that ATP roadmarkings should never be used transversely. ATP roadmarkings in New Zealand can also be used for lane lines and centrelines in restricted circumstances, and may only be used for centrelines if the edge lines are also profiled. The approval of the National Traffic and Safety Manager of the NZTA is required before ATP roadmarkings may be installed on state highway centrelines. With particular regard to placement and cyclists, and possibly all two-wheeled vehicle users, it is noted that:

> *... gaps of at least 20 metres must be left in ATP [roadmarking] edge lines wherever cyclists may have a need to cross them, eg on bridge approaches, near narrow shoulders, near intersections or junctions with off-road facilities* (NZTA 2010b).

In New Zealand, ATP roadmarkings are 'typically plastic lumps (also called blocks or ribs) that are laid onto the road surface or as a combined rib/line project normally at spacings of 250 or 500mm' (NZTA 2010a). The photographs in figure 2.1 illustrate the two configurations.

Figure 2.1 ATP road markings used in New Zealand (NZTA 2010a)



TNZ M/24 Specification for audio tactile profiled roadmarkings (TNZ 2006) gives specification of the form, installation and materials of the ATP roadmarking designs to be used in New Zealand. It is framed to 'ensure ATP roadmarkings installed on New Zealand roads provide road users with effective audio, tactile, and visual information'. The specification does not define the design of ATP roadmarkings but allows flexibility and innovation within ATP roadmarking designs, provided any design maintains effective provision of audio, tactile and visual information. The specification does include some prescription, notably that the maximum height (vertical distance) between the top of the ATP roadmarking ribs and the road surface upon which the ATP roadmarkings are installed can be no more than 9mm. (Superseded versions of MOTSAM contained dimensions to which ATP roadmarkings were to conform, but this approach to ATP roadmarking design was removed following publication of TNZ M/24.)

'Visual information' from ATP roadmarkings is communicated by the colour and retroreflectivity of the material, plus MOTSAM recommends:

> *... the profiled ribs should normally be placed on top of, overlapping or alongside the flat or structured marking and protruding at least 25mm but preferably 50mm beyond it so as to be clearly visible to users of two wheeled vehicles, except that for edge lines the profiled ribs may be installed entirely on the shoulder side of the marking* (NZTA 2010b).

3 Analysis of recent two-wheeled vehicle crash records

This analysis inspected the details of motorcycle/moped crashes that had been reported up to November 2011 to New Zealand Police in locations where ATP roadmarkings were likely to be present. The crashes were selected by the following process:

1. A listing of all ATP roadmarking state highway installation locations and dates was obtained from the NZTA in November 2011. The installations were typically either white edge lines or yellow centrelines. The earliest date of installation was within 2005. A large number of installations had no installation date in the listing.
2. In December 2011, a listing of all state highway injury and non-injury crashes involving motorcycles and/or mopeds reported to police since 2005 was obtained from the Crash Analysis System database (CAS). Although it is noted the reporting rate of non-injury crashes is low, the crash listing obtained from CAS included non-injury crashes as these could be considered ‘near misses’, indicating potential issues.
3. To identify those crashes in the listing that occurred where and when ATP roadmarkings were likely to be present, an algorithm was run to inspect the location and date of each crash against the locations and dates of ATP roadmarkings installations in that area. The location information format followed the NZTA’s Location Referencing System of state highway number/reference station/kilometres past the reference station. The CAS database warns ‘... spatial selection of state highway crashes is more reliable than using [the Location Referencing System]’. This potential migration could mean that some crashes in the listing were recorded as outside the location of ATP roadmarkings when they were actually inside, and vice versa.

Ninety-one[1] motorcycle/moped crashes were found to have occurred where ATP roadmarkings were likely to be present. The traffic crash reports for those 91 crashes were extracted from CAS and manually reviewed. The crashes covered the severity spectrum from non-injury to serious. Of the 91 crashes, 52 occurred in areas with speed limits greater than 70km/h and 39 occurred in areas with speed limits of 70km/h or less. Table 3.1 gives some detail of the movements involved in the 91 crashes.

Table 3.1 Crash type (according to CAS categories) of the 91 crashes

Crash type		Number	Comment
A	Overtaking and lane change	6	Motorcycle hit other vehicle in 2 crashes, motorcycle hit by other vehicle in 4 crashes
B	Head-on	1	
C	Lost control on straight road	12	
D	Lost control cornering or missed intersection	16	Road surface factor suspected in 11 of the 16 crashes
E	Collision with obstruction	1	
F	Rear end	11	
G	Turning versus same direction	7	
H	Crossing (no turns)	4	

[1] On inspection, one of these crashes was found to have involved a mobility scooter miscoded as a moped.

Crash type		Number	Comment
J	Crossing (vehicle turning)	11	
K	Merging	8	
L	Right turn against	7	
M	Manoeuvring	6	
N	Pedestrians crossing road	0	
P	Pedestrians other	0	
Q	Miscellaneous	1	Truck hit motorcycle after damage to truck tyre

Manual review of the traffic crash reports found no reports indicating evidence of the involvement of ATP roadmarkings in the crash.

4 Literature on ATP roadmarkings and motorcycles

4.1 Impacts on motorcycles of contacting ATP roadmarkings

This research inspected for historical crash-related evidence of the impacts on two-wheeled vehicles of contacting ATP roadmarkings.

Edgar et al (2008) conducted a review of the usability and safety of ATP roadmarkings in New Zealand. The review was consultative in nature and followed work (Baas et al 2004; Charlton 2006) related to the safety impacts of ATP roadmarkings. Motorcyclists were an integral part of the consultation. Edgar et al stated that there had been no reports of motorcycle crashes involving these roadmarkings. Highway managers reported they had received no complaints about these roadmarkings from motorcyclists, although Edgar et al did note that a motorcyclist gave a contrary view at an industry workshop conducted as part of their project.

Edgar et al (ibid) also stated that specifications and guidelines existing in New Zealand at the time of their review were designed to mitigate any impact on motorcyclists who might stray onto the ATP roadmarkings. They noted those specifications and guidelines contained limitations on the use of ATP roadmarkings '... such that they may not be placed where they may be legally driven or ridden on'. By the time of this research (2011/2012), that situation had changed and ATP roadmarkings were being used in situations where they could be legally be traversed.

MOTSAM (NZTA 2010b) states that:

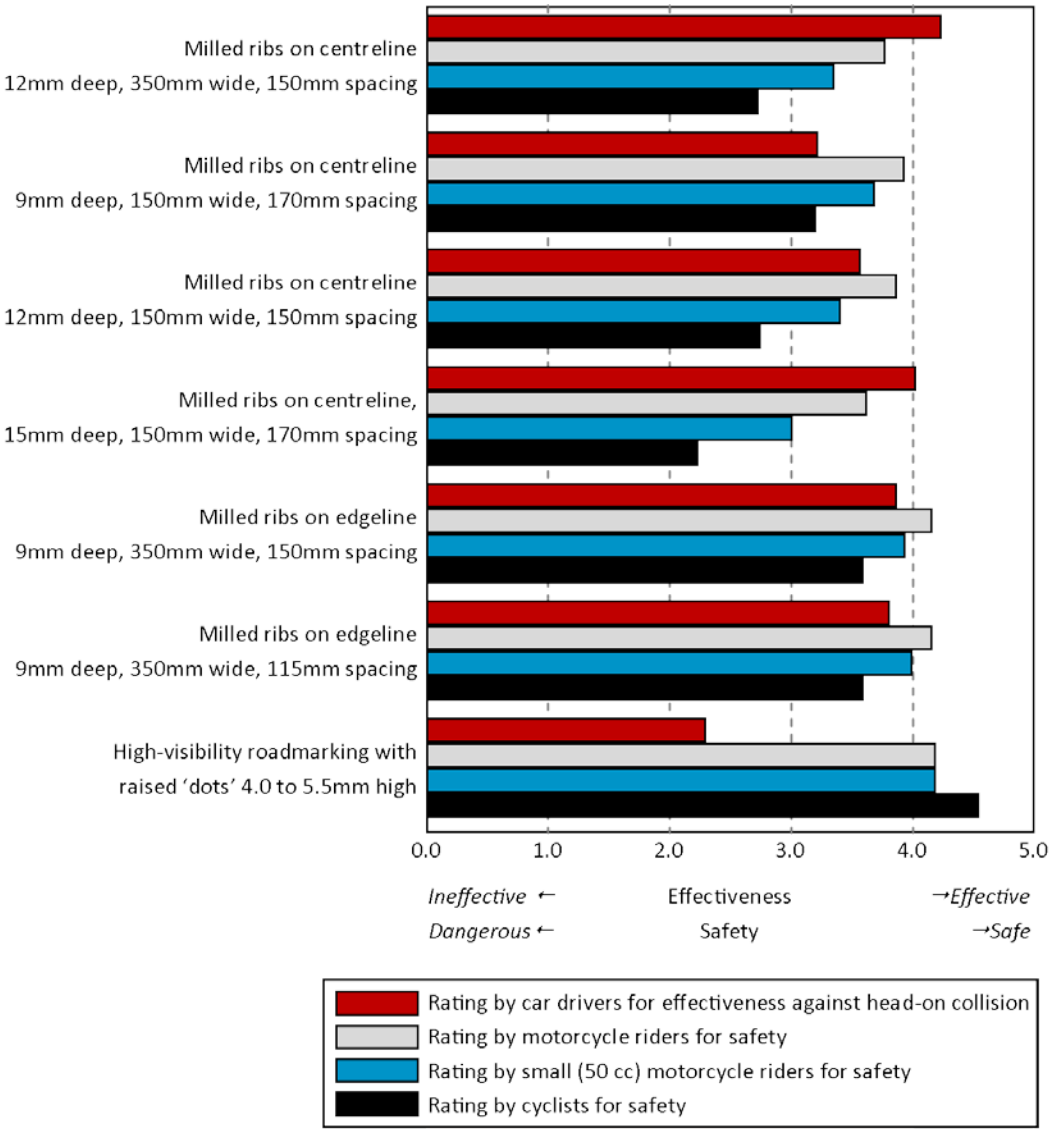
> *... some motorcyclists have indicated that as long as they can see [the ATP roadmarking ribs], they can take reasonable steps to avoid them. For this reason, ATP road markings where the rib is outside or wider than the base line are beneficial.*

This statement, however, assumes that the ATP roadmarkings may in fact be dangerous to motorcyclists. This had not been shown.

Hirasawa et al (2005) carried out test track experiments that involved various vehicles, including larger motorcycles and 50cc motorcycles, negotiating a variety of milled ATP roadmarkings that were milled at depths 9mm, 12mm and 15mm. They found no adverse outcomes with the motorcycles negotiating the milled ATP roadmarkings, although some motorcyclists 'wobbled'. Based on the field trials and the results of a questionnaire on subjective safety ratings by participants in the trial, the authors decided that the optimal groove configuration was a lateral width of 150mm, transverse width of 350mm, and depth of 12mm.

Later, further test track experiments were carried out using a similar mix of vehicles and various configurations of ATP roadmarkings. A questionnaire where safety and effectiveness were rated on a scale of 1 to 5 was answered by participants. The results are shown in figure 4.1.

Figure 4.1 Results of safety/effectiveness questionnaire (adapted from Hirasawa et al 2005, p3708)



The motorcycle riders appeared to slightly favour 9mm or 12mm milled rib depth (though differences in preference were only small) and edge line ribs were favoured slightly over centreline ribs. It is noted that the safety ratings by riders of larger motorcycles were generally slightly higher than those by riders of smaller motorcycles. It was not clear whether the same group of riders was used with each different motorcycle/vehicle. Further, there was only a small range in the safety ratings across all the different treatments; eg the range in safety ratings by motorcycle riders was approximately only 3.6–4.2.

Bucko and Khorashadi (2001) reported on some motorcycle field tests that were carried out by members of the California Highway Patrol, who were all considered to be advanced motorcyclists. The motorcyclists travelled on either a BMW R1100RTP or Harley Davidson FX motorcycle at 50 and 65mph (80 and 105km/h) over a range of ATP roadmarkings and other profiled roadmarkings or surface features. The motorcyclists rated all the treatments very high from 'a safety point of view for the average rider'. The results, though not statistically significant from the point of view of safety, were considered by the authors to be 'quite positive'.

The California Highway Patrol also featured in earlier research conducted by Tye (1976). These tests involved riding a fully equipped patrol Harley Davidson motorcycle on a straight path at speeds of 30, 50, and 60mph (48, 80, and 97km/h) over plywood ribs that were stuck to the road surface. The plywood ribs had thicknesses between 6 and 19mm and lengths between 76 and 203mm; the patterns of ribs had spacings between 76 and 152mm. Tye (ibid) reported that control of the motorcycle was not affected by any of the patterns of raised plywood ribs and speculated that the length of that motorcycle's wheelbase meant that the motorcycle was affected by only one rib at a time.

Motorcycles were also tested on ATP roadmarkings in Kansas and Massachusetts (Federal Highway Administration 2001). The rider composition of the Kansas test group was unknown but the Massachusetts test group consisted of members from the police motorcycle squad. In both studies the test groups reported noticing the ATP roadmarkings, but none of the motorcyclists reported experiencing control problems.

4.2 Impacts on motorcycles of contacting other surface irregularities

Work has been done in the US related to the interaction of motorcyclists and pavement grooving. Pavement grooving is the name for cutting transverse or longitudinal grooves onto a surface to increase skid resistance and reduce the incidence of wet-weather crashes. Martinez (1977) related a project where longitudinal grooves were tested for their impact on motorcyclists, using a 350cc non-instrumented Yamaha motorcycle that was ridden by three different motorcyclists. One motorcyclist was a highly skilled experienced professional; one was an average rider with two years of experience; and the other motorcyclist was an inexperienced rider. The motorcyclists rode the motorcycle on a straight section of road with worn grooves and on a section of road with an 18° curve and newly cut grooves. These tests were done on public roads. Testing was also carried out with a variety of tyres and at an off-road facility where high speeds were obtained. The main finding was that the grooving had no detectable detrimental impact on motorcycle handling, but at high speeds the grooves did create insecure feelings in the motorcyclists. These were the author's conclusions, notwithstanding the opinion of the test motorcyclists that at speeds over 70mph (112.6km/h), the grooves were hazardous.

Haworth (1999) reported as follows on inspections and rides-through of sites associated with the study *Case control study of motorcycle* crashes (Haworth et al 1997):

- There were 31 cases (15% of inspected sites) where it was found that the road surface actively contributed to the crash.
- In many other cases, road-related deficiencies or imperfections were present at the crash site, but no active contribution by them to the occurrence of the crash was detected.
- In 47% of cases, no site-related factors were judged to have contributed to the occurrence or severity of the crash.

The most common site-related factors were:

- lack of visibility or obstructions to visibility (20%)
- unclean road or loose material on the road (14%)
- poor condition of the road or roadmarkings (12%)
- horizontal curvature (12%).

Details of surface irregularities observed in the study are shown in table 4.1.

Table 4.1 Surface irregularities identified at the subject crash sites (with more than one irregularity possible per site) (adapted from Howarth et al 1997)

Surface irregularity	Number of crashes	Percent of crashes
Pothole	32	14
Service cover	38	17
Deformed pavement	54	24
Poor pavement integrity	33	15
Sudden change in road surface	53	24

Howarth et al (ibid) concluded:

> *Better road surfaces provide an opportunity to prevent motorcycle crashes. The extent of the likely benefits depends on how much resources are devoted to such improvements and how much riders' behaviour adapts to the better surfaces. If better surfaces lead to higher speeds, then some of the benefits may be dissipated.*

4.3 Other overseas analyses of crash records

There was one crash study specific to motorcycles and ATP roadmarkings in the subject literature.

In the US, ATP roadmarkings are typically grooves milled into the road surface. Miller (2008) described a study (undertaken by the Minnesota Department of Transport) related to the possibility of adverse effects on motorcyclists of centreline 'rumble strip' or ATP roadmarkings. These roadmarkings have been created on several hundred kilometres of Minnesota roads.

Firstly, 9845 motorcycle crashes since the first ATP roadmarkings were installed in 1999 were matched with the locations of those ATP roadmarkings, excluding ATP roadmarkings inside the metropolitan areas. Of the 9845 crashes, 29 occurred in sections of road with centreline ATP roadmarkings. One was a fatality.

Reports on 26[2] of those 29 crashes were manually reviewed to determine if the ATP roadmarkings were a primary or contributing factor. None of the 26 reports mentioned ATP roadmarkings or showed them in the diagrams. The crash reports showed that:

- 24 crashes had clear causes that were unrelated to ATP roadmarkings
- in five crashes motorcyclists had crossed the centreline during or immediately prior to the crash
- there was enough ambiguity in the reported causes of three crashes to mean that the road surface could have been a possible factor.

The study also carried out 44 hours of roadside video observation of rural highways with centreline ATP roadmarkings, and also observation in a controlled track environment of motorcyclist behaviour in the vicinity of ATP roadmarkings.

The roadside video observation showed a small number of crossings by motorcyclists of the ATP roadmarking centreline, and no directional changes or unusual riding behaviours during those crossings. The observations in the controlled track environment found no steering, braking or throttle adjustments

[2] The other three reports were unable to be accessed by the researchers.

during crossing of the ATP roadmarkings. In post-ride interviews, none of the motorcyclists expressed difficulty or concern with crossing ATP roadmarkings. Miller (ibid) reported that:

> *Half of the riders noticed the strips before crossing [them], but no rider described the strips as a hazard either on the closed course [controlled track environment] or on public roads, though eight found them a nuisance when passing another vehicle.*

Referring to the work of Miller (ibid), the US National Cooperative Highway Research Program (NHCRP) stated that:

> *Conclusive evidence exists to show that centerline rumble strips add no measurable risk to motorcyclists. Therefore, there is no need to consider potential adverse effects for motorcyclists when developing a centerline rumble strip policy. Similarly, there is no need to prohibit the use of centerline rumble strips on roadways with significant motorcycle traffic.*

In other literature, there were instances of studies from the US being used to imply that ATP roadmarkings were dangerous to motorcycles, when inspection of the original studies showed they did not include any evidence to support that implication. For example, Hatfield et al (2009) and Sayed et al (2010) both quoted *Interim report centerline rumble strips* (Outcalt 2001) as support for the theory that centreline ATP roadmarkings are hazardous to motorcycles. However, Outcalt (ibid) did not say this; rather, Outcalt suggested that ATP roadmarkings might be a potential hazard and stated that there was '... not enough data available at this time to evaluate the effects of centerline rumble strips on motorcycles'. (Note that this statement predated Miller's 2008 study.) Further, Hatfield et al (2009) also quoted *Safety evaluation of rolled-in continuous shoulder rumble strips installed on freeways* (Griffith 1999) which, in fact, was totally silent regarding motorcycles.

In Germany, Bayer and Nels (1987), quoted in Plant (1995), investigated motorcycle stability in relation to trials of seven ATP roadmarking profiles. The profile heights trialled were between 4 and 8mm high. Trials were carried out under dry conditions and the instrumented motorcycle used in the trials was loaded at the rear to accentuate 'swing'.[3] Qualitative analysis of the results indicated that the motorcycle could turn sharply over the ATP roadmarkings at speeds up to 130km/h without instability or lack of control due to 'swing'. However the report recommended that ATP roadmarking profile heights should be minimised, as motorcyclists are 'known to experience definite swinging movements when crossing conventional road markings'.

Plant (1995) also described work carried out for the UK's Department of Transport to investigate for vulnerable road users the safety implications of raised-rib type ATP roadmarkings. An analysis of crash records was unable to detect any link between the ATP roadmarkings and reported crashes involving two-wheeled vehicles for the sites investigated. Off-road trials were also conducted, using ATP roadmarkings of different heights (5 and 13mm high), widths (150 and 200mm wide), rib spacing (250 and 500mm spacings) and rib type (continuous or two-part). ATP roadmarkings were placed as straight lines, curved lines, and a line adjacent to a curb.

[3] Bayer and Nels (1987) is a publication in German. The authors of this current research project were advised by a translator that the German word for 'swing' may also mean 'wobble'.

Five motorcyclists, ranging in age from 27 to 54 years, took part. Four motorcycles were used, ranging from 100cc to 900cc. The motorcyclists travelled at 20, 30 and 40mph (32, 48 and 64km/h) and controlled braking tests were carried out along the lines. Results for the motorcycles included the following:

- Handling problems were more prevalent than comfort problems.
- Most problems occurred when travelling along the line and were most associated with the 13mm ribs rather than the 5mm ribs.[4]
- Motorcycles with larger tyres had more problems than motorcycles with smaller tyres.
- Crossing the line at an angle presented few problems at any rib height.
- The motorcyclists were concerned about possible problems in the event of travelling over the ATP roadmarkings while they were riding 'banked over' in order to negotiate a curve.

There have also been some more general studies of ATP roadmarkings where the considered vehicles included motorcycles, but they did not contain a large enough sample of motorcycles to come to any conclusions. For example, in *The effectiveness of audio-tactile lane-marking in reducing various types of crash: a review of evidence, template for evaluation, and preliminary findings*, Hatfield et al (2009) looked at crash records from sections of New South Wales roads before and after the installation of ATP roadmarkings. (ATP roadmarkings in New South Wales are broadly similar to those in New Zealand.) There were not enough crashes in the study for any reliable analysis of either 'all motorcycle crashes' or 'out-of-control motorcycle crashes'. The authors considered that the raw numbers of crashes observed did not support the view that ATP roadmarkings increase the crash rate for motorcycles.

4.4 The likelihood of motorcycles contacting ATP roadmarkings

The specifications described in chapter 2 state that in New Zealand, the ATP roadmarkings ribs should protrude from the line in order to promote the visibility of the ribs; thus motorcyclists should be aware of the ATP roadmarking, and its effects, prior to any contact with them.

Currently in New Zealand, where ATP roadmarkings exist they cover a relatively small part of the road surface, being predominantly applied longitudinally at the edge line or sometimes longitudinally as a 'no overtaking' centreline. These applications of ATP roadmarkings are thus typically not in the expected wheel tracks of motorcycles, which generally stay within the traffic lane. *The official New Zealand road code for motorcyclists* (NZTA 2010c) advises motorcyclists to keep left, though it also notes:

> *... positioning your motorcycle behind the right-hand wheels of the vehicle ahead (at the correct following distance) can make it easier to see and be seen. However, you must still remember to keep well to the left of the centre line.*

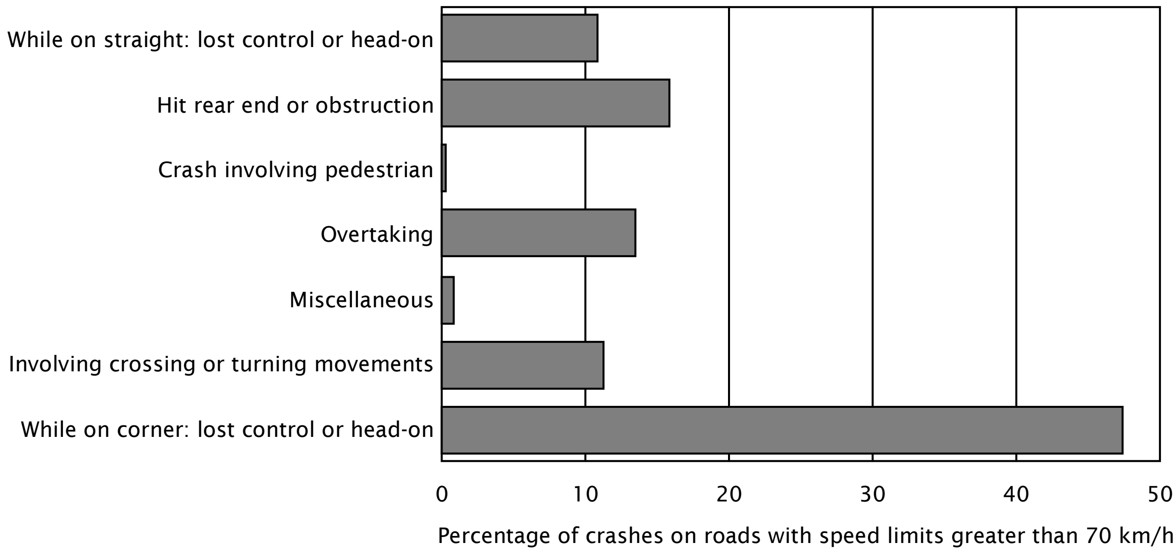
Section 4.08 in MOTSAM: Part 2 (NZTA 2010b) states:

> *ATP edge line markings should be installed continuously across minor access-ways, but discontinued at least 20 metres clear of major access-ways and intersections and their diverge and merge areas.*

[4] Currently in New Zealand, the maximum height (vertical distance) between the top of the ATP roadmarking ribs and the road surface upon which the ATP roadmarkings are installed can be no more than 9mm (NZTA 2006).

This practice further reduces another instance where motorcycles could contact ATP roadmarkings – the edge lines on the inside of curves. These could be more readily contacted by a motorcycle when it is cornering, which is considered one of the more dangerous manoeuvres for a motorcycle (NZTA 2010c). Figure 4.2 shows this as the most common movement type involved in motorcycle crashes on roads with speed limits greater than 70km/h during the 10-year period from 2001 to 2010.

Figure 4.2 Movement types of all motorcycle crashes on roads with speed limits greater than 70km/h, 2001–2010 (adapted from NZTA 2012)



As noted earlier in chapter 2, section 4.08 in MOTSAM: Part 2 notes that the approval of the NZTA's National Traffic and Safety Manager is required before ATP roadmarkings may be installed on state highway centrelines. Approvals have been granted for ATP roadmarkings on continuous yellow 'no overtaking' centrelines. However, over time it is expected that the use of ATP roadmarkings will increase, including on white centrelines and possibly other lane lines that can be expected to be traversed by motorcyclists in normal circumstances – therefore the likelihood of motorcycles contacting ATP roadmarkings could increase.

The situations discussed above imply the motorcyclist has control over their motorcycle. During a loss-of-control event, the likelihood of the motorcycle contacting ATP roadmarkings will be related to the extent of ATP roadmarkings usage at that specific location.

5 Simulations of motorcycles contacting ATP roadmarkings

The third research objective was to examine the effects of ATP roadmarkings on motorcycle stability, via the use of an existing vehicle-behaviour model. This comprised two parts:

1. validation of the model via full-scale physical tests within the limits of safe and ethical experimentation
2. extension of the model to simulate motorcycle travel over ATP roadmarkings at open road speeds.

With reasonable agreement between the full-scale physical data and the model data confirmed, the modelling could be used to investigate motorcycle stability on ATP roadmarkings at higher speeds without risk to the motorcycle or its rider.

5.1 Data from low-speed full-scale physical testing

Full-scale physical tests were undertaken with an instrumented motorcycle ridden on:

- a range of ATP roadmarking profiles, at
- a range of speeds, on
- ‘straights’ and ‘tight corners’ with low radius of curvature.

5.1.1 Bike and instrumentation

A 2007 Honda CBR 1100XX, as shown in figure 5.1, was chosen for the testing. It was instrumented as follows:

- A strain-gauge-based load cell was fitted between the rear suspension arm and the body of the motorcycle, so that the vertical rear wheel load could be measured.
- One 6g accelerometer was mounted to measure the vertical accelerations of the front wheel, and another to measure the rear wheel vertical accelerations.
- A three-axis Crossbow unit incorporating three orthogonal gyroscopes to measure pitch, roll, and yaw, and three accelerometers to measure longitudinal (x-axis), lateral (y-axis), and vertical (z-axis) accelerations, were fitted into a box strapped immediately behind the front rider’s seat.
- A power supply and a data acquisition system that was linked to all the instruments were also fitted into this box.
- The box was positioned to be level when the rider’s weight was fully on the seat.

Figures 5.2 and 5.3 show views of the instrumented motorcycle.

Figure 5.1 Honda CBR 1100XX motorcycle (Image from www.totalmotorcycle.com)

Figure 5.2 View of the instrumented motorcycle used for full-scale physical testing, including showing the box fitted behind the front rider's seat

Figure 5.3 View of the rear wheel of the instrumented motorcycle used for full-scale physical testing

5.1.2 Full-scale physical testing programme

A testing programme was designed to methodically investigate the effects of ATP roadmarkings of different rib heights and rib spacings for different travel speeds on both straights and small-radius corners. Design of the testing programme also considered the safety and confidence of the motorcycle rider, with a gradual increase of the test-run complexity. Table 5.1 shows the testing programme as a matrix of the variables.

Table 5.1 Full-scale physical testing programme

Test-run	Curve radius (m)	Motorcycle speed (km/h)	Rib height (mm)	Rib spacing (mm)	Comment
1	Straight	30	n/a	n/a	No ribs
2	Straight	50	n/a	n/a	No ribs
3	Straight	30	Various	Various	Testing
4	Straight	50	Various	Various	Testing
11	50	30	0	n/a	One rib
12	50	50	0	n/a	One rib
5	50	30	3	n/a	One rib
6	50	50	3	n/a	One rib
7	50	30	6	n/a	One rib
8	50	50	6	n/a	One rib
9	50	30	9	n/a	One rib
10	50	50	9	n/a	One rib
13	100	30	0	n/a	One rib
14	100	50	0	n/a	One rib
15	100	30	3	n/a	One rib
16	100	50	3	n/a	One rib
17	100	30	9	n/a	One rib
18	100	50	9	n/a	One rib
19	50	30	3	500	Multiple ribs
20	50	50	3	500	Multiple ribs
25	50	30	9	500	Multiple ribs
26	50	50	9	500	Multiple ribs
21	50	30	3	250	Multiple ribs
22	50	50	3	250	Multiple ribs
23	50	30	9	250	Multiple ribs
24	50	50	9	250	Multiple ribs
27	100	30	9	250	Multiple ribs
28	100	50	9	250	Multiple ribs
29	Straight	30	9	250	Multiple ribs
30	Straight	50	9	250	Multiple ribs
31	Straight	30	9	500	Multiple ribs
32	Straight	50	9	500	Multiple ribs

The testing was carried out on a relatively smooth asphalt surface, with texture and roughness similar to those found on the New Zealand open road network. Curve radii of 100m and 50m were selected as representative of the tighter-radii corners found on the New Zealand state highway network.

For test-runs that included ATP roadmarking ribs, the ribs were laid for a 10-metre length. Figure 5.4 shows one of the ATP roadmarking test-run layouts. The ribs were uniform wooden blocks adhered to the surface so there was no movement of the ribs as they were traversed by the motorcycle. The ribs were approximately 150mm wide. This is wider than some ribs in current use on the road network but the additional width was chosen to facilitate the required full and regular contact between the motorcycle wheel and the ribs.

Figure 5.4 Example test-run layout showing a 10-metre length at 50m radius with ribs 9mm high at 500mm spacing

The motorcycle was ridden for each test-run with the specified speed and riding-line being as consistent as possible. Data from any test-runs with exceptional or irregular riding were excluded. Data was recorded continuously at a rate of 1000Hz for each test-run.

5.1.3 Data processing and analysis

The data file for each of the test-runs in table 5.1 was processed using the appropriate calibration equations to provide output data files listing the following information:

1 elapsed time (s)

2 motorcycle roll (rad/s)

3 motorcycle pitch (rad/s)

4 motorcycle yaw (rad/s) – this is also termed ‘the heading angle’

5 motorcycle seat acceleration for the x-axis (m/s^2)

6 motorcycle seat acceleration for the y-axis (m/s^2)

7 motorcycle seat acceleration for the z-axis (m/s^2)

8 vertical acceleration for the front wheel (m/s^2)

9 vertical acceleration for the rear wheel (m/s^2)

10 rear wheel load (kg) (based on a 200kg datum for the combined rest-load of the motorcycle and rider).

Figures 5.5 to 5.9 show plots of the data for a representative sample (five) of the 32 test-runs outlined in table 5.1. The sample comprised a:

- 50m radius corner at 30km/h with one rib 9mm high at the apex (Run 9)
- 50m radius corner at 30km/h with ribs 9mm high at 500mm spacing (Run 26)
- 50m radius corner at 50km/h with ribs 9mm high at 500mm spacing (Run 27)
- 50m radius corner at 30km/h with ribs 9mm high at 250mm spacing (Run 24)
- 50m radius corner at 50km/h with ribs 9mm high at 250mm spacing (Run 25).

Figure 5.5 Data from full-scale physical testing for motorcycle on 50m radius corner at 30km/h with one rib 9mm high at the apex of the corner

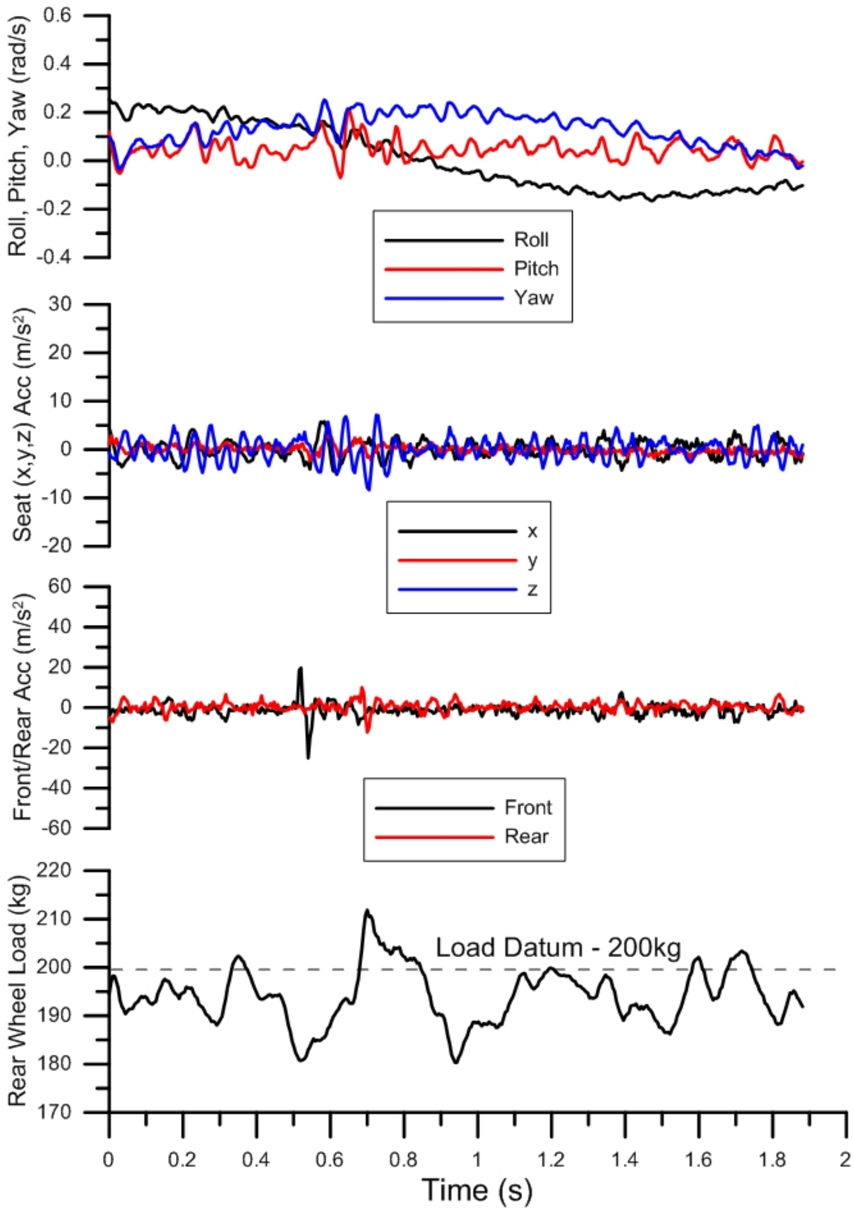


Figure 5.6 Data from full-scale physical testing for motorcycle at 30km/h on 50m radius corner with ATP roadmarkings of rib height 9mm at 500mm spacing

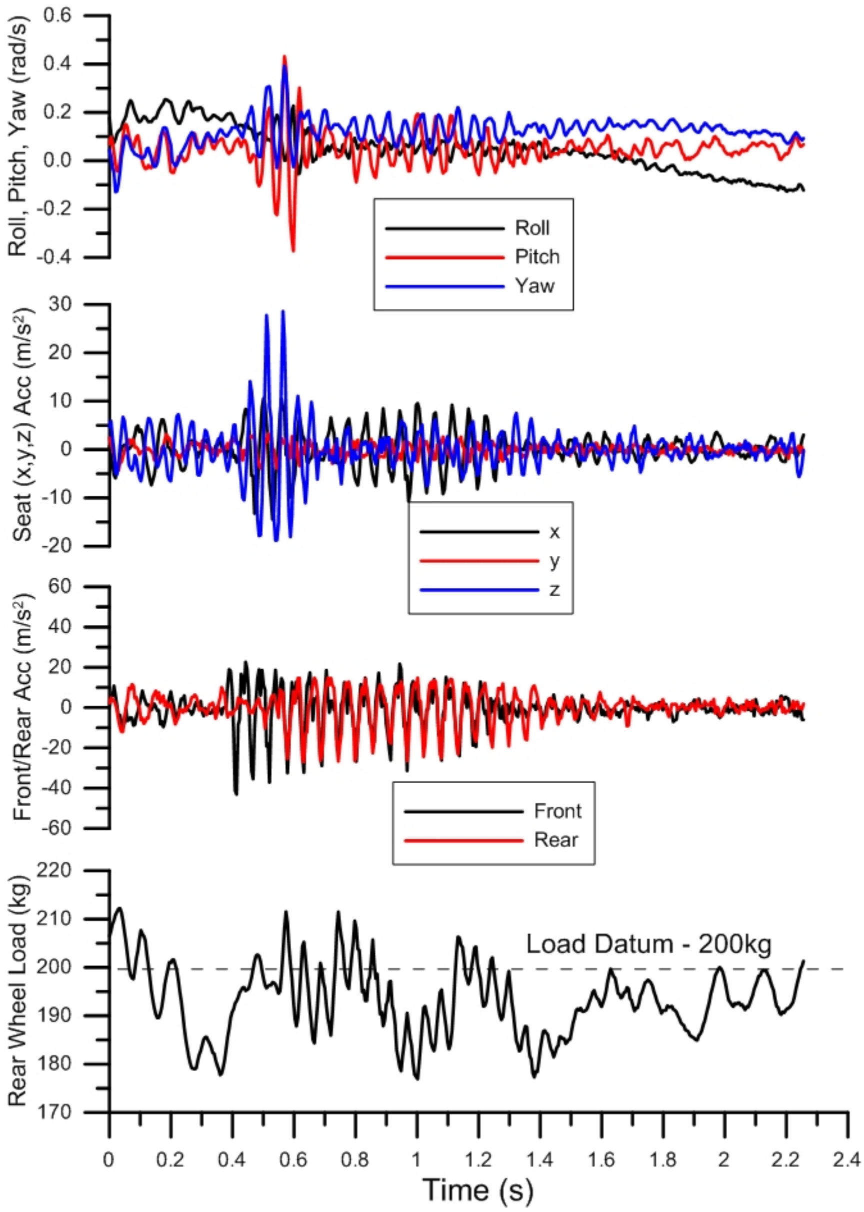


Figure 5.7 Data from full-scale physical testing for motorcycle at 50km/h on 50m radius corner with ATP roadmarkings of rib height 9mm at 500mm spacing

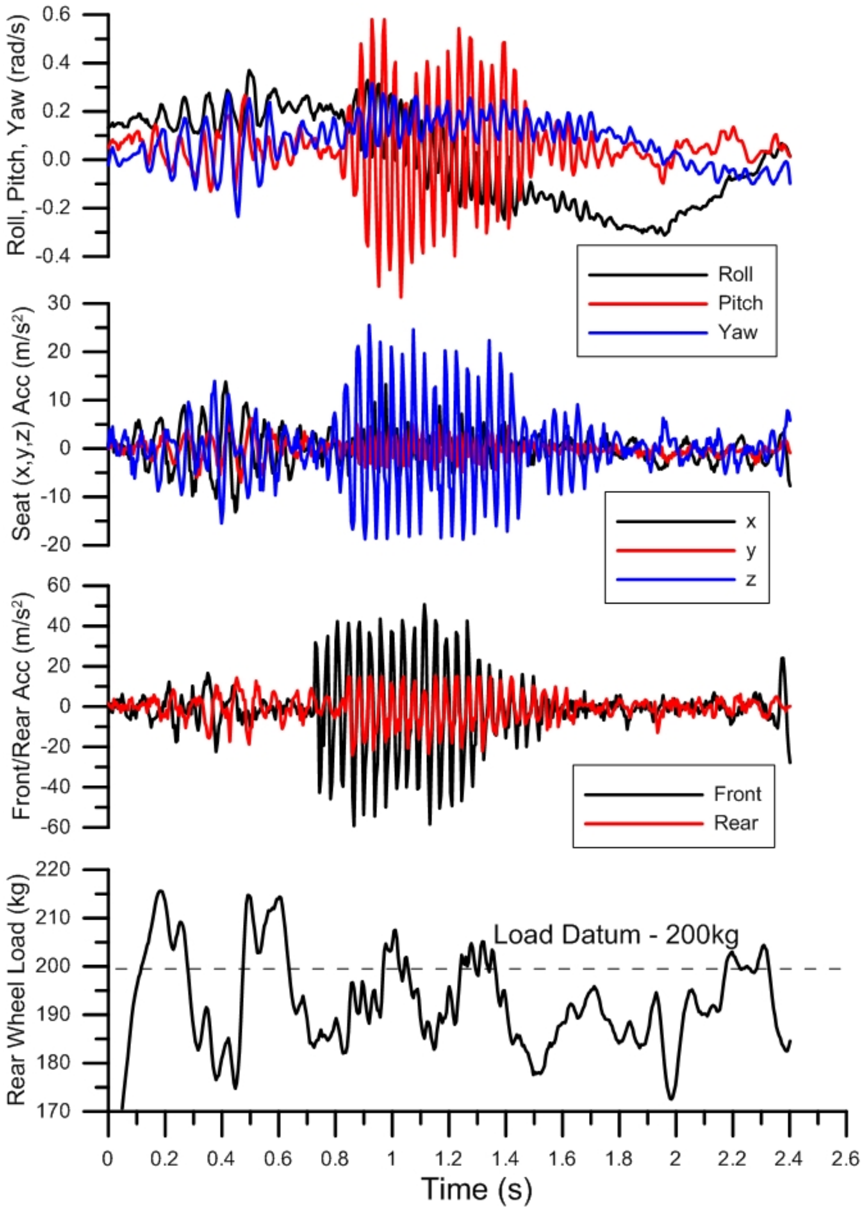


Figure 5.8 Data from full-scale physical testing for motorcycle on 50m radius corner at 30km/h with ribs 9mm high at 250mm spacing

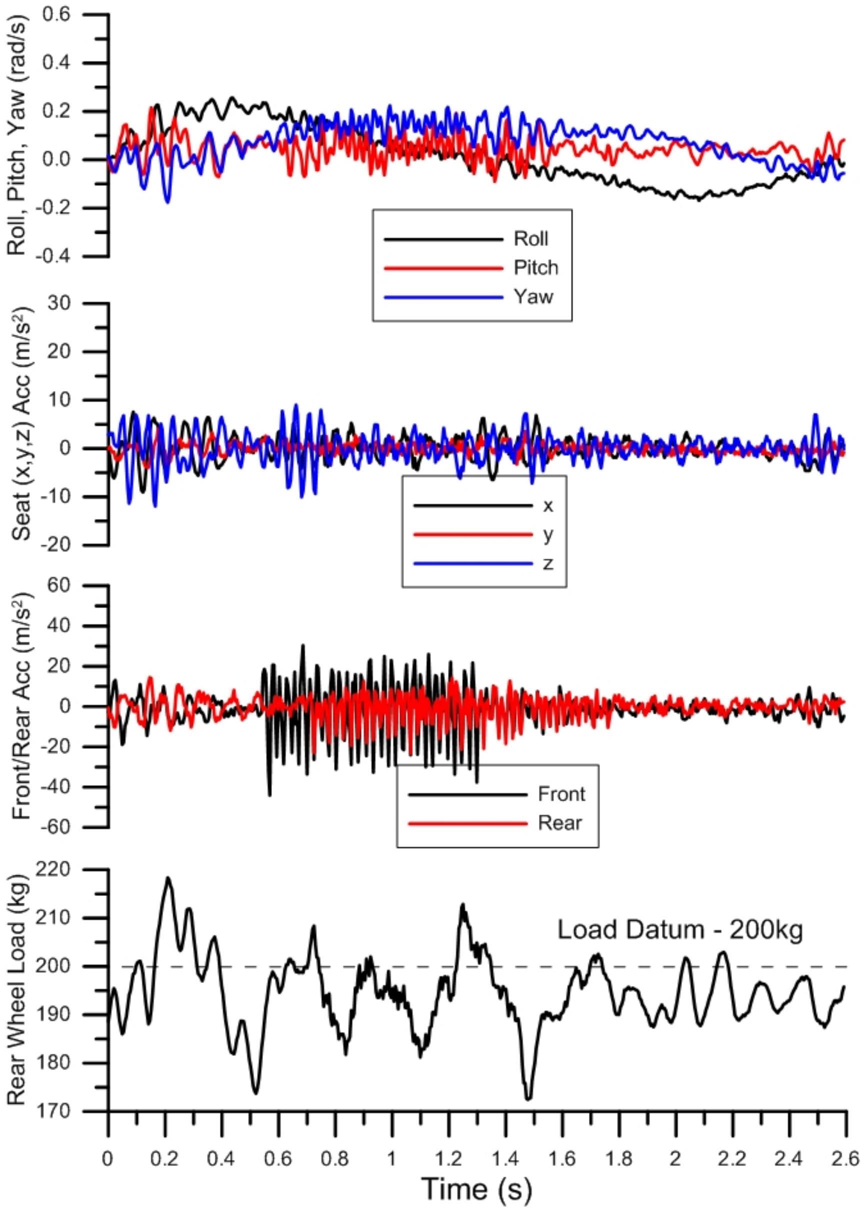
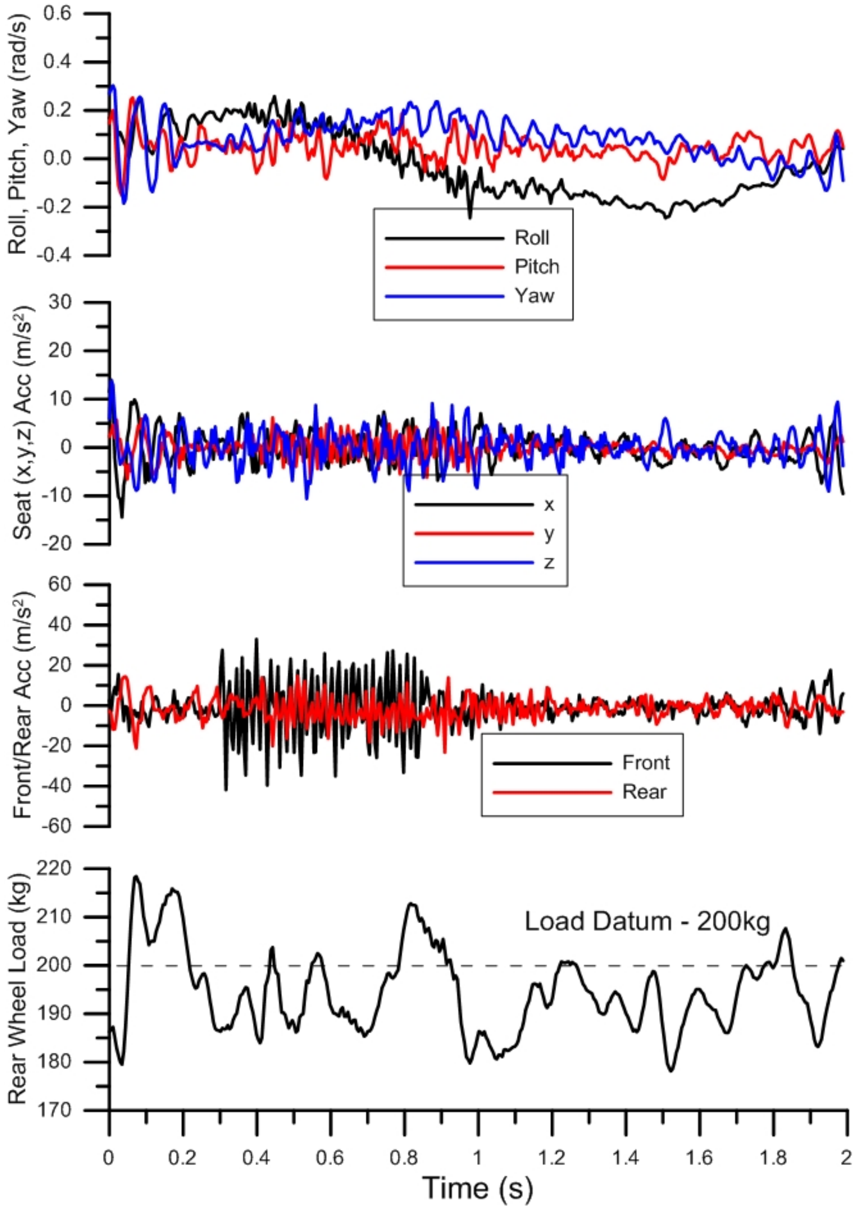


Figure 5.9 Data from full-scale physical testing for motorcycle on 50m radius corner at 50km/h with ribs 9mm high at 250mm spacing



5.1.4 Comments and discussion on the full-scale physical testing

The motorcycle rider who performed the riding for the full-scale physical testing was a trained rider and a member of the New Zealand Police. He was asked to comment on any ride or safety concerns regarding riding the motorcycle over the ATP roadmarkings. The 'most extreme' test-runs were on a 50m radius curve at 50km/h – the motorcycle rider did not have any safety concerns. While 50km/h may seem like a relatively modest speed, a 50m radius curve on flat terrain in a 100km/h speed limit zone would be assigned a 35 or 45km/h curve advisory speed. The motorcycle rider said he could distinctly *feel* the ribs only when they had a height of 9mm and a spacing of 500mm, but otherwise the noticeable cues he received from the ATP roadmarkings were mainly visual and audible.

From the data measured during the 32 test-runs, including the data shown in figures 5.5–5.9, the following points were found:

1 Test-runs with no ribs or with one single rib:

a) When the motorcycle was moving on a relatively flat surface with no ATP roadmarking ribs, there was continued steady variation in the measured wheel and body acceleration levels, as well as in the pitch, roll and yaw data. There was less variation in the rear wheel load data, but there were still fluctuations of around ±10%.

b) As expected, the most significant responses to riding the motorcycle over a single rib element were in the vertical axes, shown particularly by the front wheel accelerometer and also by the rear wheel accelerometer and the motorcycle seat accelerometer for the z-axis. There were also noticeable changes in the pitch and yaw responses. There was no strong evidence of the single rib having a significant effect on the rear wheel load.

2 Test-runs with multiple ribs:

a) As for the test-runs with the single rib, when the motorcycle was moving over multiple ribs, the most significant responses were in the vertical axes, shown particularly by the front wheel accelerometer, and also by the rear wheel accelerometer and the motorcycle seat accelerometer for the z-axis. There were also noticeable changes in the pitch and yaw responses.

b) The degree of response appeared to be dependent on the speed of the motorcycle. For example, comparing figures 5.8 and figure 5.9: at 30km/h the rear wheel vertical accelerations were of similar scale to the front wheel vertical accelerations, but at 50km/h the rear wheel vertical accelerations were much smaller than the front wheel vertical accelerations.

c) The degree of response was dependent on the spacing of the ribs. For example, comparing figures 5.7 and 5.9: in terms of pitch, motorcycle seat accelerometer for the z-axis, front wheel vertical accelerations, and rear wheel vertical accelerations, the scale of response at 500mm rib spacing was much larger than the scale of response to the 250mm rib spacing.

d) There were distinct variations in the rear wheel load due to the profile elements. These were largest for the slower speed (30km/h) but at the larger spacing (500mm). However, as for the surface with no profile elements, the variations in the wheel load were still no more than ±10%. This would suggest that at these speeds there is no danger of the wheel load reducing enough to make losing control an issue.

It is important to note that these test-runs were carried out with the motorcycle rider maintaining a consistent riding-line over the ATP roadmarking. Accordingly, the test-runs do not provide any information on what might happen if a motorcycle rider makes a sudden steering correction or change after initial contact with the ATP roadmarking.

5.2 Acceptance of the PC-Crash model

5.2.1 PC-Crash (3D Version 9)

The computer software used for the simulation modelling was PC-Crash (3D Version 9). Appendix A contains information on PC-Crash, supplementing the introduction here.

PC-Crash is an internationally recognised three-dimensional vehicle crash and trajectory simulation modelling software.

Three-dimensional road models can be created in PC-Crash by:

- importing a computer-assisted drawing (CAD) based on data from a three-dimensional survey of a physical site
- drawing contours and laying a road element over those contours
- generating a three-dimensional road element with elevation, radius, width and crossfall parameters.

Surface friction values are defined as a single friction value for the entire surface, or the entire surface can be divided into polygons of specific dimensions and friction values.

The physical characteristics and performance of vehicles, including cars, trucks, buses, vans and motorcycles, are imported from a number of different databases covering a range of vehicle manufacturers. The modelling of the vehicles includes the parameters required to simulate their motion in response to internal forces (such as acceleration, braking, and steering) and in response to external forces (such as the road geometry, surface friction and tyre properties).

The movements to be simulated are specified via vehicle paths and speeds or sequences of acceleration, steering or braking. When the simulation is run, PC-Crash uses (by default) a kinetic model to determine the vehicle response, as the vehicle performs the intended movement specified as far as possible under application of the laws of physics.

PC-Crash has been used successfully in New Zealand on research projects for the NZTA (Cenek et al 2011) and the Road Safety Trust (Jamieson 2012). Each of these projects involved comparisons of the computer simulation model outputs with full-scale data for vehicles ranging from a front-wheel-drive passenger car, a rear-wheel-drive passenger car, an SUV and a light truck. The assessment and verification of PC-Crash that was carried out as part of these projects is summarised within appendix A of this report. Overall, the comparisons undertaken showed generally good agreement between the simulation data and the full-scale physical testing data.

5.2.2 Verification of modelling of ribs

Appendix A summarises data and experience with PC-Crash that gives confidence it can produce reasonably accurate simulation results with respect to vehicle trajectories, locked-wheel braking and sliding. However, prior to commencing this research there was no information on how PC-Crash would identify responses to ATP roadmarkings, as the ribs were only 3–9mm high. Accordingly, the project included a phase investigating (for verifying) this aspect of PC-Crash responsiveness.

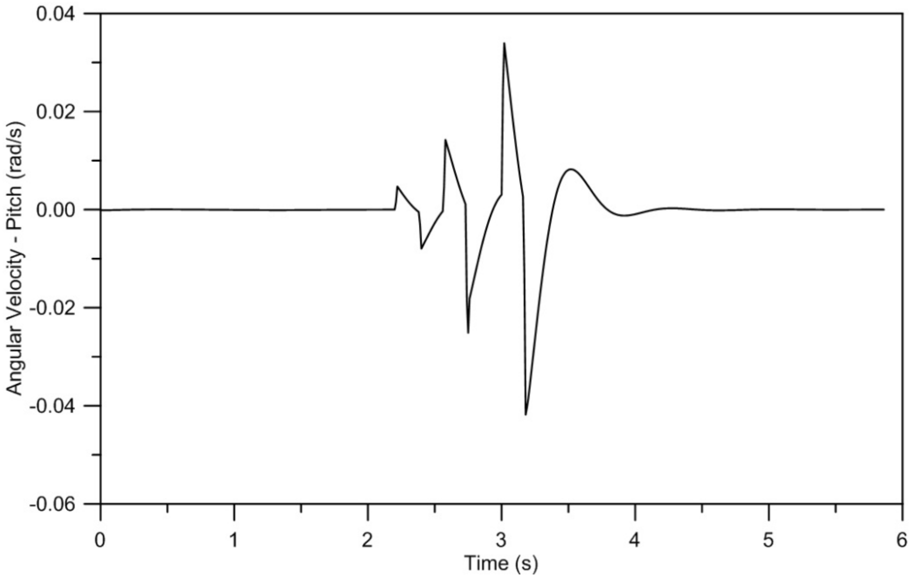
A three-dimensional model situation was generated with a road 100m long and straight, on flat terrain. A late-model motorcycle was imported into the situation and set to follow a straight line path along the road. The simulation was run in the following two conditions:

- only the flat road surface (with no ribs)
- the flat road surface with one rib 3mm high, then one rib 6mm high, then one rib 9mm high (positioned to be in the path defined for the motorcycle).

For each condition, the motorcycle travelled along the road for a number of model-runs, each at constant speed ranging from 30km/h to 120km/h.

The PC-Crash data was inspected and figure 5.10 illustrates the finding. Figure 5.10 is from PC-Crash's pitch data for the condition with the three individual ribs, with the motorcycle travelling at 30km/h. The figure clearly shows that PC-Crash identifies the response to the ribs, with the pitch rates varying consistently for the different rib heights. This trend was also observable and similar for all the speeds tested, from 30km/h up to 120km/h.

Figure 5.10 Pitch angular velocity at 30km/h over 3mm, 6mm and 9mm profile heights



5.2.3 Replication modelling of full-scale physical testing

One purpose of the full-scale physical testing was to provide data for comparative validation of PC-Crash. Accordingly, PC-Crash was set up to replicate the test-runs of the full-scale physical testing.

Three separate PC-Crash model environments were created based on the combinations of parameters used for the full-scale physical testing. The three model-environments were:

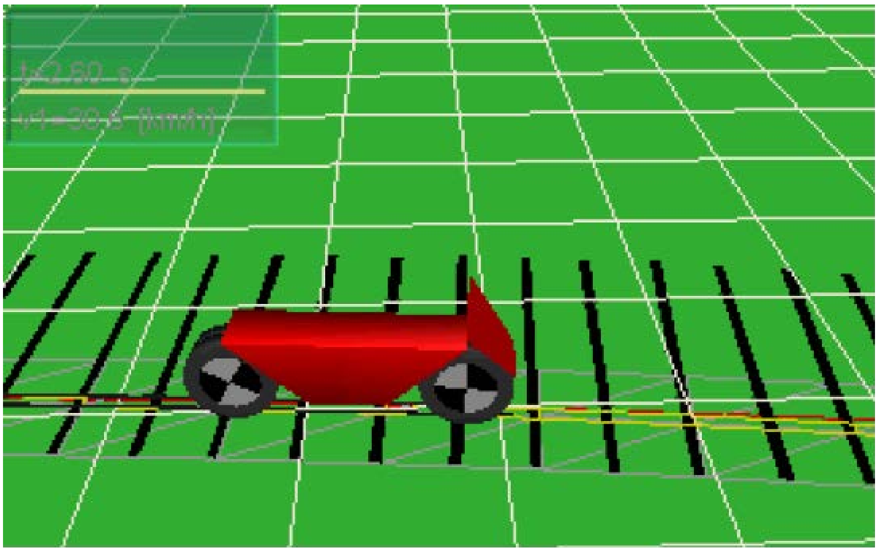
- 100m road section – straight, on flat terrain
- 100m road section – middle 30m curved with 100m radius, on flat terrain
- 100m road section – middle 30m curved with 50m radius, on flat terrain.

The following steps were followed in each of the three model environments:

- The road surface was initially assigned a surface friction value of 0.8, which is typical of a dry road.
- A Honda CBR 1100XX motorcycle was imported from the appropriate vehicle database.
- A rider was added to the motorcycle, having the same weight as that of the rider for the full-scale physical testing.
- The motorcycle's path along the 100m road section was defined using consecutive path points. According to the rules of the model setup, the motorcycle attempted to follow these path points but, using the PC-Crash kinetics simulation model, the motorcycle's motion was governed by the laws of physics and the properties of the motorcycle, rider and road environment. Where the motorcycle speed, road geometry and surface friction determined, the motorcycle departed from the intended path points, demonstrated as minor variations through to total loss of control or sliding.
- In the PC-Crash model-runs, the motorcycle was simulated at 30km/h and 50km/h, as per the full-scale physical testing test-runs.

Figure 5.11 shows a screenshot from PC-Crash for a rendered simulation of the motorcycle passing over a series of ribs of an ATP roadmarking. For those PC-Crash model-runs including multiple ribs, a 10m long section of spaced ribs was centred on the apex of the corner.

Figure 5.11 PC-Crash screenshot showing rendered simulation of the motorcycle passing over a series of ribs



The yaw, pitch and roll data from the full-scale physical testing was compared with the same data from the equivalent PC-Crash model-runs. As examples:

- Figure 5.12 compares yaw, pitch and roll data from the full-scale physical testing and the PC-Crash modelling for a 100m radius curve at 30km/h with one rib 9mm high at the apex of the corner.
- Figure 5.13 compares yaw, pitch and roll data from the full-scale physcial testing and the PC-Crash modelling for a 50m radius curve at 30km/h with one rib 9mm high at the apex of the corner.

Figure 5.12 Yaw, pitch and roll data from full-scale physical testing (in red) and PC-Crash modelling (in blue) for a 100m radius corner at 30km/h with one rib 9mm high at the apex of the corner

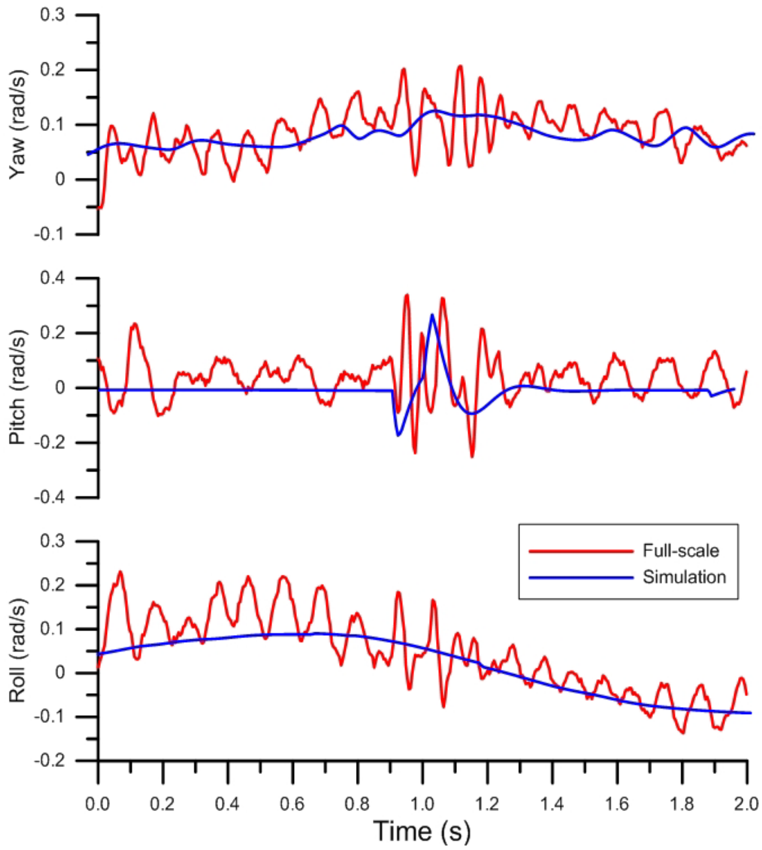
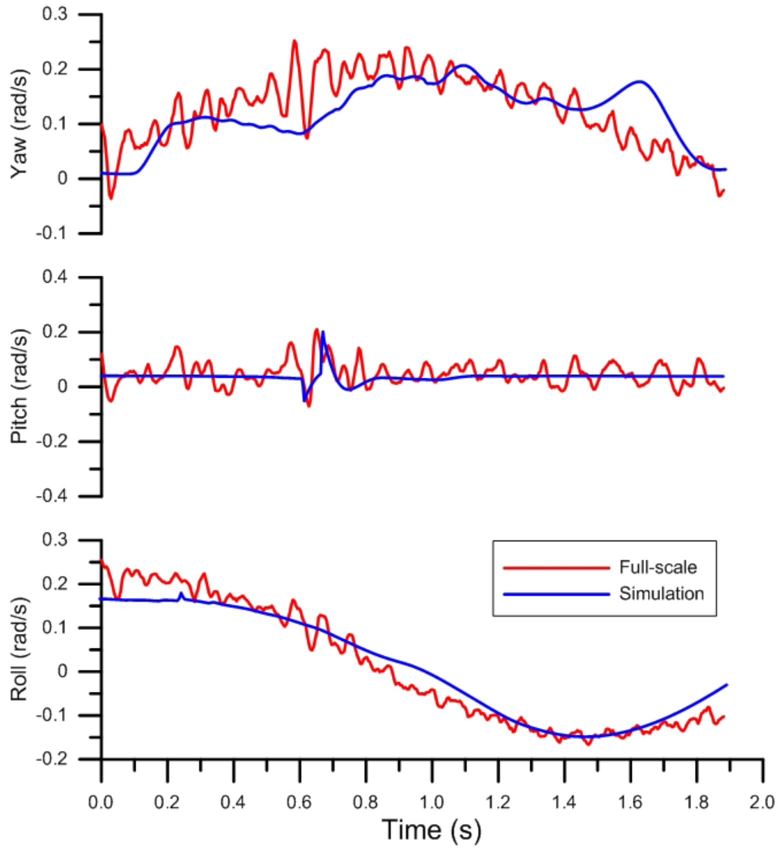


Figure 5.13 Yaw, pitch and roll data from full-scale physical testing (in red) and PC-Crash modelling (in blue) for a 50m radius corner at 30km/h with one rib 9mm high at the apex of the corner



Figures 5.12 and 5.13, and comparisons of other test-runs to PC-Crash model-runs, show general agreement of the yaw, pitch and roll data between the full-scale physical testing and the PC-Crash modelling. There were differences, most notably the small fluctuations throughout the data from the full-scale physical testing compared with the ‘smooth’ response from the PC-Crash modelling. The road surface in the PC-Crash model did not include the roughness inherent in the road surface of the full-scale physical testing, nor the minor corrections and movements of the rider, nor some of the higher-frequency vibrations of the motorcycle. However, the overall agreement in magnitude of response, if somewhat damped, gave some confidence that the PC-Crash model was a reasonable replication of the full-scale physical motion.

As noted previously, during the full-scale physical testing, the motorcycle rider did not have any safety or stability concerns about passing over the ribs at 3mm, 6mm or 9mm heights, at 500mm or 250mm spacing, at 30km/h or 50km/h. For the same set of test-run conditions, the PC-Crash model-runs also showed no stability or loss-of-control issues. Noting that all these model-runs had a road surface friction value of 0.8, corresponding to a dry surface, the set of model-runs was repeated with a surface friction value of 0.5, corresponding to a wet surface. Again, the set of PC-Crash model-runs showed no stability or loss-of-control issues.

5.2.4 Modelling of heading angles and steering angles

The concern in this research regarding ATP roadmarkings and motorcycles was instability, or other effects that could cause the motorcycle to skid, slide, or otherwise lead to loss of control. Heading and steering angles can indicate such effects. The research needed to verify that PC-Crash would respond with the steering angle corrections and consequent heading angle variations that could be expected when a motorcycle rides over ATP roadmarkings.

Appendix A describes how overall responses of PC-Crash were verified and the replication modelling of the full-scale physical testing produced yaw, pitch and roll results that verified the PC-Crash response to the ATP roadmarkings; the heading and steering angle response of PC-Crash remained to be verified.

A model environment was established with a 100m radius curve. Set-up of the Honda CBR 1100XX motorcycle, the motorcycle rider and the motorcycle path were as for the replication modelling described in section 5.2.3. The road surface friction value was set at 0.5, corresponding to a wet surface.

Model-runs were undertaken:

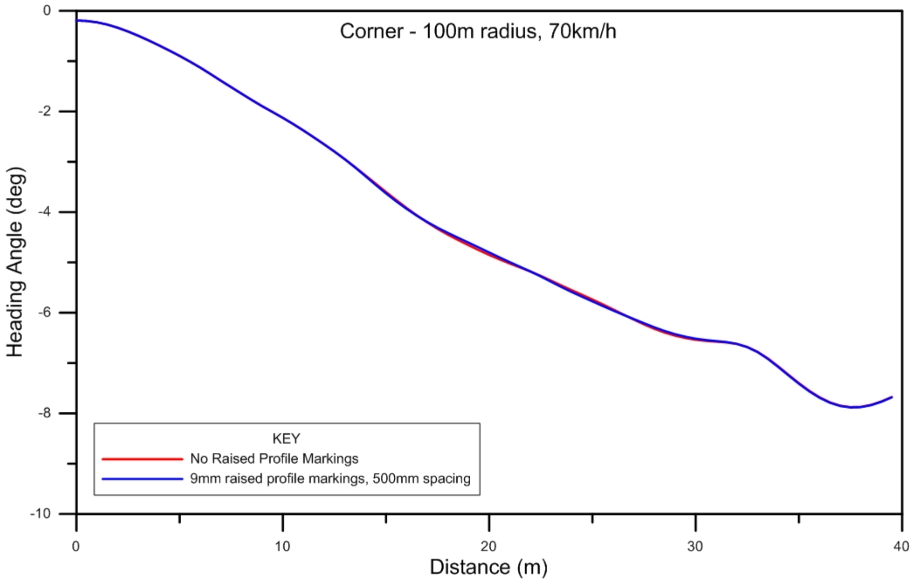
- Figure 5.14 shows the results from two-model runs with the motorcycle travelling at 70km/h.
- Figure 5.15 shows the results from two-model runs with the motorcycle travelling at 120km/h.

Each figure shows a pair of plots: the first plot for heading angle and the second plot for steering angle. The heading angle plots indicate the direction of the motorcycle travelling around the corner and the steering angle plots indicate the adjustments to the motorcycle front wheel angle made by the motorcycle rider in order to achieve the heading angle.

Each plot contains two lines: red for data from a model-run with *no* ATP roadmarkings, and blue for data from a model-run *with* ATP roadmarkings with ribs 9mm high at 500mm spacing. (This rib height and rib spacing was selected as that demonstrating the most effect during the full-scale physical testing.)

At this stage, the key observation from these plots was the small differences in the lines plotted for steering angles. The motorcycle in the model-runs was trying to follow the same path, so these differences showed that the steering angle in PC-Crash did respond to the ATP roadmarkings. The PC-Crash data on heading angles also showed small differences, being consequences of the steering angle differences.

Figure 5.14 Heading and steering angles at 70km/h for *no* ATP roadmarkings (in red) and for *with* ATP roadmarking with ribs 9mm high at 500mm spacing (in blue)



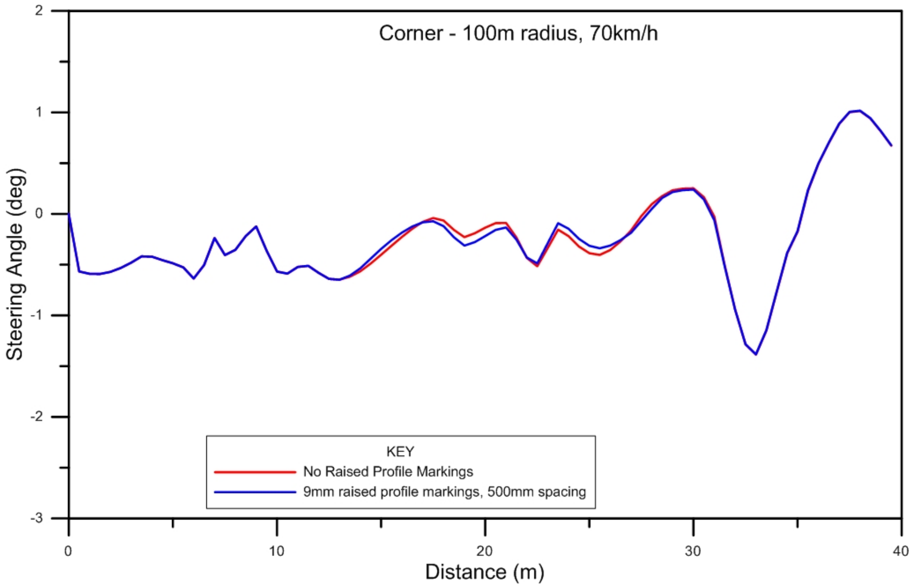
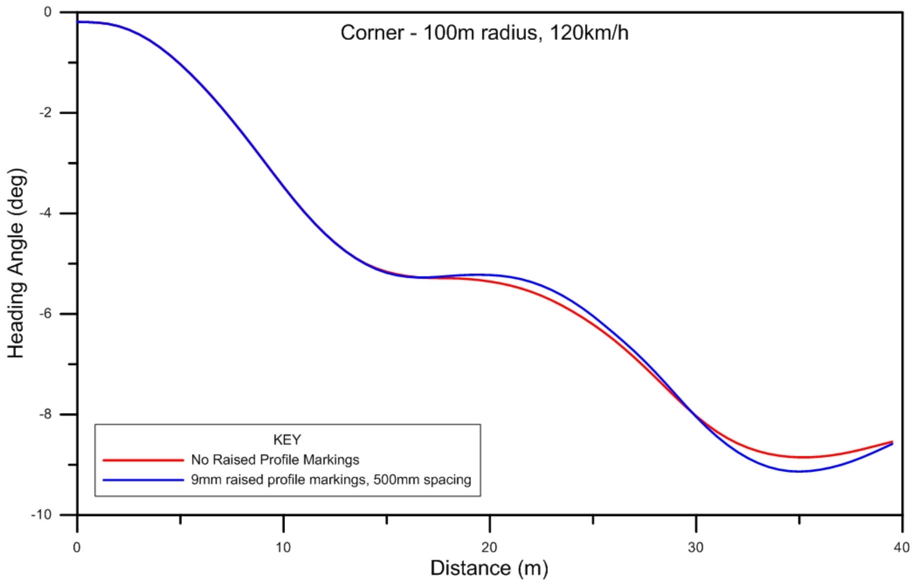
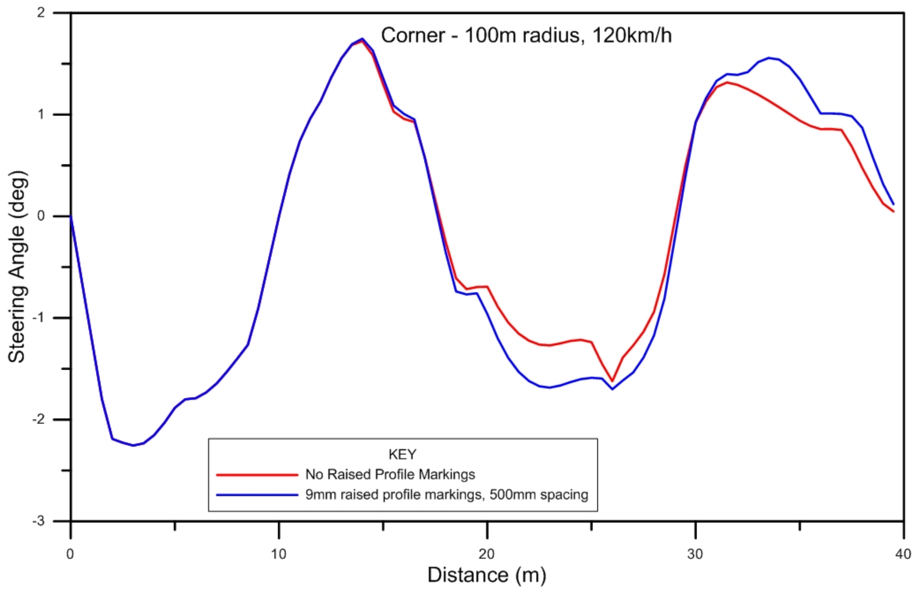


Figure 5.15 Heading and steering angles at 120km/h for *no* ATP roadmarkings (in red) and for *with* ATP roadmarking with ribs 9mm high at 500mm spacing (in blue)





5.2.5 Acceptance of the PC-Crash model

From the work and information contained in this section, the research team considered that PC-Crash appeared suitable for further investigation regarding assessing the effect of ATP roadmarkings on motorcycle stability. This was discussed with the project's Steering Group, which included members of the project team and NZTA representatives, with additional input from the Bikers Rights Organisation New Zealand (BRONZ). The verification of the PC-Crash model was accepted as suitable for the tasks intended in the remainder of the project. (The Steering Group also discussed details of those tasks, directing aspects such as selection of the types and models of motorcycles, and the conditions of braking and cornering.)

5.3 Computer simulation testing with the PC-Crash model

The PC-Crash model was used to investigate ATP roadmarkings and motorcycles at higher speeds – 100km/h and 140km/h. These speeds were considered to be more representative of the open road speeds likely when a motorcycle is contacting ATP roadmarkings, but speeds not viable for full-scale physical testing.

5.3.1 Motorcycle models selected for computer simulation testing

The motorcycles available in New Zealand and ridden on New Zealand open roads include a wide range of characteristics. Three motorcycle models were selected to reasonably cover the most typical characteristics, or those perceived with particular risk. The motorcycle models for simulation testing were:

- Honda CBR 600RR (sports bike) – see figure 5.16
- BMW R1200RS (road/track bike) – see figure 5.17
- Harley Davidson Softail – see figure 5.18 (images from www.totalmotorcycle.com).

Figure 5.16 Honda CBR 600RR

Figure 5.17 BMW R1200GS

Figure 5.18 Harley Davidson Softail

5.3.2 Motorcycle path and cornering for simulation testing

A path and cornering situation that was considered likely to test the motorcycle stability was selected. It combined:

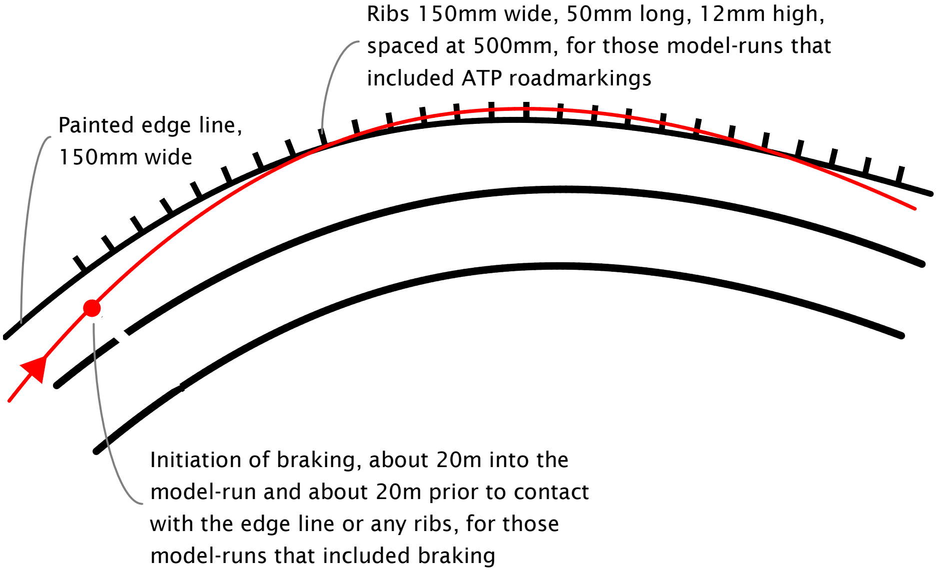
- a wide/poor approach to a ‘tight’ corner of 50m radius
- a surface friction value of 0.5, corresponding to a wet surface
- ribs on the outside of the corner adjacent to a painted continuous edge line for those model-runs that included ATP roadmarkings
- only the painted continuous edge line on the outside of the corner for those model-runs that did not include ATP roadmarkings.

For those model-runs that included ATP roadmarkings, the ribs were modelled as 150mm wide, 50mm long and 12mm high. The rib spacing was 500mm.

The path points defined for the motorcycle approached the corner moving from the inside of the lane (right wheelpath) towards the outside of the lane, passing over the ATP markings around the apex of the corner, and then returning to the road after the apex.

Figure 5.19 shows a simplified representation of the situation.

Figure 5.19 Representation of the corner simulation scenario (not to scale)



Two speeds were selected for the model-runs:

1 the posted open road speed limit of 100km/h

2 a significantly higher speed of 140km/h.

Three different braking scenarios were also defined:

1 no braking (constant speed)

2 50% braking

3 maximum (100%) braking.

For those model-runs that included braking:

- figure 5.19 shows the approximate position where the braking was initiated – about 20m into the model-run and about 20m prior to contact with the edge line or any ATP roadmarkings.
- figure 5.20 shows a representative plot illustrating the effect of the 50% braking – the plot is the speed profile from a model-run for the Honda CBR 600RR at 100km/h with 50% braking
- figure 5.21 shows a representative plot illustrating the effect of the 100% braking – the plot is the speed profile from a model-run for the Honda CBR 600RR at 100km/h with 100% braking.

Figure 5.20 Demonstration of speed profiles with 50% braking (for the Honda CBR 600RR)

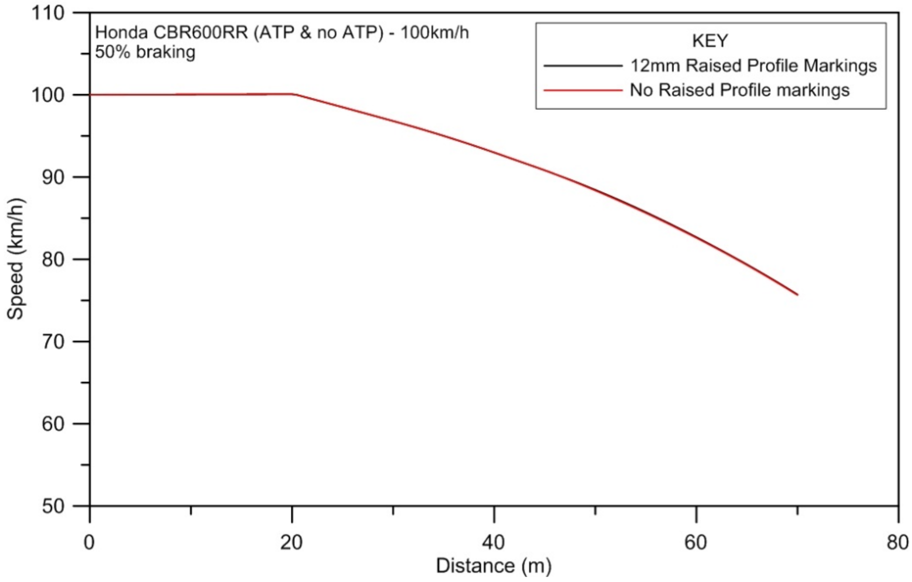
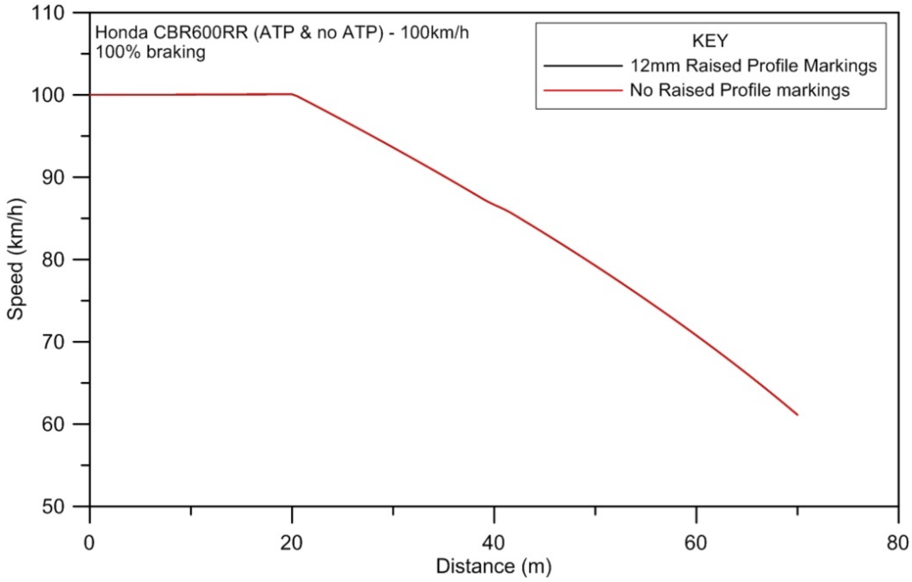


Figure 5.21 Demonstration of speed profiles with 100% braking (for the Honda CBR 600RR)



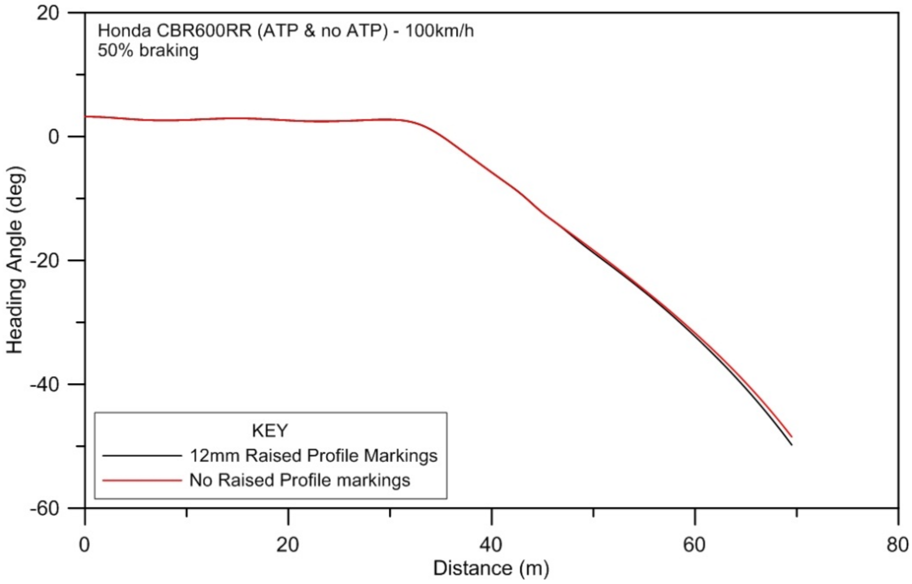
5.3.3 Computer simulation model-runs and results

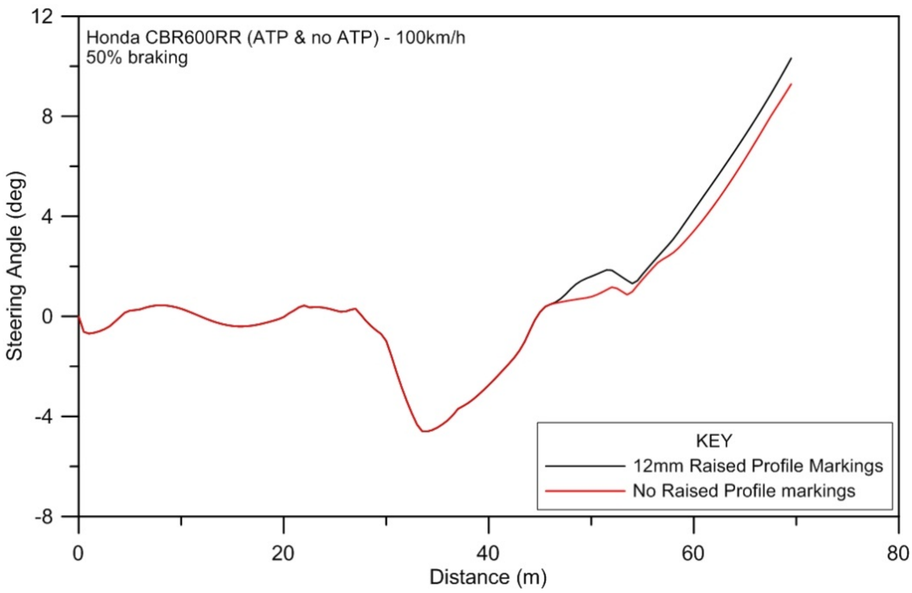
PC-Crash was used to simulate the model-runs for each of the three motorcycles, each of the two speeds, and each of the three braking scenarios – both *with* and *without* ATP roadmarking ribs, so the effects of the ATP roadmarkings on motorcycle stability could be produced. The heading angle and steering angle data were generated from each of the 36 model-runs and plotted to compare the model-runs with *no* ATP roadmarkings to the model-runs *with* ATP roadmarkings. The full set of plots are in:

- appendix B for the Honda CBR 600RR
- appendix C for the BMW R1200GS
- appendix D for the Harley Davidson Softail.

Figure 5.22 shows one representative pair of plots, being for the Honda CBR 600RR motorcycle initially travelling at 100km/h, then applying 50% braking.

Figure 5.22 Honda CBR 600RR heading and steering angles at 100km/h with 50% braking for *no* ATP roadmarkings (in red) and for *with* ATP roadmarking with ribs 9mm high at 500mm spacing (in blue)





The first plot in figure 5.22 compares the heading angle for the motorcycle through the corner with *no* ATP roadmarkings (in red) to the heading angle for the motorcycle for that same movement *with* ATP roadmarkings adjacent to the edge line (in blue). The motorcycle in each model-run was trying to maintain the same vehicle path around the corner. The shape of the plotted lines principally matches the layout of the corner as the motorcycles successfully travelled around the corner without event. If the motorcycle in a model-run did slip or lose control and could not maintain the intended vehicle path around the corner, the plotted line would depart from the expected shape shown in the plot here.

The second plot, in figure 5.22, compares the steering angle for the motorcycle through the corner with *no* ATP roadmarkings (in red) to the steering angle for the motorcycle for that same movement *with* ATP roadmarkings adjacent to the edge line (in blue). The two plotted lines are coincident on the approach to the corner and the ATP roadmarkings; then the plotted lines show a slight departure, indicating that when traversed, the ATP roadmarkings did generate an effect on the motorcycle steering angle. However, the differences between the two plotted lines are in the order of one degree and so are considered small.

If there was a significant cornering difference between the two model-runs, then the steering angle plots would show larger differences between the two plotted lines.

5.4 Discussion of simulation of ATP roadmarkings and motorcycles

PC-Crash was used to simulate a selection of motorcycles travelling at speeds up to 140km/h, in dry conditions and wet conditions, on straight and curved alignments. Simulations were undertaken including both *no* ATP roadmarkings and *with* ATP roadmarkings with ribs of heights 3mm, 6mm, 9mm and 12mm, and rib spacings of 250mm and 500mm.

The simulations showed no significant stability or loss-of-control differences between the simulations with *no* ATP roadmarkings and the simulations *with* ATP roadmarkings. Some simulations included conditions that led to motorcycle instability or loss of control, and in these simulations there were also no significant differences between the simulations with *no* ATP roadmarkings and the simulations *with* ATP roadmarkings.

When trying to maintain the same vehicle path, the PC-Crash simulations showed that contacting ATP roadmarkings did effect small differences in the steering angles, and consequently the heading angles, compared with not contacting ATP roadmarkings.

It is important to note the motorcycles in these PC-Crash simulations were set to follow a specified path, as far as physically possible. These simulations took no account of behavioural responses from motorcycle riders, such as, for example, a sudden steering change by the driver after initial contact with an ATP roadmarking rib. While it is conceivable that a motorcycle rider could react adversely to contact with ATP roadmarkings, this research extensively reviewed the existing crash reports and the literature and found no indication of this being an issue.

6 Summary, conclusions and recommendations

Through an inspection of existing crash records and literature, and both physical and computer simulations, this research project investigated interactions between two-wheeled vehicles and ATP roadmarkings. The findings were as follows:

- Reports of motorcycle crashes that occurred at locations where ATP roadmarkings were present did not identify the ATP roadmarkings as a factor in the crash.
- A broad collection of associated literature contained no evidence that the current dimensions of ATP roadmarkings would cause significant instability issues.
- The data on motorcycle response to ATP roadmarkings from full-scale physical testing up to 50km/h appeared to be replicated by the PC-Crash model.
- Using the PC-Crash model, computer simulations of motorcycles for speeds up to 140km/h showed no significant stability differences between the simulations with *no* ATP roadmarkings and the simulations *with* ATP roadmarkings.
- The research indicated that increasing rib height effects more motorcycle response, and 500mm rib spacing effects more motorcycle response than 250mm rib spacing.
- The research indicated that increased speed of the motorcycle while encountering the ATP roadmarkings effects more motorcycle response.

This research found no evidence from the existing crash records, in the literature, or from the validated computer simulation modelling, that ATP roadmarkings as currently used in New Zealand create any significant instability issues for motorcycles. Therefore, at this stage it appears there is no need to change current practice in this area.

Recommendations from the research were as follows:

- The NZTA should stay alert to developments in the associated literature and international practices relating to ATP roadmarkings, including addressing motorcycle rider behaviours regarding ATP roadmarkings.
- If NZTA practices for ATP roadmarking dimensions or other properties of ATP roadmarkings usage are to change, computer simulation testing could be included as one stage in testing the proposed ATP roadmarking modification, prior to road trial.

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Appendix A PC-Crash (3D Version 9)

A.1 Information from www.pc-crash.com and the software's operating manual

PC-Crash is a collision and trajectory simulation tool that enables the accurate analysis of a wide variety of motor vehicle collisions and other incidents. The level of complexity of mathematical models corresponds to the specific nature of road accidents.

PC-Crash contains several different calculation models, including:

- Impact model: Kubar-Sidlich
    a) Momentum-impulse model
    b) Automatic impact detection
    c) Secondary impacts – can have different properties specified than those for the primary impact
- Trajectory models
    a) Full 3-D forward rigid-body dynamics
    b) Including effects of tyre friction
    c) Including anti-lock braking systems and electronic stability control systems.

PC-Crash simulation results can be viewed and outputted in scale plan and elevation views, 3D perspective view, and in numerous diagrams and tables.

A.2 Overview of the model

The model to be used is the computer simulation software package called PC-Crash (Version 9). This is an internationally recognised 3D vehicle collision and trajectory simulation tool used by police and civilian crash investigators and analysts. PC-Crash is used by New Zealand Police to prepare evidence for driver prosecutions and coroner inquests. The model as it already exists is used to investigate motorcycle crashes. The model recognises vehicles from 34 different motorcycle manufacturers, and for each manufacturer, their range of motorcycles. These databases will therefore include motorcycles typical of the New Zealand fleet. Therefore while the application of PC-Crash to the behaviour of motorcycles traversing ATP roadmarkings is probably novel, its application to motorcycle crash analysis is common.

The model was used as follows:

- A three-dimensional road model can be generated by modifying elevation, radius, cross-fall and width parameters of a road element. Surface friction values can be defined either as a standard value for the entire surface or as friction polygons with specific defined dimensions and values. Road surface irregularities can be incorporated into the model and we used this feature to simulate ATP roadmarkings.
- Characteristics of vehicles (typically cars, trucks, buses and vans, but in this instance motorcycles) were imported from a number of different databases covering a wide range of vehicle manufacturers.
- Vehicle paths and speeds, including sequences of acceleration and braking, were defined. When the simulation is run using the default kinetic model, the vehicle will obey the laws of physics and will

follow the path specified unless the speed becomes too great for the simulation conditions; eg if the surface friction is too low, or if a surface irregularity causes loss of contact with the road.

A.3 Preliminary testing that the model was fit for the intended purpose

We already had PC-Crash and had been using it for the past 18 months on Road Safety Trust and NZTA research projects, and therefore believed that it would be appropriate for the intended research. The Road Safety Trust requested validation of the simulations obtained with PC-Crash as part of its use on a research project looking at clear zones on curves. This involved (for cars) comparing simulated braking distances and vehicle paths around curves with on-road observations.

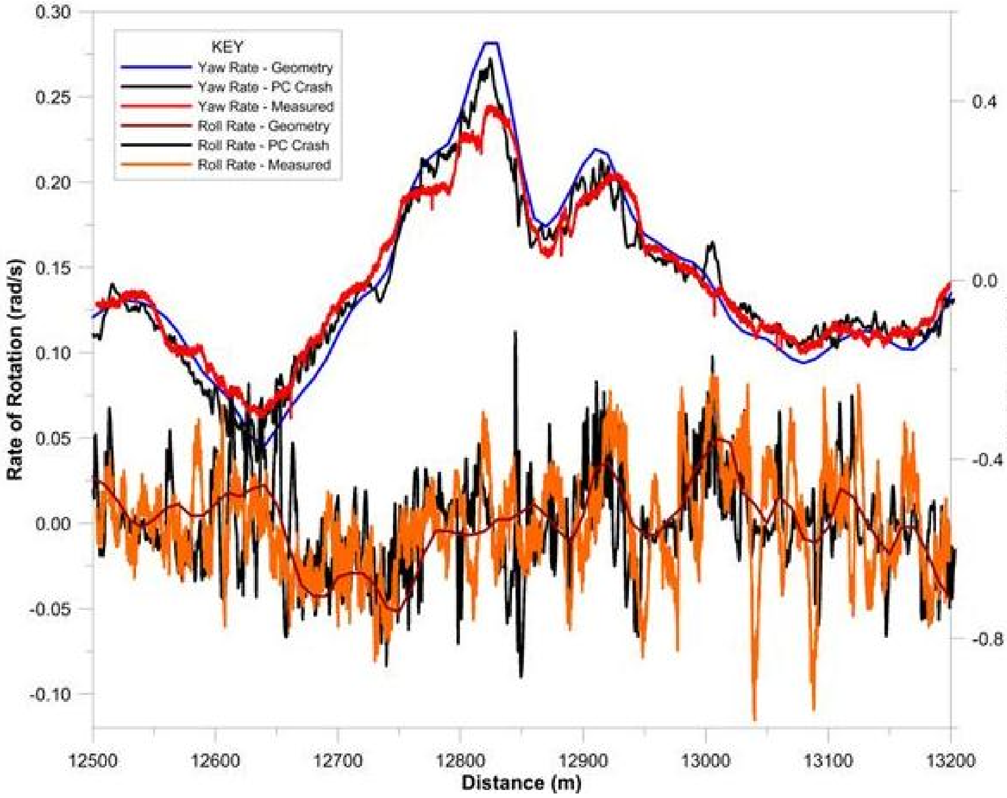
We undertook (for motorcycles) the following preliminary evaluation so as to be satisfied that the model was fit for the intended purpose.

- We examined the ability to input an ATP roadmarking into the model. It would accept a profile with rectangular cross-section that could be adjusted in dimensions in 1mm increments if required. (Note that we could also exactly replicate this shape in the full- scale tests that were used to validate the model.)
- We modelled 5mm- and 10mm-high strips that were 100mm wide, and ran motorbike simulations over them to assess whether PC-Crash would show identifiable variations in the normal wheel forces. It did show changes in the normal wheel forces for both of these elements, with the variation being larger for the thicker elements, and increasing with increasing speed. The variations were generally consistent with the limited amount of data available in the literature.
- We also ran limited PC-Crash motorcycle simulations to investigate (1) stopping distances and (2) lateral tyre forces and roll rates during slalom manoeuvres. The results showed reasonable agreement with the data provided in the literature, allowing for the fact that much of the literature was not highly detailed on the exact characteristics of the motorcycle tested.

A.4 Assessment and verification of PC-Crash

PC-Crash is an internationally recognised three-dimensional vehicle collision and trajectory simulation tool that is currently used by police and civilian crash investigators and analysts, with over 4000 licences worldwide. Since its initial development as a commercially available software package there have been a number of technical papers describing its use and agreement with real-life scenarios. These references include Moser and Steffan (1996), Spit (2000), Gopal et al (2004), Batista et al (2005), Tejera (2006) and Kunz (2007). They have found generally good agreement with real-life situations. PC-Crash was also used recently by Cenek et al (2011) to compare measured rates of yaw and rotation with values from the computer simulations. Figure A.1 shows an example comparison of the yaw and roll rates derived from geometry data in RAMM, on-road measurements, and the PC-Crash simulation.

Figure A.1 Comparison of geometry, on-road and computer simulation data for a car at 80km/h



This suggests reasonably good agreement between measured and simulated vehicle response data for yaw and roll. However, it was also considered appropriate to also assess whether PC-Crash produced results that were in reasonable agreement with the braking and sliding conditions likely during real crash situations. Accordingly, a PC-Crash 3D model of a straight, flat road section was constructed so that locked-wheel-braking tests carried out during other on-road testing programmes by Opus Central Laboratories (Jamieson et al 2002; Cenek et al 2005) could be simulated. Friction and braking distance data was taken from a range of studies carried out on different surface types and conditions. The surface types included asphaltic concretes, chipseals and different grass types, and the conditions included dry and wet surfaces, as well as differential friction. Differential friction was achieved by wetting one wheelpath and leaving the other dry. PC-Crash simulations were then run using vehicles matching those used in the full-scale studies. Braking distances were measured for the same test speeds used in the full-scale testing, and yaw angles were also measured for the tests using differential friction. The results of these tests are listed in table A.1.

Table A.1 Comparison of full-scale physical testing and PC-Crash for condition of locked-wheel braking

Surface	Condition (dry/wet)	Speed (km/h)	Differential friction	Coefficient of friction	Full-scale physical testing		PC-Crash	
					Braking distance (m)	Yaw angle (°)	Braking distance (m)	Yaw angle (°)
Chipseal	Dry	52	No	0.60	16.5	NA	17.0	N/A
Chipseal	Wet	50	No	0.51	19.2	NA	20.2	N/A
Chipseal	Wet	69	No	0.53	33.0	NA	34.2	N/A
AC[a]	Dry	50	No	0.73	12.6	NA	13.0	N/A
AC	Wet	73	No	0.59	36.6	NA	35.8	N/A
AC	Wet	52	No	0.64	16.9	NA	16.0	N/A
Clover	Dry	40	No	0.21	30	NA	31.1	N/A
Clover	Wet	40	No	0.17	37	NA	38.8	N/A
Ryegrass	Dry	40	No	0.38	17	NA	17.3	N/A
Ryegrass	Wet	40	No	0.24	26	NA	27.1	N/A
AC	Dry	50	No	0.73	13.0	NA	13.0	N/A
AC	Dry & wet	48	Yes	0.65	13.5	23.4	14.3	22.0
AC	Dry & wet	58	Yes	0.59	19.8	43.9	20.5	42.0
AC	Dry & wet	68	Yes	0.64	28.0	22.2	27.1	21.5

a) Asphaltic concrete

This shows good agreement between the full-scale measured braking distances and those derived from the computer simulation, not only in straight-line braking, but also under conditions of differential friction. In addition, there was good agreement between the measured and computer-derived yaw angles. These findings indicated that PC-Crash provides a reasonably accurate simulation of vehicle movement in both the longitudinal and lateral directions across a broad range of friction values.

It was also considered appropriate to assess how well the PC-Crash simulation would replicate an actual crash situation. Given the good agreement shown above between real braking/sliding performance, it was not considered necessary to investigate more than one run-off-the-road crash situation. One run-off-the-road vehicle crash on a corner was selected as having sufficiently detailed information about the crash to give some confidence about choosing the simulation parameters. Figure A.2 shows a view of the corner.

Figure A.2 State highway 53 RP0/0 13990-14080 (decreasing direction is from bottom to top)

This 2008 crash involved a 4WD Mitsubishi Pajero, which was travelling in the decreasing direction around a right-hand curve with a curve advisory speed of 75km/h. According to the driver it was raining heavily after a spell of dry weather and the vehicle was travelling at around 70km/h. The driver lost control of the vehicle and skidded off the road, just missing the power pole and advertising hoarding (see above), and eventually coming to a stop a short distance past this point.

The 3D model for this corner was imported into PC-Crash and the appropriate vehicle was loaded. Friction values for the road surface and the roadside were chosen as for a very wet surface ($\mu = 0.3$). Vehicle tracks based on several different driving lines were used to run simulations at speeds around 70km/h and higher. The simulations suggested that the vehicle speed was at least 75km/h, possibly as high as 90km/h, and was cutting towards the middle of the corner, then beginning to encroach out of the lane past the apex of the corner. Figure A.3 shows a plot of the simulated vehicle path. This shows reasonably good agreement with the identified encroachment location and the path of the vehicle past the pole and hoarding. Together with the locked-wheel braking comparisons described in table A.1, this gave us some confidence that PC-Crash provides an acceptable simulation of vehicle trajectory, braking and sliding behaviour.

Figure A.3 Vehicle path simulated in PC-Crash

A.5 Appendix A references

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Appendix B Simulated heading and steering angles for the Honda CBR 600RR

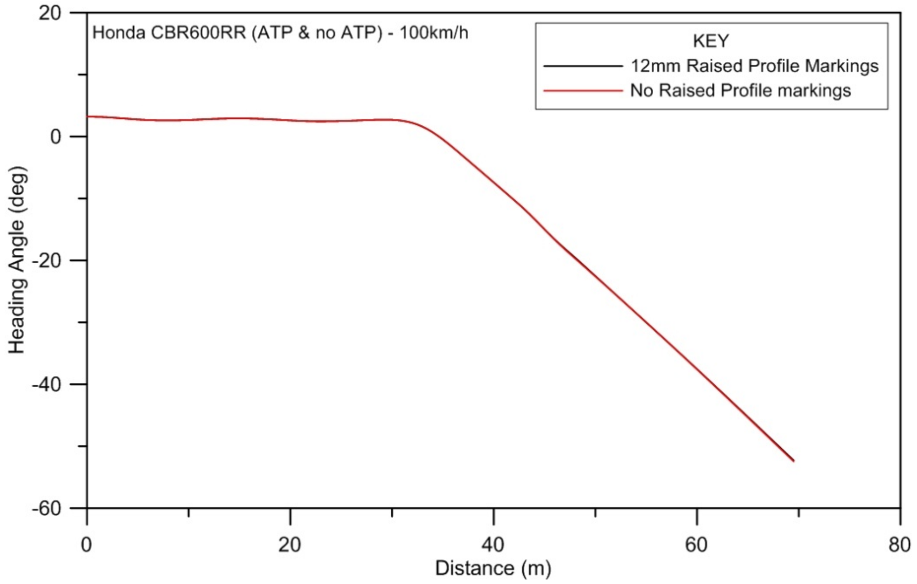
This section contains six pairs of plots; the first plot in each pair is for heading angle and the second plot for steering angle. The plots are from modelling of a Honda CBR 600RR motorcycle taking a wide/poor approach to a 'tight' corner of 50m radius, as explained section 5.3.2.

Each plot contains two lines; red for data from a model-run with *no* ATP roadmarkings and blue for data from a model-run *with* ATP roadmarkings 12mm high at 500mm spacing.

The pairs of plots are as follows:

	No braking	**50% braking**	**100% braking**
100km/h	Figure B.1	Figure B.2	Figure B.3
140km/h	Figure B.4	Figure B.5	Figure B.6

Figure B.1 Honda CBR 600RR heading and steering angles at 100km/h (with no braking) for *no* ATP roadmarkings (in red) and for *with* ATP roadmarking with ribs 12mm high at 500mm spacing (in blue)



The lines on the heading angle plot match the path specified in the modelling indicating the motorcycle can physically achieve the cornering in each model-run.

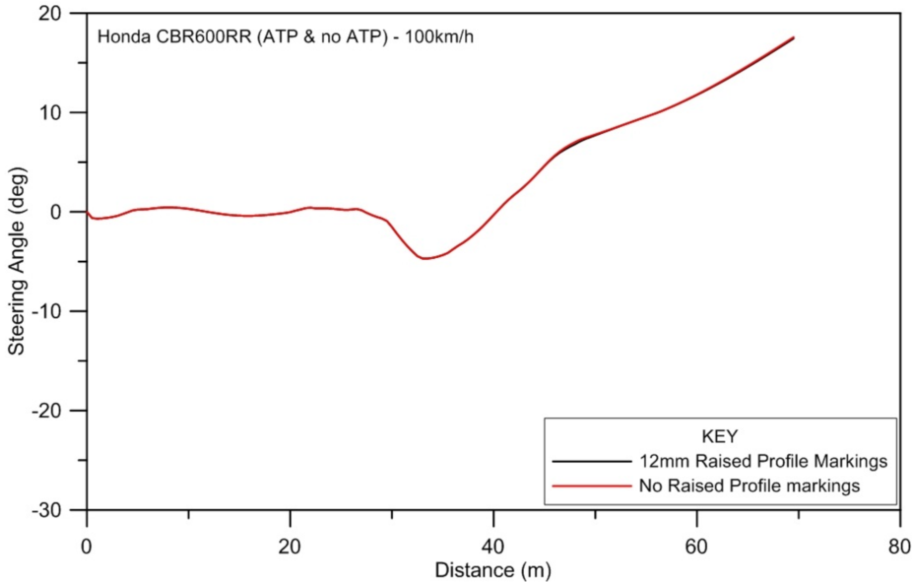
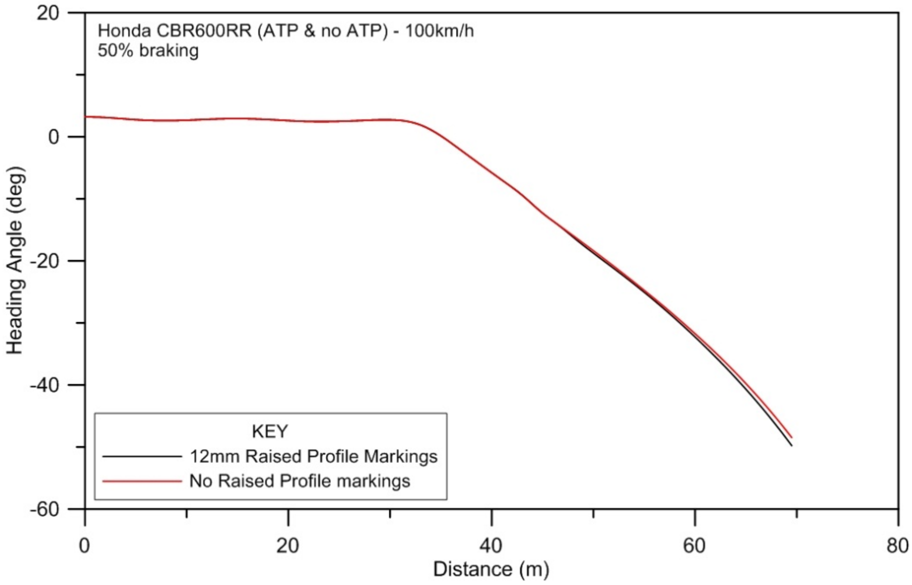


Figure B.2 Honda CBR 600RR heading and steering angles at 100km/h with 50% braking for *no* ATP roadmarkings (in red) and for *with* ATP roadmarking with ribs 12mm high at 500mm spacing (in blue)



The lines on the heading angle plot match the path specified in the modelling, indicating the motorcycle can physically achieve the cornering in each model-run.

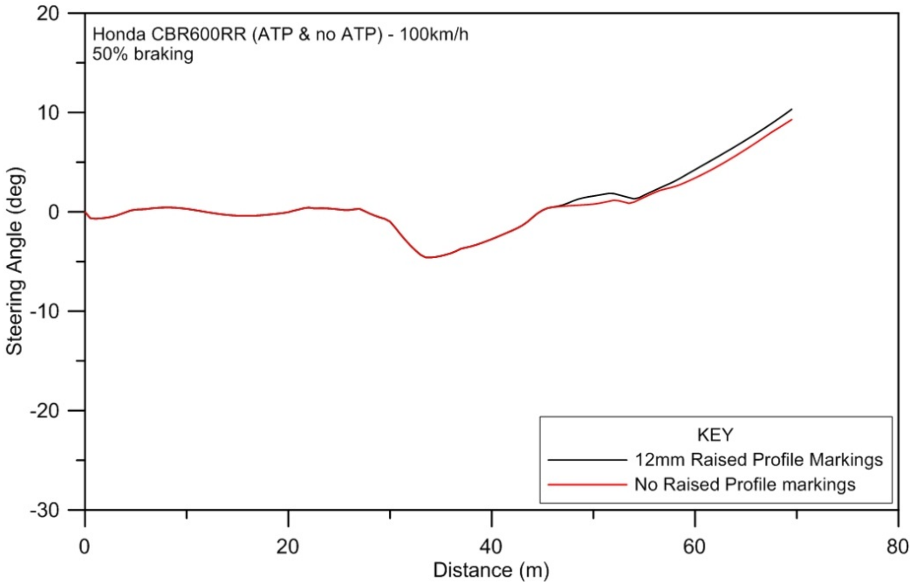
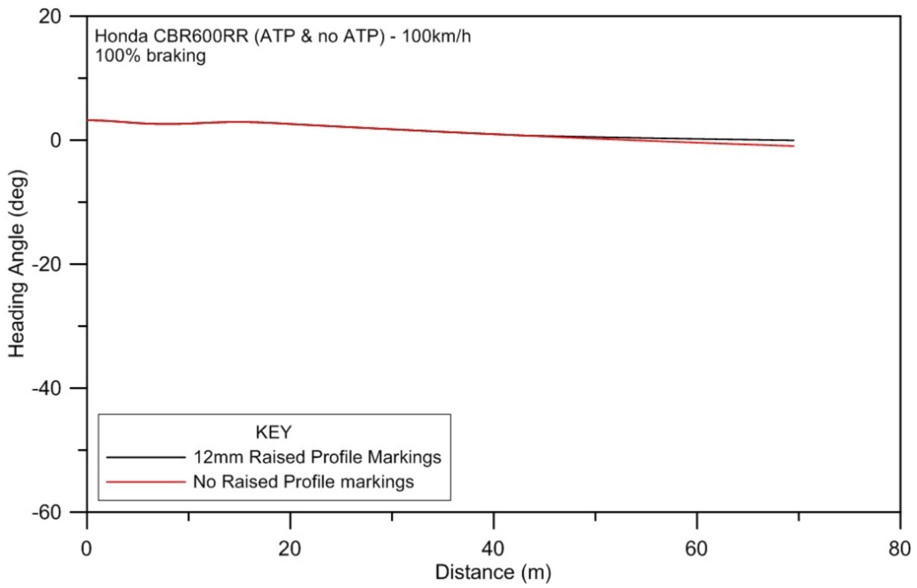


Figure B.3 Honda CBR 600RR heading and steering angles at 100km/h with 100% braking for *no* ATP roadmarkings (in red) and for *with* ATP roadmarking with ribs 12mm high at 500mm spacing (in blue)



The lines on the heading angle plot do not match the path specified in the modelling, indicating the motorcycle cannot physically achieve the cornering; however, the significant observation is the extent of similarity in the results from each of the two model-runs.

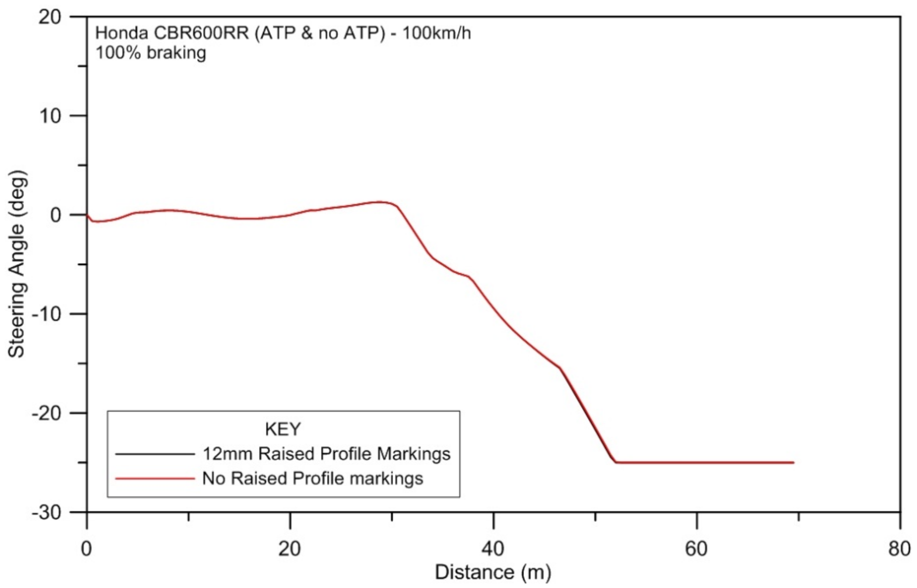
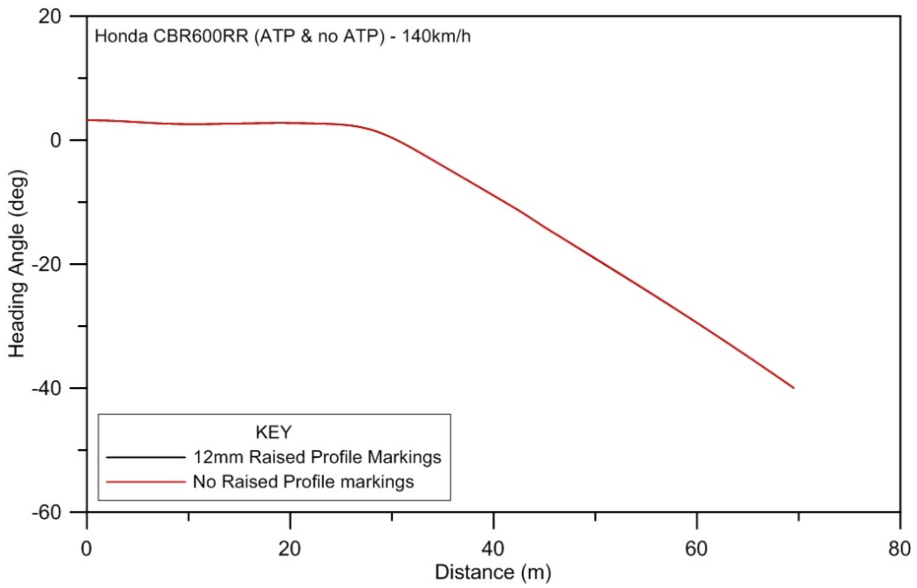


Figure B.4 Honda CBR 600RR heading and steering angles at 140km/h (no braking) for *no* ATP roadmarkings (in red) and for *with* ATP roadmarking with ribs 12mm high at 500mm spacing (in blue)



The lines on the heading angle plot match the path specified in the modelling, indicating the motorcycle can physically achieve the cornering in each model-run.

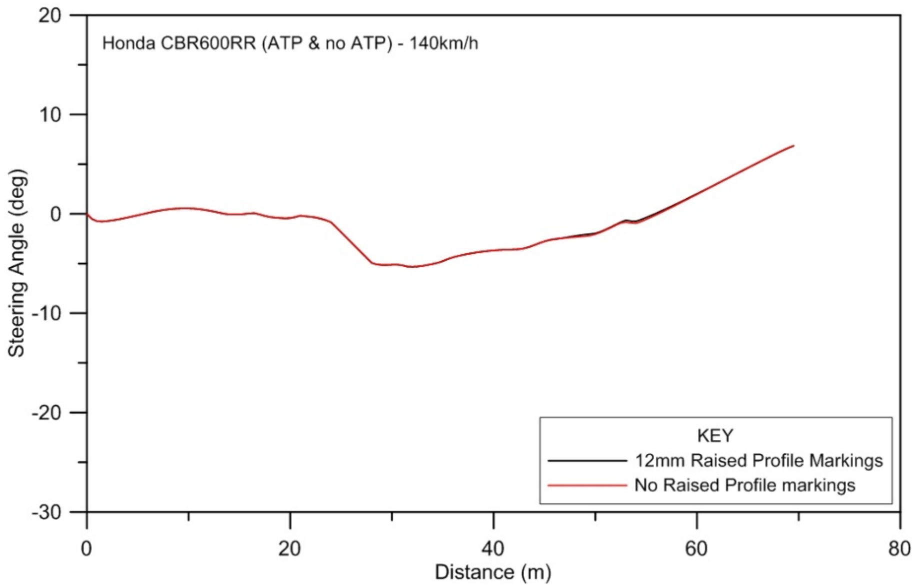
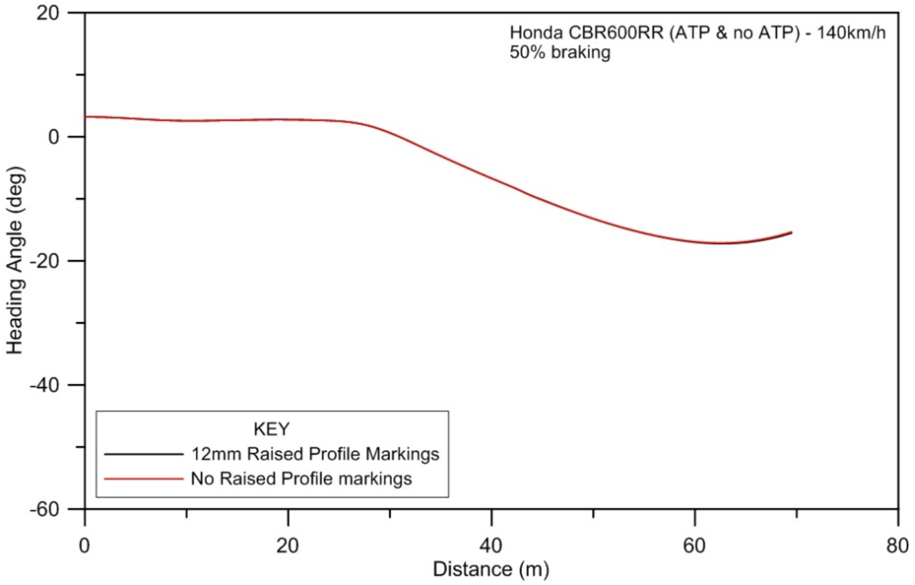


Figure B.5 Honda CBR 600RR heading and steering angles at 140km/h with 50% braking for *no* ATP roadmarkings (in red) and for *with* ATP roadmarking with ribs 12mm high at 500mm spacing (in blue)



The lines on the heading angle plot do not match the path specified in the modelling, indicating the motorcycle cannot physically achieve the cornering; however, the significant observation is the extent of similarity in the results from each of the two model-runs.

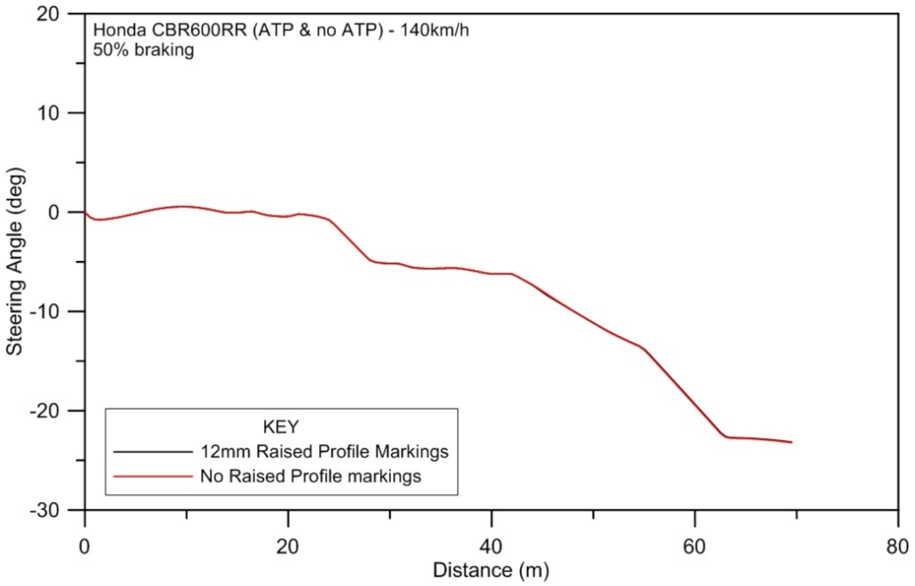
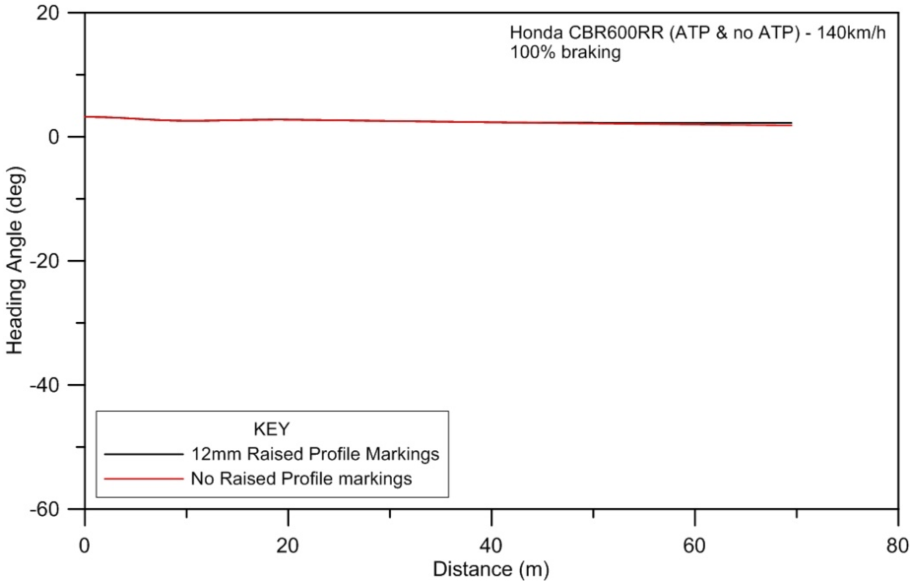
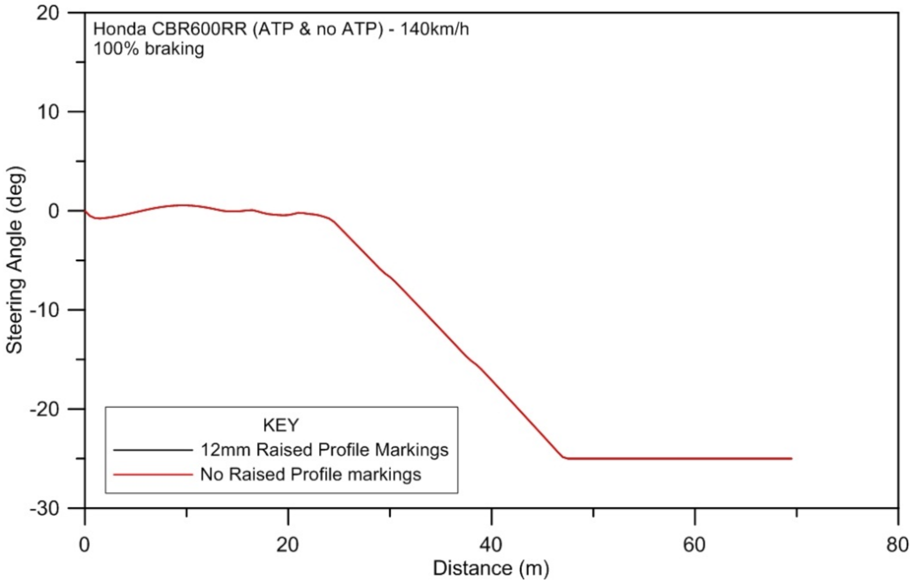


Figure B.6 Honda CBR 600RR heading and steering angles at 140km/h with 100% braking for *no* ATP roadmarkings (in red) and for *with* ATP roadmarking with ribs 12mm high at 500mm spacing (in blue)



The lines on the heading angle plot do not match the path specified in the modelling, indicating the motorcycle cannot physically achieve the cornering; however, the significant observation is the extent of similarity in the results from each of the two model-runs.



Appendix C Simulated heading and steering angles for the BMW R120GS

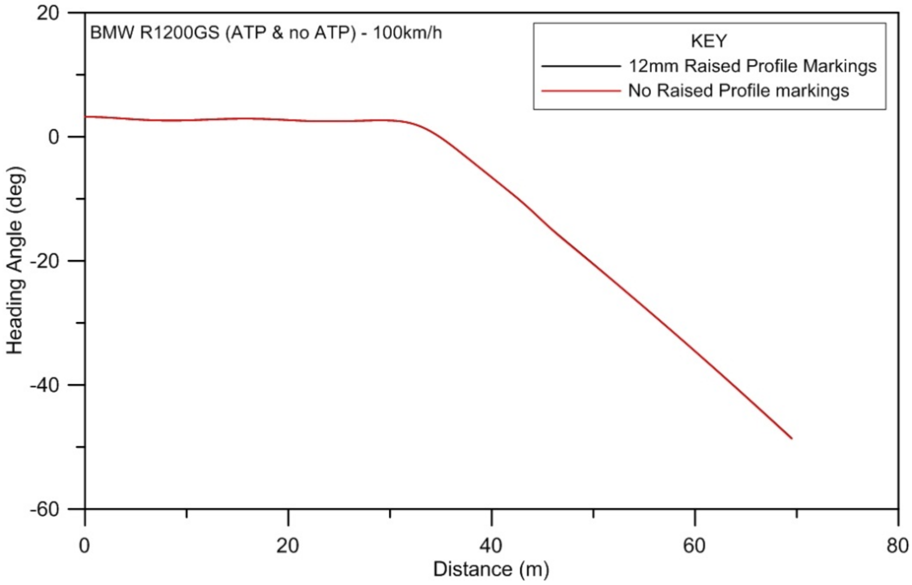
This section contains six pairs of plots; the first plot in each pair is for heading angle and the second plot for steering angle. The plots are from modelling of a BMW R120GS motorcycle taking a wide/poor approach to a ‘tight’ corner of 50m radius, as explained section 5.3.2.

Each plot contains two lines; red for data from a model-run with *no* ATP roadmarkings, and blue for data from a model-run *with* ATP roadmarkings 12mm high at 500mm spacing.

The pairs of plots are as follows:

	No braking	50% braking	100% braking
100km/h	Figure C.1	Figure C.2	Figure C.3
140km/h	Figure C.4	Figure C.5	Figure C.6

Figure C.1 BMW R120GS heading and steering angles at 100km/h (no braking) for *no* ATP roadmarkings (in red) and for *with* ATP roadmarking ribs 12mm high at 500mm spacing (in blue)



The lines on the heading angle plot match the path specified in the modelling, indicating that the motorcycle can physically achieve the cornering in each model-run.

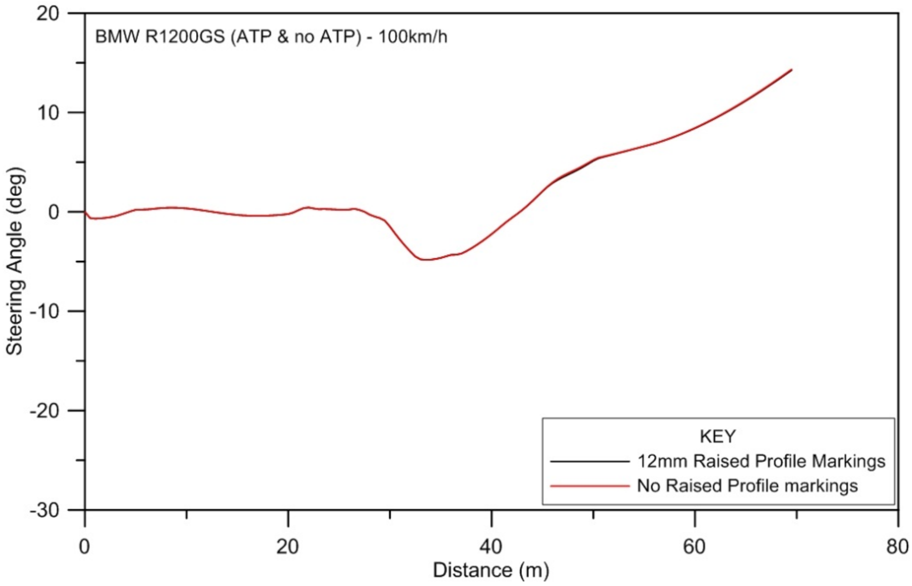
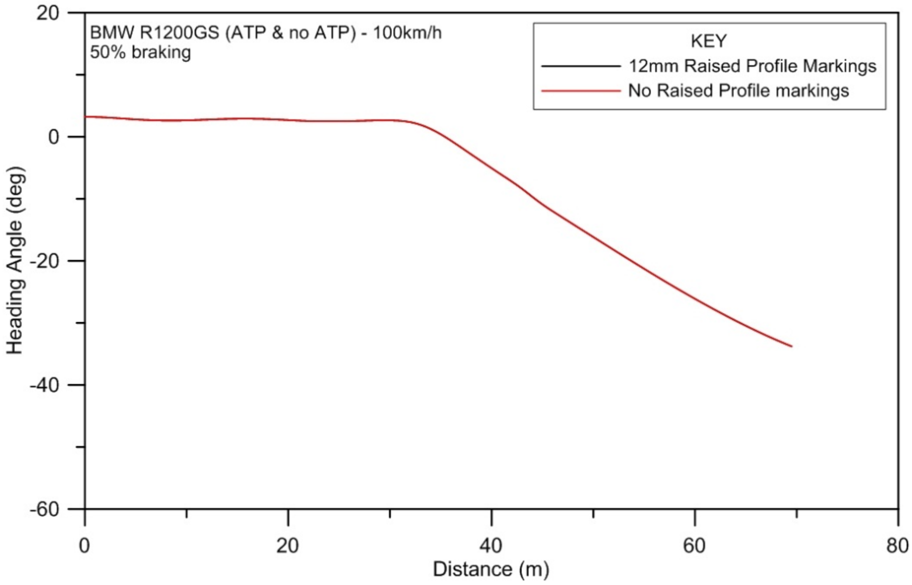


Figure C.2 BMW R120GS heading and steering angles at 100km/h with 50% braking for *no* ATP roadmarkings (in red) and for *with* ATP roadmarking ribs 12mm high at 500mm spacing (in blue)



The lines on the heading angle plot match the path specified in the modelling, indicating that the motorcycle can physically achieve the cornering in each model-run.

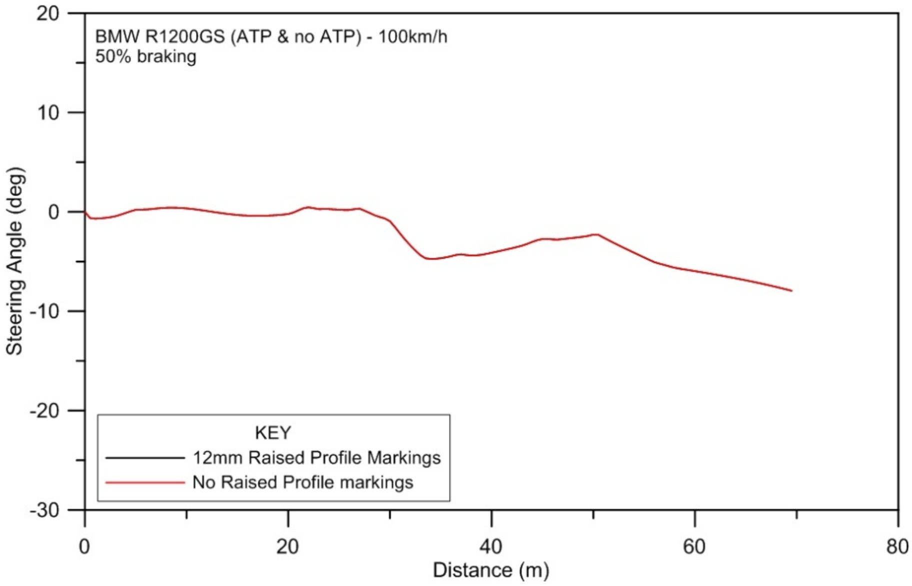
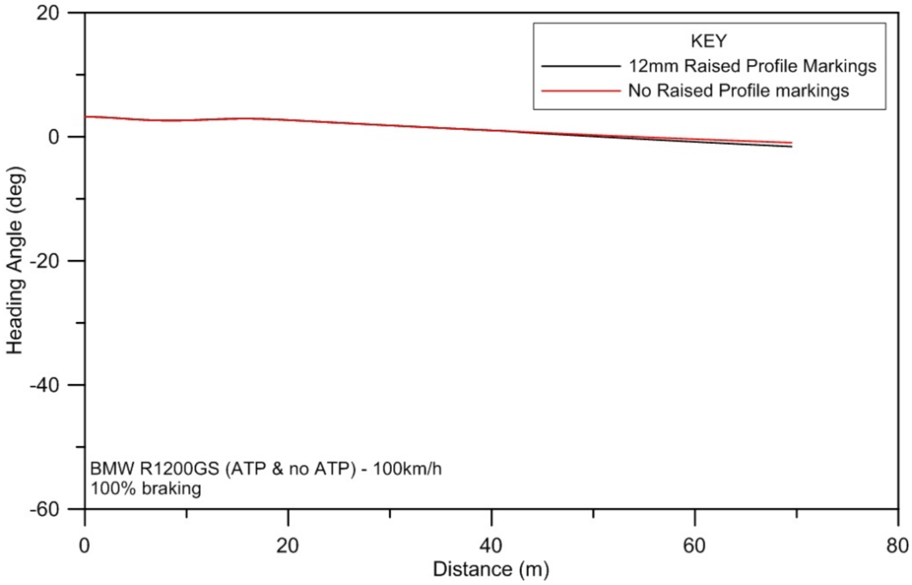


Figure C.3 BMW R120GS heading and steering angles at 100km/h with 100% braking for *no* ATP roadmarkings (in red) and for *with* ATP roadmarking ribs 12mm high at 500mm spacing (in blue)



The lines on the heading angle plot do not match the path specified in the modelling, indicating that the motorcycle cannot physically achieve the cornering; however, the significant observation is the extent of similarity in the results from each of the two model-runs.

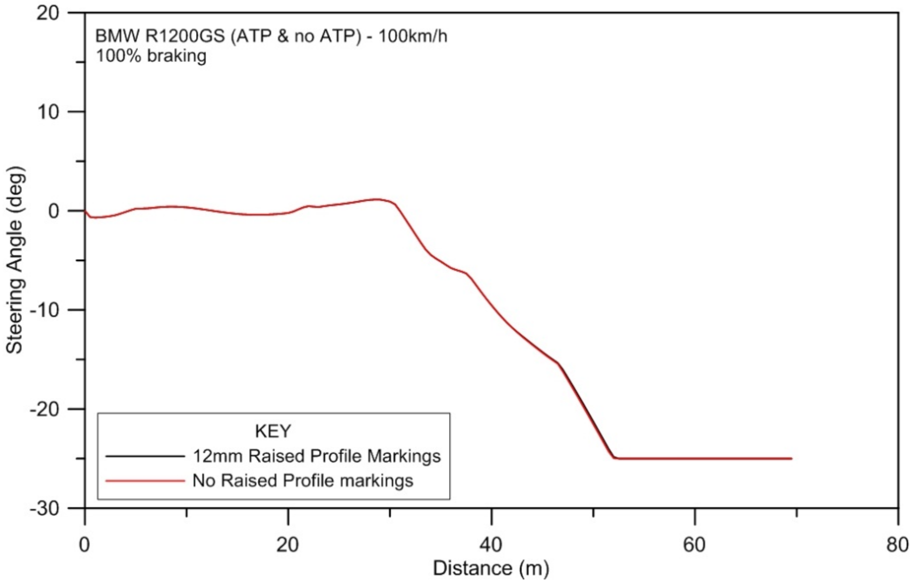
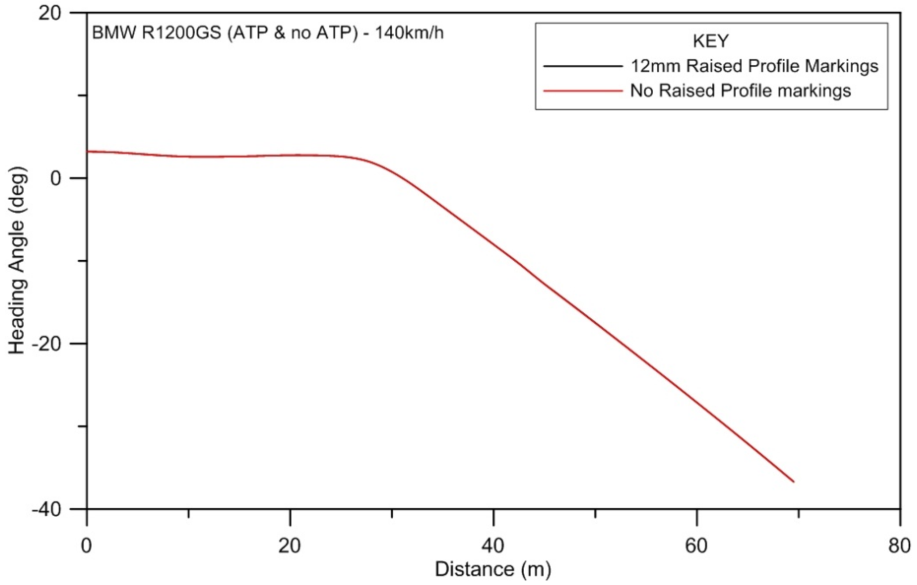


Figure C.4 BMW R120GS heading and steering angles at 140km/h (no braking) for *no* ATP roadmarkings (in red) and for *with* ATP roadmarking ribs 12mm high at 500mm spacing (in blue)



The lines on the heading angle plot match the path specified in the modelling, indicating that the motorcycle can physically achieve the cornering in each model-run.

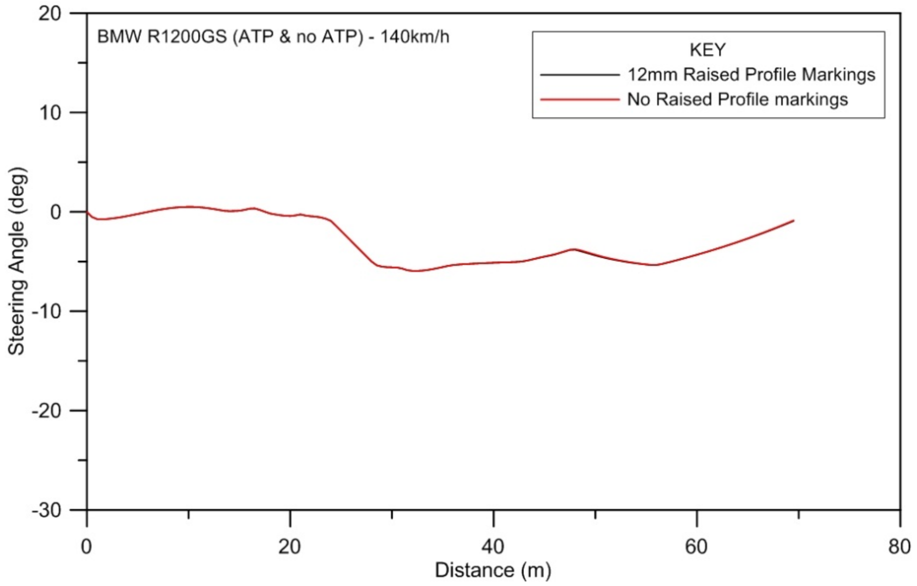
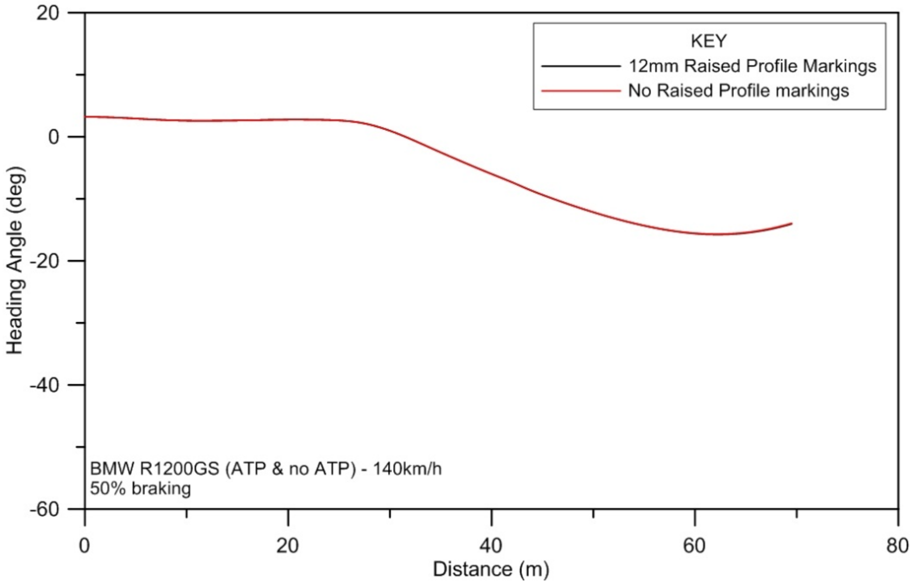


Figure C.5 BMW R120GS heading and steering angles at 140km/h with 50% braking for *no* ATP roadmarkings (in red) and for *with* ATP roadmarking ribs 12mm high at 500mm spacing (in blue)



The lines on the heading angle plot do not match the path specified in the modelling, indicating that the motorcycle cannot physically achieve the cornering; however, the significant observation is the extent of similarity in the results from each of the two model-runs.

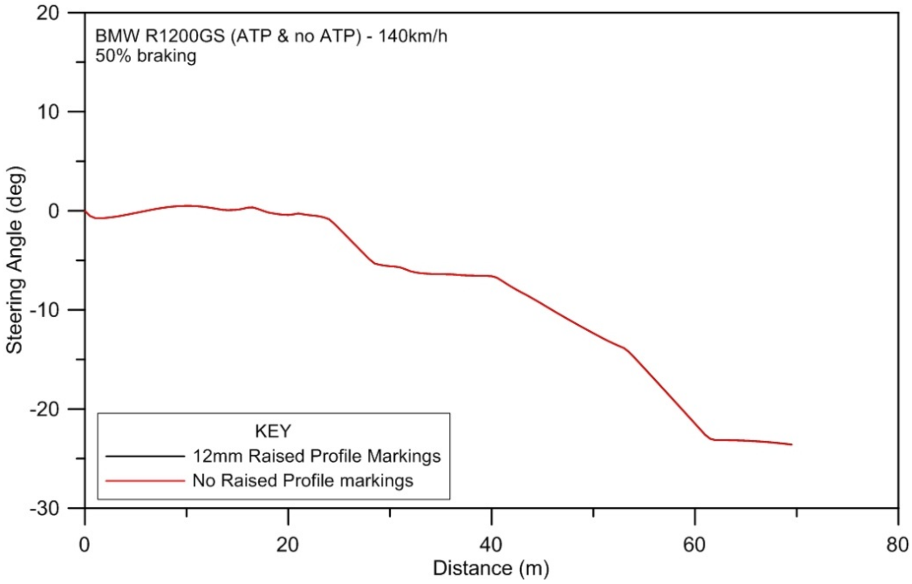
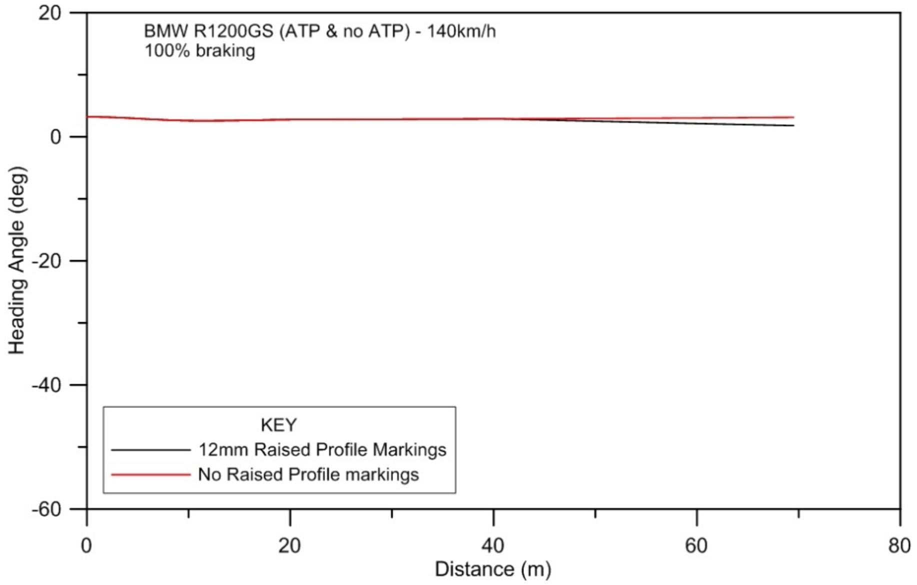
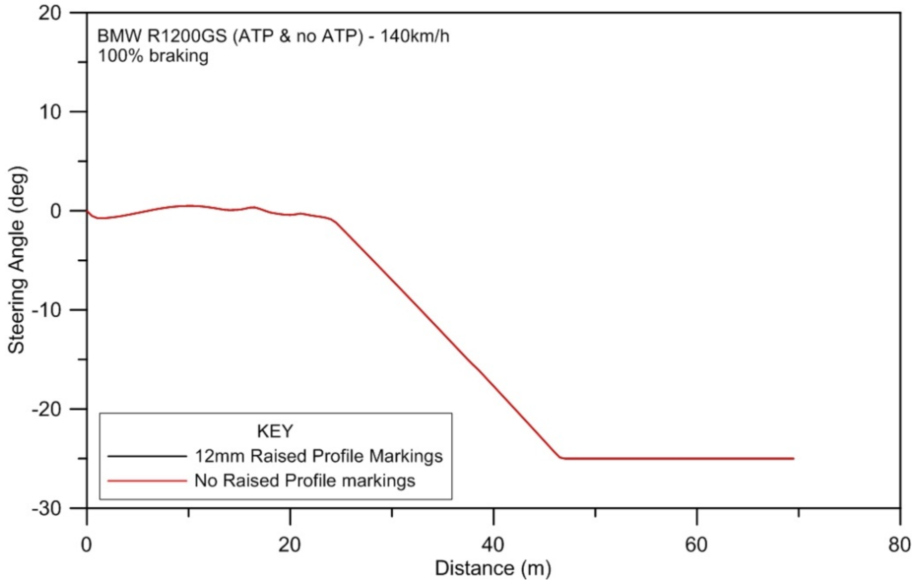


Figure C.6 BMW R120GS heading and steering angles at 140km/h with 100% braking for *no* ATP roadmarkings (in red) and for *with* ATP roadmarking ribs 12mm high at 500mm spacing (in blue)



The lines on the heading angle plot do not match the path specified in the modelling, indicating that the motorcycle cannot physically achieve the cornering; however, the significant observation is the extent of similarity in the results from each of the two model-runs.



Appendix D Simulated heading and steering angles for the Harley Davidson Softail

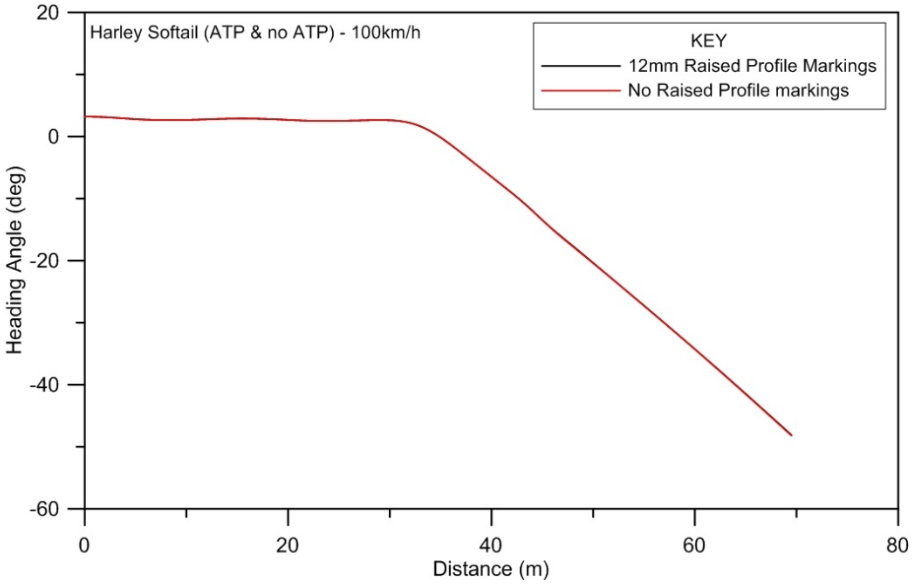
This section contains six pairs of plots; the first plot in each pair is for heading angle and the second plot for steering angle. The plots are from modelling of a Harley Davidson Softail motorcycle taking a wide/poor approach to a 'tight' corner of 50m radius, as explained section 5.3.2.

Each plot contains two lines; red for data from a model-run with *no* ATP roadmarkings and blue for data from a model-run *with* ATP roadmarkings 12mm high at 500mm spacing.

The pairs of plots are as follows:

	No braking	**50% braking**	**100% braking**
100km/h	Figure D.1	Figure D.2	Figure D.3
140km/h	Figure D.4	Figure D.5	Figure D.6

Figure D.1 Harley Davidson Softail heading and steering angles at 100km/h (no braking) for no ATP roadmarkings (in red) and for with ATP roadmarking ribs 12mm high at 500mm spacing (in blue)



The lines on the heading angle plot match the path specified in the modelling, indicating that the motorcycle can physically achieve the cornering in each model-run.

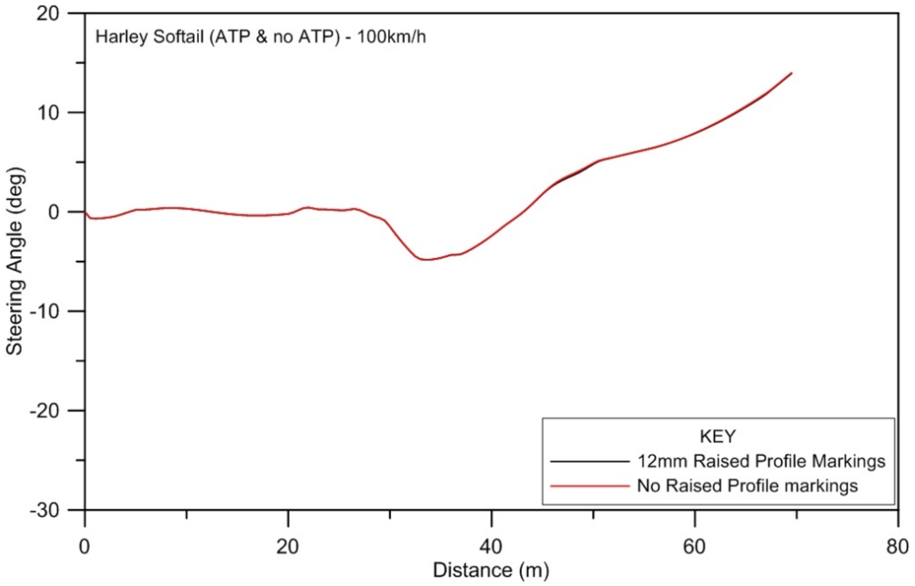
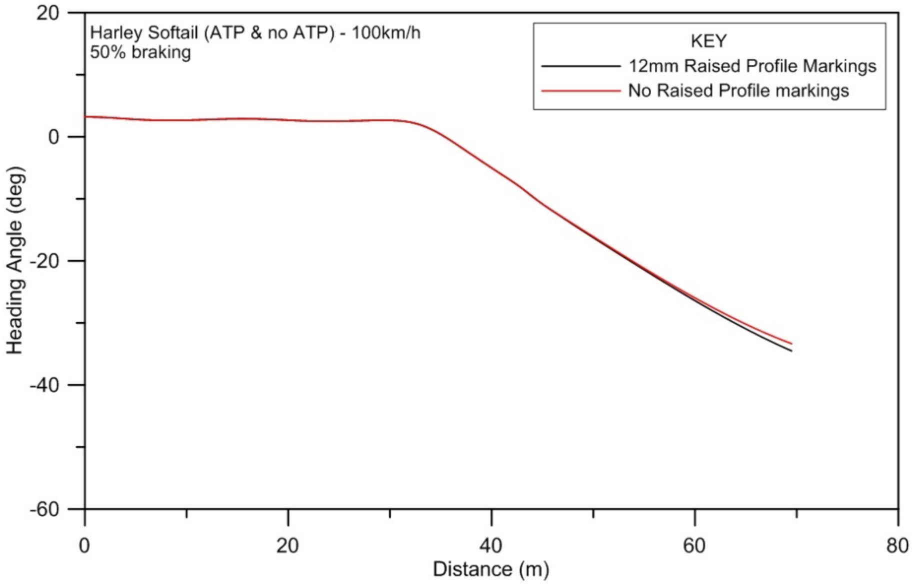


Figure D.2 Harley Davidson Softail heading and steering angles at 100km/h with 50% braking for *no* ATP roadmarkings (in red) and for *with* ATP roadmarking ribs 12mm high at 500mm spacing (in blue)



The lines on the heading angle plot match the path specified in the modelling, indicating that the motorcycle can physically achieve the cornering in each model-run.

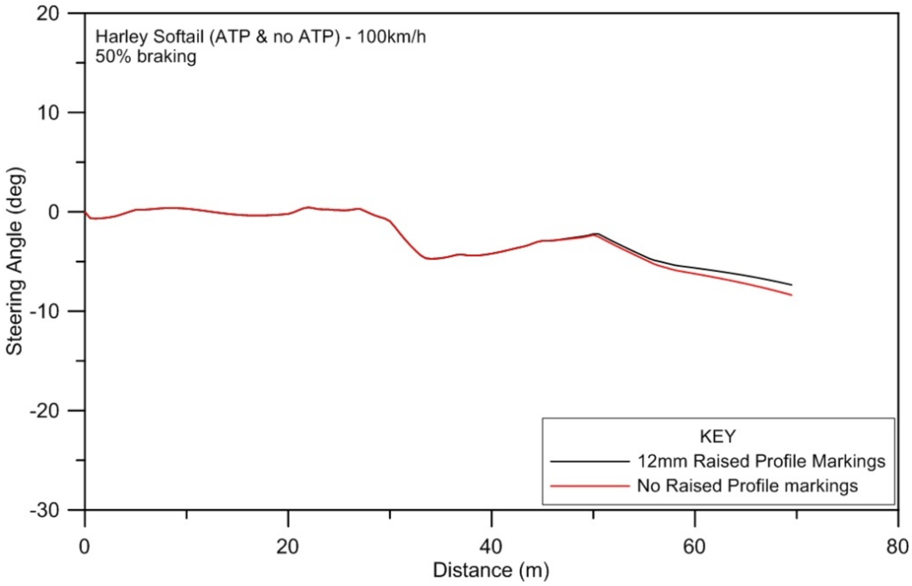
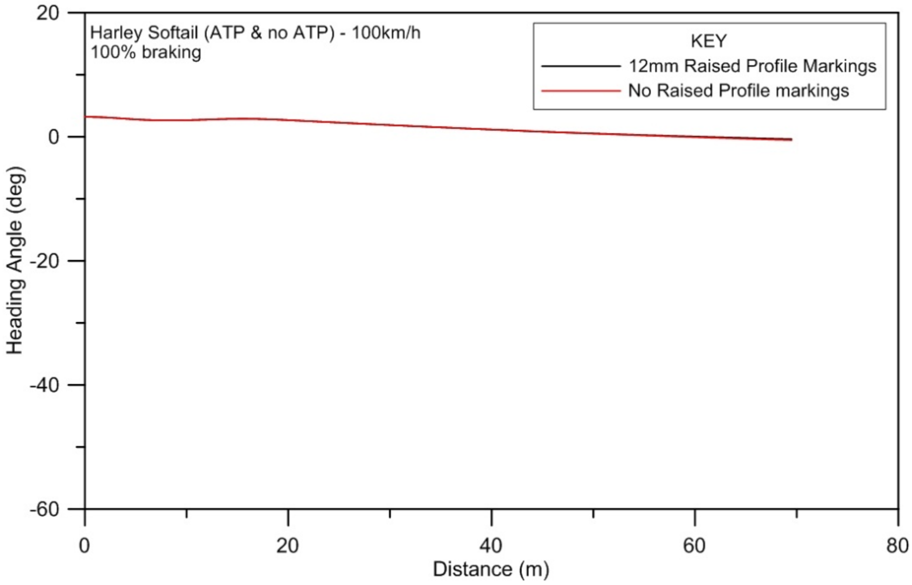


Figure D.3 Harley Davidson Softail heading and steering angles at 100km/h with 100% braking for *no* ATP roadmarkings (in red) and for *with* ATP roadmarking ribs 12mm high at 500mm spacing (in blue)



The lines on the heading angle plot do not match the path specified in the modelling, indicating that the motorcycle cannot physically achieve the cornering; however, the significant observation is the extent of similarity in the results from each of the two model-runs.

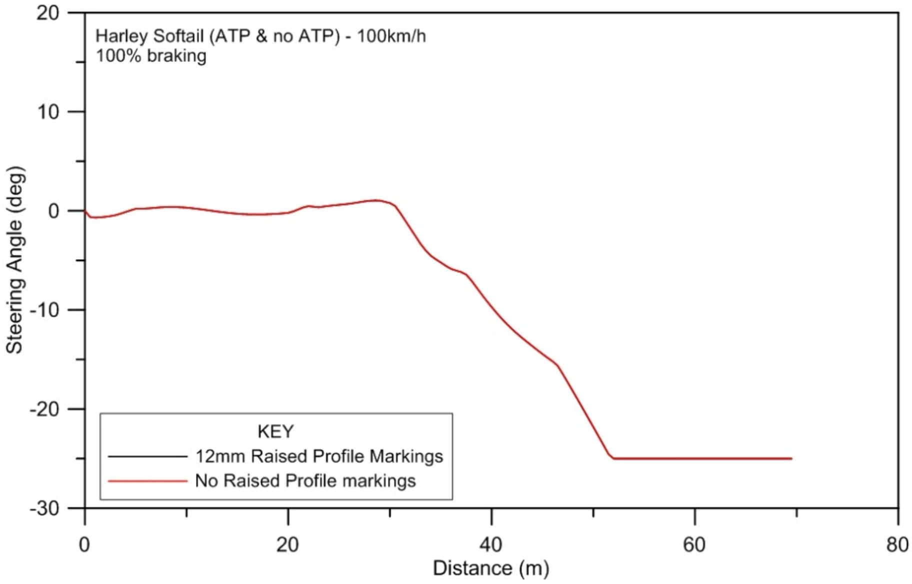
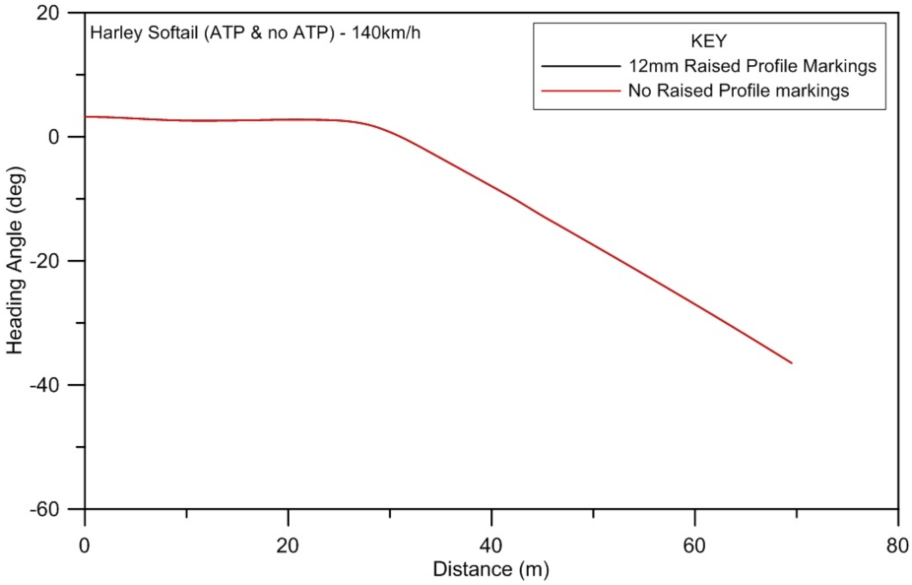


Figure D.4 Harley Davidson Softail heading and steering angles at 140km/h (no braking) for *no* ATP roadmarkings (in red) and for *with* ATP roadmarking ribs 12mm high at 500mm spacing (in blue)



The lines on the heading angle plot match the path specified in the modelling, indicating that the motorcycle can physically achieve the cornering in each model-run.

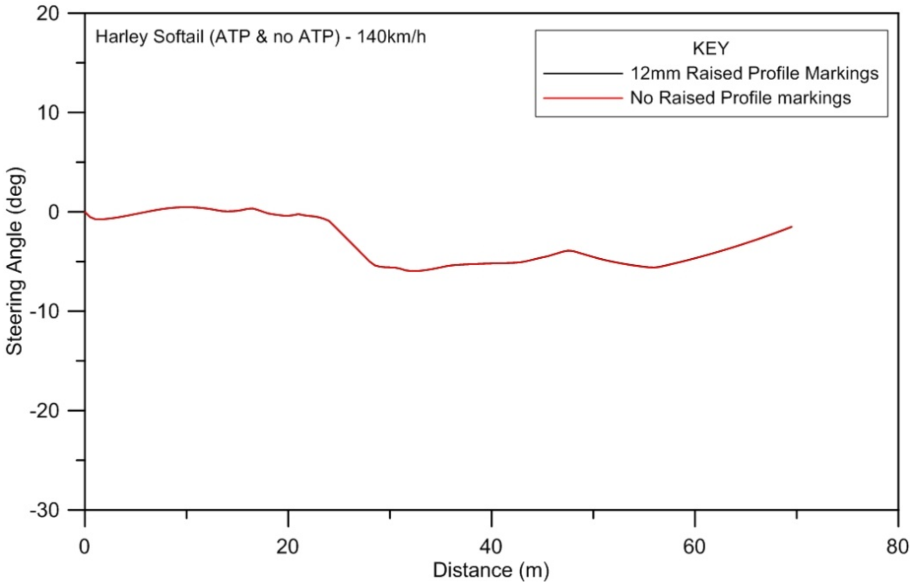
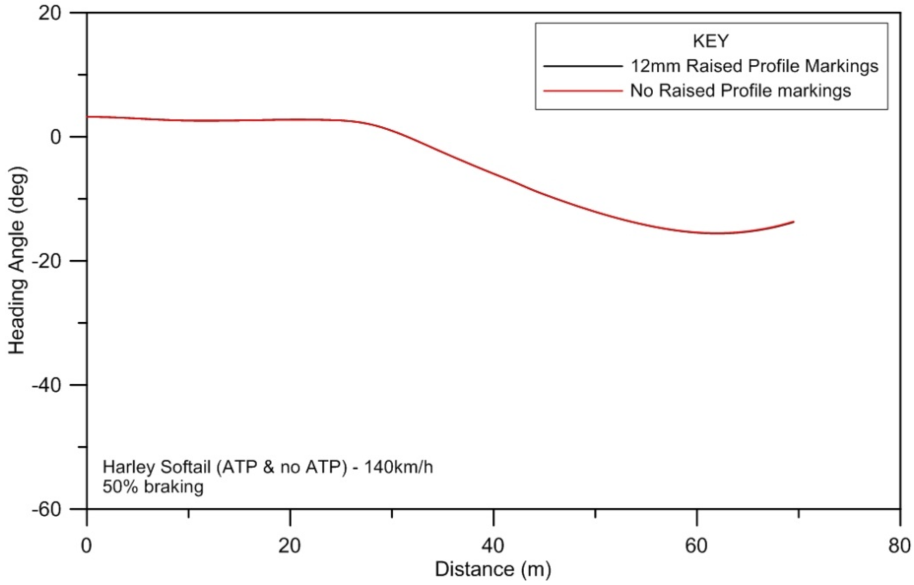


Figure D.5 Harley Davidson Softail heading and steering angles at 140km/h with 50% braking for *no* ATP roadmarkings (in red) and for *with* ATP roadmarking ribs 12mm high at 500mm spacing (in blue)



The lines on the heading angle plot do not match the path specified in the modelling, indicating that the motorcycle cannot physically achieve the cornering; however, the significant observation is the extent of similarity in the results from each of the two model-runs.

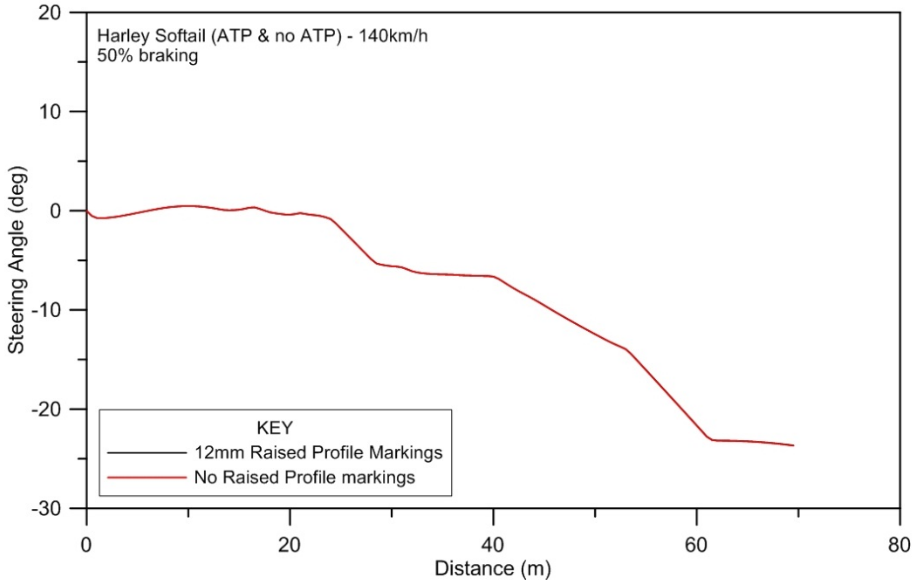
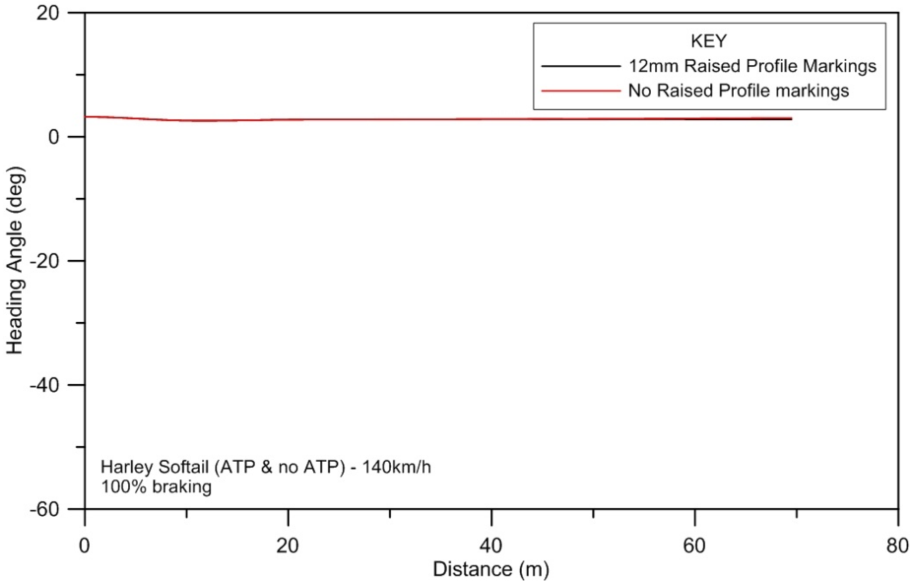


Figure D.6 Harley Davidson Softail heading and steering angles at 140km/h with 100% braking for *no* ATP roadmarkings (in red) and for *with* ATP roadmarking ribs 12mm high at 500mm spacing (in blue)



The lines on the heading angle plot do not match the path specified in the modelling, indicating that the motorcycle cannot physically achieve the cornering; however, the significant observation is the extent of similarity in the results from each of the two model-runs.