

# Braking Deceleration of Motorcycle Riders

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## Abstract

In a long-term study braking deceleration was measured with an instrumented motorcycle on a training facility. Straight-path braking maneuvers under dry road conditions starting from approximately 60 km/h (37 mph) to a full stop were conducted. Test persons were volunteers of all kinds of age and riding experience. It was found that half of the tested individuals did exploit only 56% or less of the possible maximum deceleration. By using data from an earlier study it could be confirmed that the use of an unfamiliar motorcycle cannot be blamed for this result. Therefore the study is a clear indication for a lack of braking skills among Austrian motorcyclists. Improvements on motorcycle braking systems and educational work within the motorcycle riders community are suggested as counter-measures.

## 1 Introduction

One of the most difficult tasks for a motorcycle rider certainly is braking. A proficient and safe braking maneuver is a benchmark for the driving skills of every motorcyclist. Especially in a dangerous traffic situation a well performed emergency braking maneuver frequently is the only option to avoid an accident. Tires and braking equipment of today's motorcycles permit an impressive deceleration, provided that the skills of the rider are at the same high level.

A simple analysis of the dynamics of a vehicle during braking conditions shows that every vehicle is subject to a load transfer from the rear to the front axle. Since the possible maximum braking force on a wheel increases with increasing vertical wheel force and vice versa, the level of brake effort has to be adjusted accordingly during a braking maneuver with significant deceleration. For cars this effect is less severe due to the long wheelbase in relation to the height of the center of gravity. However, the elevation of the center of gravity of a motorcycle with a rider on top is almost half of the length of its wheelbase. Therefore the optimum brake force distribution between front wheel and rear wheel varies considerably with deceleration, with tire-road friction coefficient and with weight (load).

Whereas all cars are operated with just one brake pedal and as anti-lock braking systems (ABS) are becoming increasingly popular, the situation concerning motorcycles is totally different. It is known since long that the optimal control of two independent braking systems is difficult for a majority of motorcyclists, see e.g. (Donne, Watson, 1985), (Mortimer, 1986 and 1988) and (Prem, 1987). Nevertheless little has improved for most riders during the last fifteen years to facilitate break application and give them more support in an

emergency braking maneuver. At present only an insignificant minority of motorcycles in use is equipped with anti-lock systems and/or integral brake systems. The German manufacturer BMW is the only one worldwide to offer all regular models (at least optionally) with anti-lock systems. BMW has recently achieved a significant progress by introducing a combined ABS and integral braking system in series production (Braunsperger, et al., 2000).

Therefore good braking skills are still in demand for motorcyclists. These skills have to be taught in rider schools when earning a license and must be trained and improved subsequently by each motorcyclist. To get some up-to-date insight into the braking skills of motorcyclists, a long-term field study was initiated in 1992 and carried out over the following years. This contribution reports some of the results with respect to braking deceleration achieved in the tests. More details can be found in (Grill, 1994), (Hauer, 1995) and (Ruspekhofer, 1996). Other results from this field study were presented in (Ecker, et al., 2000) and (Ecker, et al., 2001).

## 2 Research Method

The main goal of this study was to evaluate Austrian motorcyclists with respect to their braking behavior. Over a period of several years altogether more than 300 individuals were tested and approximately 600 single braking maneuvers were recorded and analyzed. Most of the volunteer test riders were participants of motorcycle safety courses organized by the Austrian Automobile Association OeAMTC. Our braking tests were conducted on one of the training facilities of the OeAMTC.



Figure 1: Instrumented motorcycle Honda CB500 as used in the experiments.  
2.1 Measurement equipment

To measure the braking deceleration a special on-board equipment for the motorcycle is necessary and therefore an instrumented Honda CB500 was used, see Figure 1. This rather conventionally designed and medium sized motorcycle is easy to handle and allows fast adaptation of riders not used to this model. The motorcycle was equipped with a Digital Accident Data Recorder (UDS) (Kienzle, 2000) as available in commerce. However, since these “black boxes“ are designed for use in passenger cars, some effort was necessary to make it work on a motorcycle. It was mounted in a side case on the right hand side of the motorcycle, see Fig.2.

The relevant signals that have been recorded by the data recorder were the longitudinal acceleration, the vehicle speed and the traveled distance. Additionally, the logical state (on/off) of the signal light to trigger the braking maneuver and the front and the rear brake light switch were recorded. The sampling rate for the acceleration signal was 500 Hz. Due to the pitch motion of the motorcycle during braking the originally horizontal direction of measurement of the accelerometer is slightly tilted. Thereby a minor contribution of gravity force falsifies the signal. An estimate of this measurement error was made (Ruspekhofer, 1996), and results presented here were corrected for this error.

A red signal light was mounted on the instrument panel of the motorcycle, see a figure in (Ecker, et al., 2001). The light could be activated at any time by the test coordinator via remote control. So the trigger signal for starting the braking maneuver was rather unexpected for the riders.



Figure 2: Accident-data recorder UDS (“black box“) installed in the data acquisition box, mounted on the right-hand-side of the motorcycle.

## 2.2 Test procedure

Every test started with a familiarization procedure of the test person with the instrumented motorcycle. Each individual was allowed to make a couple of braking trials on his or her own, in order to get as much used to the motorcycle as possible within the given time frame. Then the test persons were assigned to drive at a speed of about 60 km/h (37 mph) on a long straight part of the test and training facility of which a section is shown in Fig. 3. As soon as the bright red flare of the signal light went on they had to make a full stop emergency braking maneuver. The test persons were aware of the imminent signal to start the maneuver. However, the test coordinator could vary the instant of triggering the maneuver via remote control within several seconds so that there was some uncertainty involved for the test persons. The assignment for the test person was “to bring the motorcycle to a stop in as short a distance and time as possible.” Each rider was asked to perform two braking maneuvers. All braking maneuvers were conducted on a flat and straight road section on the test facility, see Figure 3. The road surface was asphalt and the condition was dry during all tests for braking deceleration.

## 2.3 Personal data

Personal data were ascertained for every individual with a questionnaire. Beside the questions about general data like age, weight, sex and drivers license ownership also specific data related to the personal use of motorcycles were collected. Some of these data were motorcycle riding experience expressed in years and kilometers, self-characterization with respect to riding behavior and information on training courses and racing experience. All data were entered into a database, together with the deceleration values achieved in the tests.



Figure 3: View of test facility and road section used in the braking tests.

## 2.4 Characteristic parameters of a braking test

For each braking test a time series of the deceleration (negative acceleration) was recorded. A simple and meaningful characterization of a braking maneuver is obtained by averaging the deceleration with respect to time. Averaging starts at  $t_a$  when the first brake light switch is triggered, and ends at  $t_e$  when the motorcycle has stopped and the maneuver is completed. With a sampling interval  $\Delta t$  the average deceleration with respect to time  $a_{t\text{-mean}}$  can be calculated from a discrete time series  $a(t_i)$  as

$$a_{t\text{-mean}} = \frac{1}{(t_e - t_a)} \sum_{t_a}^{t_e} a(t_i) \Delta t . \quad (1)$$

However, this is not the only way to calculate an average deceleration value. Another method is to represent deceleration as a function of braking travel  $a(s_i)$  and compute the distance-averaged deceleration for the braking distance  $(s_e - s_a)$  similar to Eq. (1)

$$a_{s\text{-mean}} = \frac{1}{(s_e - s_a)} \sum_{s_a}^{s_e} a(s_i) \Delta s . \quad (2)$$

Sampling and recording of the deceleration signal only occurred for constant time intervals  $\Delta t$ . The need for a constant travel interval  $\Delta s$  in Eq. (2) is somewhat inconvenient, and another formula which uses the initial velocity  $v_a$  at  $t_a$  (beginning of the maneuver) can be used alternatively

$$a_{s\text{-mean}} = \frac{v_a^2}{2(s_e - s_a)} . \quad (3)$$

Equation (3) shows that  $a_{s\text{-mean}}$  is directly related to the overall braking travel  $s_b = (s_e - s_a)$  and therefore the distance-averaged deceleration is more meaningful compared to the average with respect to time. In the special case of  $a(t_i) = \text{const.}$  both average values are the same, but in general this is not true.

Figure 4 shows three idealized and different deceleration time series with identical time-averaged deceleration. For simplicity reasons rise and fall at the beginning and at the end of the deceleration period are neglected. Measurements that resemble case (a) with increasing deceleration were frequently encountered, case (b) is an ideal assumption and case (c) is a rare case, but nevertheless also occurred occasionally during the tests. Now let us calculate the deceleration ratio  $r_a$

$$r_a = \frac{a_{s\text{-mean}}}{a_{t\text{-mean}}} . \quad (4)$$

It can be shown (Hauer, 1995) for case (a) with increasing deceleration that  $r_a > 1$  holds. Consequently, for case (c)  $r_a < 1$  is valid. For the separating case (b) with constant deceleration  $r_a$  equals 1. Therefore the deceleration ratio  $r_a$  can be used as a typical parameter to characterize the shape of a deceleration time series. For a regular braking maneuver a value close to 1 indicates an almost constant deceleration during the maneuver.

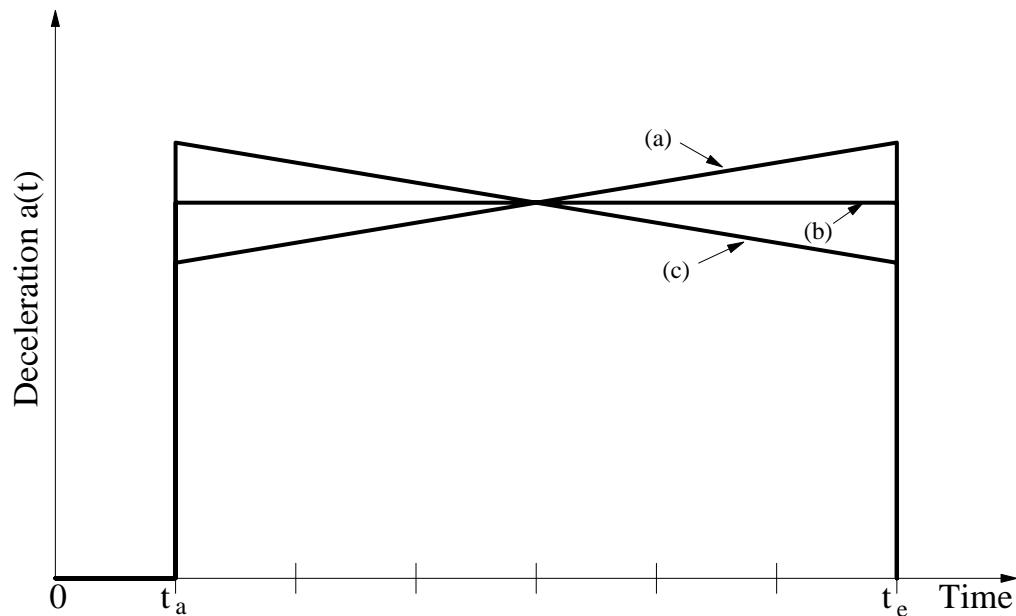


Figure 4: Different idealized time series of deceleration.

We will use the expression “average braking deceleration“ in the following chapter for the mean of the computed average value of the total deceleration of the motorcycle during a braking maneuver. However, the measured deceleration signal not only originates from the braking forces generated at the wheels. Also aerodynamic drag and rolling resistance have an effect on the results. With the equipment used in this study it was not possible to measure and separate external contributions to the total deceleration. In (Fischer, 1997) an equipment was used to directly measure the braking force. Thereby it was possible to quantify the amount of deceleration due to additional resistance.

### 3 Results

Normally each tested person was asked to perform two braking maneuvers. Occasionally only one test was possible, but sometimes even more than two tests could be run. In order to equally weight the contribution of each individual, an average value was calculated for results of multiple experiments of a single person. Finally, results obtained by 276 riders were included in the analysis.

#### 3.1 Average braking deceleration

Figure 5 shows a histogram for the distance-averaged deceleration, obtained from more than 500 single braking experiments. The statistical parameters for this set of  $n = 276$  samples are  $a_{s\text{-mean}} = 6,19 \text{ m/s}^2$  and a standard deviation of  $s_{s\text{-mean}} = 1,20 \text{ m/s}^2$ . The confidence interval for the mean is  $\pm 0,142 \text{ m/s}^2$ .

To see whether these results are within the expected range we compared them with results from (Mortimer, 1986), who used a different but at least comparable test setup. For 27 experienced motorcyclists using their own motorcycles he obtained a mean deceleration of  $8,2 \text{ m/s}^2$ . Apparently this mean value is significantly higher than what was found in the present study. From findings discussed in Section 3.4 it can be concluded

that the use of one's own motorcycle cannot be considered as a significant reason for the higher mean deceleration obtained by Mortimer. On the other hand, for a subset of experienced riders of our study the mean value also did not exceed  $6,8 \text{ m/s}^2$ . There might be another not obvious factor or a combination of factors that explain the difference of the two means. The different test methods also could be a reason, but the indisputable fact remains that this mean of  $6,19 \text{ m/s}^2$  is surprisingly low. Moreover, the confidence interval is quite narrow, which can be put down to the large sample size.

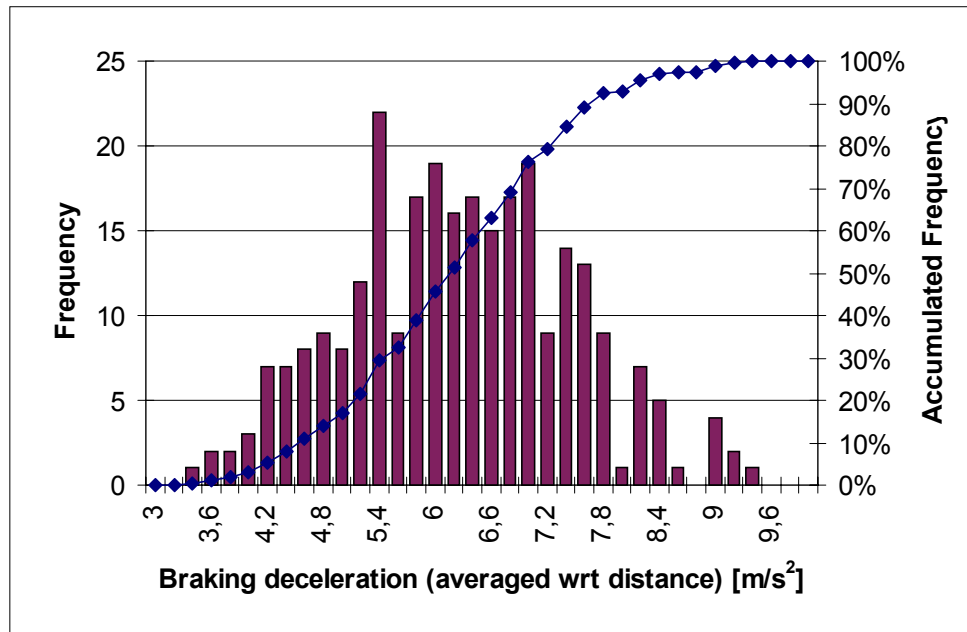


Figure 5: Frequency distribution of average braking deceleration  $a_s$  for  $n=274$  individuals.

To call this a low mean value is also based on the theoretically achievable maximum deceleration for the Honda CB 500 used in the tests. In (Fischer, 1997) a maximum value of about  $11 \text{ m/s}^2$  was derived from measurements of braking forces on both wheels. In fact, in braking tests with very experienced riders average deceleration values of more than  $10 \text{ m/s}^2$  were measured. This demonstrates that the theoretical maximum deceleration is realistic and could be reached by a perfect braking maneuver.

In contrast to the results obtained by professionals, the braking performance of a large part of the test persons was not at all impressive. An exploitation level of the maximum deceleration can be calculated for the mean value by referring to the maximum value:  $6,19 / 11,0 = 0,56$ . This means that approximately half of the tested individuals did exploit only 56% or less of the possible braking performance of the motorcycle. Of course the test persons were instructed not to go for a high risk level, but nevertheless wheel locking occurred quite often and this proves that they were ambitious and tried to achieve good results in the tests. Therefore a lack of braking skills among Austrian motorcyclists is suspected. Possible causes and consequences will be discussed in the next chapter.

To demonstrate the difference between distance-averaged and time-averaged deceleration, Fig. 6 shows the corresponding histogram for the time average. The statistical parameters for this data set are mean  $a_{t\text{-mean}} = 6,38 \text{ m/s}^2$ , standard deviation  $s_{t\text{-mean}} = 1,20 \text{ m/s}^2$  and a confidence interval of  $\pm 0,142 \text{ m/s}^2$ . As one can see, the difference in the results for the mean of the two averaging methods is about 3% and therefore not significant. However, the difference can be larger for a single braking maneuver and can give a crude characterization of the riders behavior. This is also discussed in the following section.

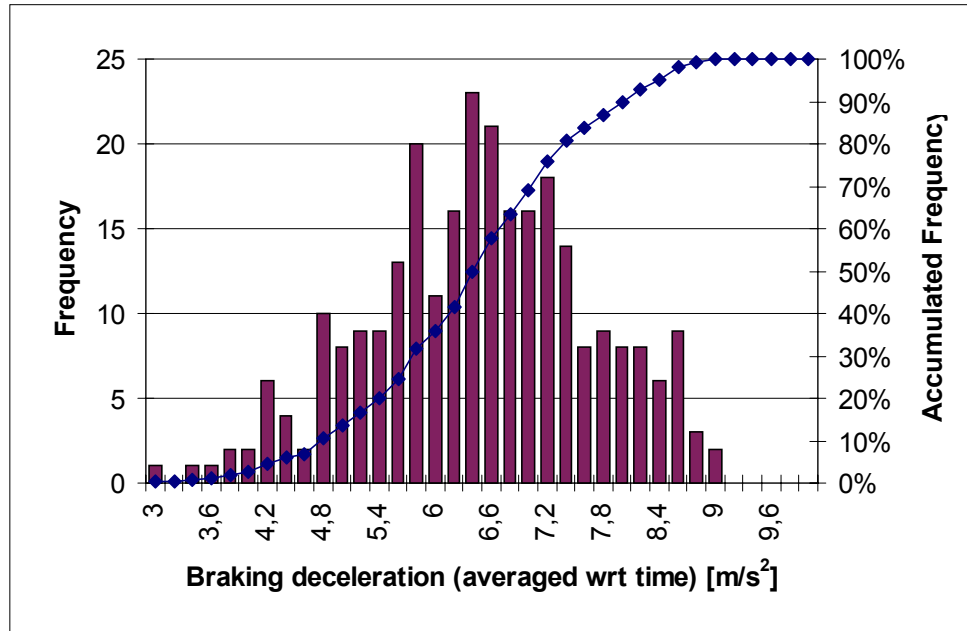


Figure 6: Frequency distribution of average braking deceleration  $a_t$  for  $n=274$  individuals.

### 3.2 Deceleration ratio

As outlined in the previous chapter the deceleration ratio  $r_a$  can be used to characterize a braking maneuver. For the investigated set of data the mean value of the deceleration ratio is  $r_{a\text{-mean}} = 0,977$ , with a standard deviation of  $s_{a\text{-mean}} = 0,125$ . The mean value is quite close to the ideal value of 1, which would indicate a constant deceleration during the entire braking maneuver. However, the standard deviation also has to be observed and reveals that there is a significant variation in the data. Figure 7 shows a scatter plot of the deceleration ratio versus the braking deceleration averaged with respect to distance. Although data points are quite dense just below  $r_a = 1,0$ , data range from minimum values of 0,7 to maximum values as high as 1,5. Even for braking maneuvers with a definitely better than average mean deceleration  $a_{s\text{-mean}} > 7 \text{ m/s}^2$  the bandwidth of ratio values is still significant.

Almost 15% of the individuals did exceed a ratio of 1,1. This indicates that a significant decrease in braking deceleration did occur during the maneuver. A common reason for such a behavior was identified by analyzing the time series and turned out to be wheel locking. A number of riders did apply the brakes too hard in the early stage of the maneuver and soon locked either the rear or (occasionally) the front wheel. Instead of just releasing the brake at the locked wheel, drivers frequently overreacted and unnecessarily opened both brakes simultaneously. Thereby they wasted considerable time and travel to reestablish a high braking deceleration.

For another 10% of the test riders the deceleration ratio was at or below 0,85. Such a low value indicates that the deceleration was increased gradually during the maneuver, reaching maximum values only shortly before stoppage. This was typical for very cautious riders who increased braking force slowly and were obviously not sure about how much braking force they should apply without risking too much.



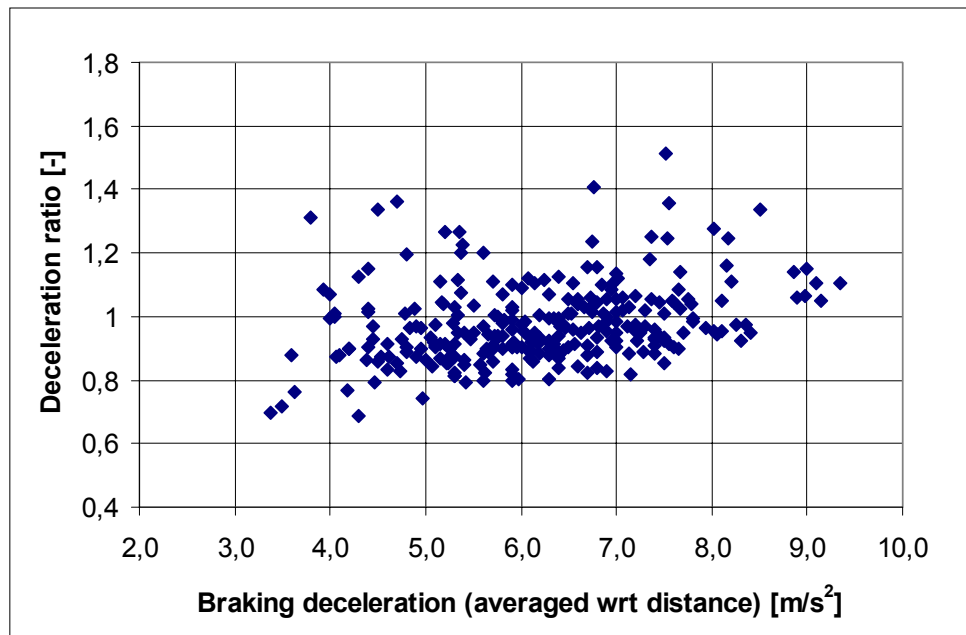


Figure 7: Scatter plot of deceleration ratio vs. average braking deceleration  $a_s$  for  $n=274$  individuals.

### 3.3 Deceleration and riding experience

Every individual was asked to report his or her motorcycle riding experience in the questionnaire. Since “riding experience” can be expressed and defined in different ways, three measures were used in the data analysis: (a) years of motorcycle use, (b) average miles each year and (c) total of miles on motorcycles. For each measure the correlation coefficient with respect to the braking deceleration was calculated. The most significant correlation coefficient of about 12% with a confidence interval of  $\pm 11\%$  was obtained for (a) years of motorcycle use. Measures (b) and (c) did not show any significant correlation.

Figure 8 shows a scatter plot of “riding experience expressed in years of motorcycle use” versus braking deceleration. Note the logarithmic scale on the axis for riding experience. This diagram shows that this sample of test persons covered a wide range of riding experience, starting with novice riders up to seniors with more than 40 years of experience. Nevertheless, a correlation between experience and deceleration is hardly recognizable, especially for more than 1 year of riding experience. Also the data turned out to be rather inconsistent. For different subsets of the data set a rather large variation of the correlation coefficient (within the confidence interval) was obtained.

However, for a group of 53 riders with one year or less of riding experience, a definitely significant correlation with deceleration of about 52% was obtained. The mean value of the braking deceleration for this subset was  $a_{s\text{-mean}} = 5,77 \text{ m/s}^2$  which is  $0,42 \text{ m/s}^2$  below the mean value of  $a_{s\text{-mean}} = 6,19 \text{ m/s}^2$  for the full data set. This results shows that within the first year of motorcycle riding experience a major improvement in braking performance takes place. In general a further increase of riding experience cannot be expected to contribute significantly to the braking performance. Of course this statement does not include experience gained in motorcycle training courses. This topic will be addressed in a following section.

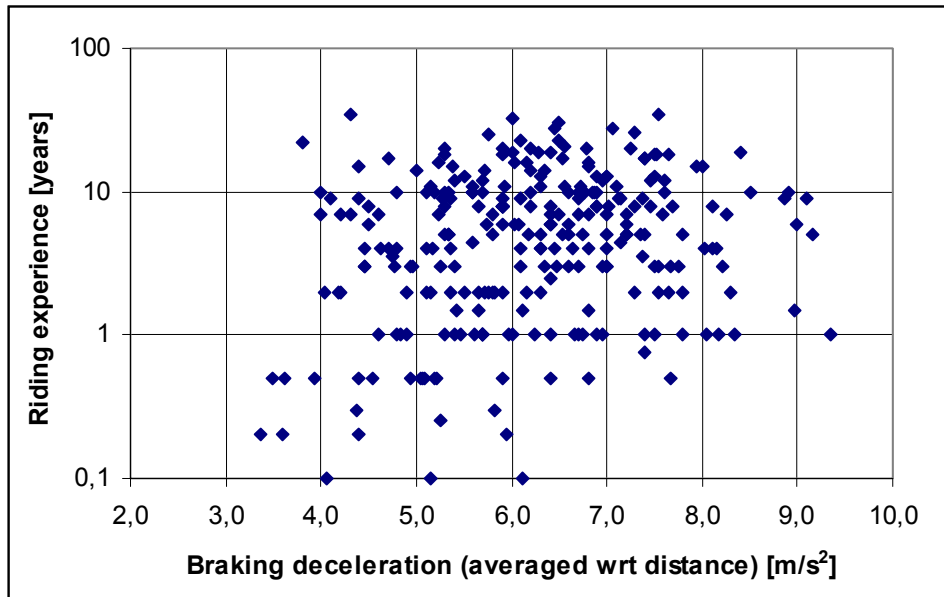


Figure 8: Scatter plot of riding experience vs. average braking deceleration  $a_s$  for  $n=274$  individuals.

### 3.4 Comparison with results obtained with own motorcycle

To investigate a possible effect of the use of an unfamiliar motorcycle on the braking performance of the test persons, a comparison can be made with an earlier study by the authors. In (Grill, 1994) more than 1400 braking maneuvers of almost 200 individuals with their own motorcycle were analyzed. The experimental setup in this study was a different one. Traffic cones marked the beginning of a braking lane. Initial speed was measured after brake reaction and response time had passed. Braking distance was measured beginning at the location of the speed measurement. From distance and initial speed the distance-averaged deceleration was calculated. Since the distance traveled during brake response and braking force rise time was excluded from the total braking distance, somewhat higher mean deceleration values can be expected, compared to the results of the present study.

Since the volunteers for the braking tests were participants of motorcycle safety courses, there was the unique opportunity to conduct tests before and after the training program. Therefore it was possible to distinguish between “untrained” and “trained” braking maneuvers. The average deceleration of 196 untrained maneuvers was  $a_{s\text{-mean}} = 5,7 \text{ m/s}^2$ . This value is lower than the average value obtained in this study and even lower than the mean value for riders with one or less than one year of experience. After instructions and training the volunteers had to perform a final braking maneuver. The average deceleration of 644 trained maneuvers was  $a_{s\text{-mean}} = 6,5 \text{ m/s}^2$ , which is 15% better than before training but only 5% better than the mean value of this study. Since the braking performance of riders using their own motorcycle is only better, compared to this study, after a training program, it can be concluded that an unfamiliar motorcycle, as used in this investigation, has almost no detectable effect on the measurement of the braking performance.

To demonstrate the gain in shortening the braking travel by a higher braking deceleration, Figure 9 compares the braking travel for results obtained in this study and the findings from the study with own motorcycles. Braking travel was calculated just for comparison by a simple formula equivalent to Eq. (3), which is based on the mean deceleration and the initial speed. Two different initial speeds (60 km/h and 100 km/h) were used to show also the effect of speed on the braking travel. To make a reference to what can

be achieved by using recent ABS technology, measurement results obtained with a BMW K1200 LT (Braunsperger, et al., 2000) and a mid-size passenger car (Oldsmobile Alero) were also included in Figure 9.

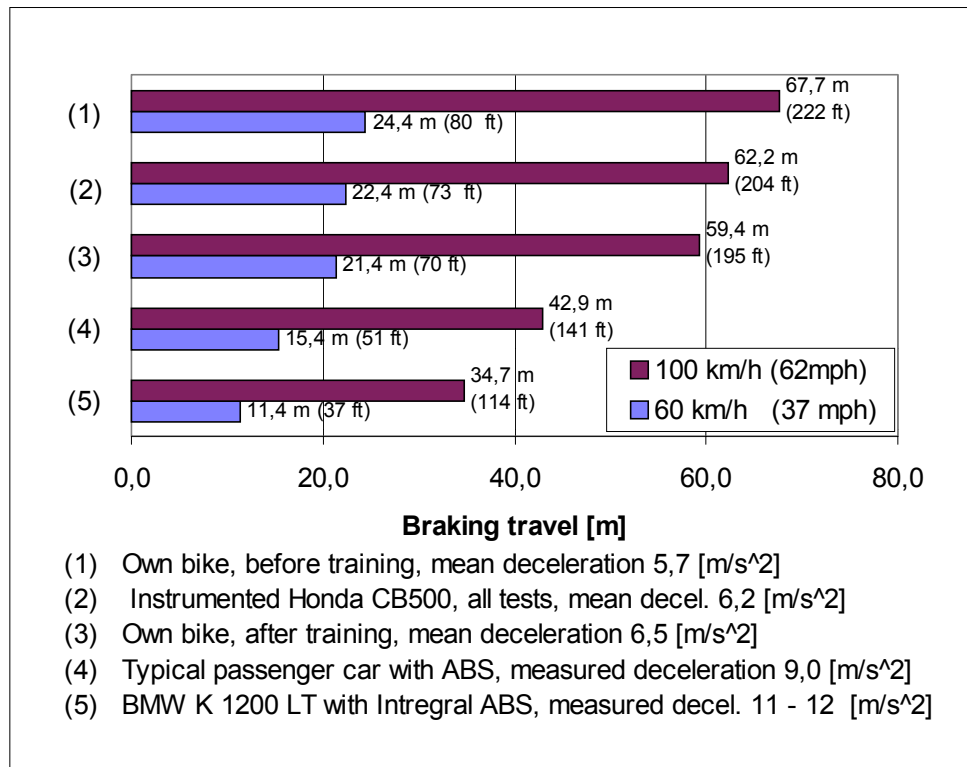


Figure 9: Comparison of braking travel calculated from path-averaged mean deceleration obtained in this study with results from (Grill, 1994) and (Braunsperger, et al., 2000) for different initial speeds.

### 3.5 Braking deceleration and wheel locking

The major concern of the volunteers in the tests was to overbrake and to lock the front wheel. Riders have been aware of the potential loss of dynamic stability in such a situation and the imminent danger of a fall. In fact the only two accidents that happened during the test program were caused by front wheel locking. Therefore it is worth to analyze riders behavior with respect to wheel locking.

Front wheel locking could be identified by analyzing the rotational speed signal at the front wheel. In case of front wheel locking a false speed signal of zero was recorded. For about 10% of the test persons short-term front wheel locking did occur. This result is in good agreement with results in (Fischer,1997), where 9% was reported. It is very interesting to note that the riding experience of those riders who overbraked the front wheel was higher than average. Also the distance-averaged deceleration of those riders was about 14% higher than average, despite of front wheel locking. Therefore it can be concluded that this group of test persons consisted mostly of riders with good braking skills that tried to exploit the bounds of maximum braking force at the front wheel. Accepting a higher risk level increased the probability of front wheel locking. Although the mean deceleration of those maneuvers with locked front wheel is higher than average, it would have been even better (and also safer) if wheel locking would not have occurred.

During this study the equipment implemented on the motorcycle did not allow to identify rear wheel locking. However, from simple visual observations, but also from measurements with improved equipment (Fischer,1997) we know that probably almost 60% of the riders did overbrake the rear wheel! In a straight-

path braking maneuver and under dry road conditions wheel locking at the rear wheel is easy to handle. However, in an actual traffic situation with other than ideal conditions rear wheel locking may also be hazardous. This result clearly demonstrates that for most riders it was very difficult to control effectively two independent wheel brakes.

## 4 Conclusions

Probably the most important result of this long-term study is the fact that the average deceleration obtained from numerous braking tests is only about 56% of the maximum deceleration achievable with the motorcycle used in the experiments. Moreover, about 2/3 of the riders applied at least one of the brakes too hard and provoked wheel locking. Especially a locked front wheel is quite hazardous and can lead to an immediate fall of the rider. These findings undoubtedly indicate that there was a deficiency of braking skills among the motorcycle riders tested in the study. The large number of experiments and of tested individuals certainly suggests that this result is also true for the majority of Austrian motorcyclists.

One conclusion from these results is the need for improvements concerning the handling of the braking system(s) of a motorcycle. We have to note that most riders are not able to make full use of the capabilities of the braking system. The simple reason for this shortcoming is that the handling of the two independent brakes is too demanding, especially for riders who use their vehicle only occasionally. Solutions for this problem have been developed already: Integral braking systems and anti-lock systems (ABS). However, customers demand for such systems was rather slow in the past, and also the motorcycle industry hesitated to push and promote (expensive) safety features. This vicious circle has to be broken for several reasons. To name just one of them, the braking performance of motorcycle riders is more and more falling behind that of car drivers, which is a potential hazard for motorcyclists in dense traffic. Therefore major efforts should be made to develop and improve combined braking systems with anti-lock devices. It will be very important to find economical solutions so that all kinds of motorcycles can be improved, not only expensive high-end models.

Also more educational work is necessary to convince motorcycle riders of the importance of good braking skills. They need to realize that braking is a complex combined perceptual-motor task which must be trained particularly. Once a motorcyclist has learned how to perform a good braking maneuver, he has to practice these skills every once in while in order to stay proficient. If one succeeds to create problem awareness among motorcycle riders there will be motivation for additional instruction and training as well as increasing demand for improvements on motorcycle braking systems.

## Acknowledgment

Part of this study was funded by the Austrian Road Safety Board (KuSS). The Austrian Automobile Association (OeAMTC) generously offered the possibility to use its drivers test and training facilities. Honda of Austria provided the motorcycle used in the experiments. The authors would like to thank all organizations for their valuable support.

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