Braking Performance of Motorcyclists

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Abstract
The paper presents measurements of the braking skill for 18 motorcyclists. The test persons were set with the task to decelerate their (own) motorcycle out of a given initial speed to standstill within the shortest possible distance. The recording of the deceleration is described by a functional pattern derived from control science. Applicability of the experimental results to real world accidents is discussed.

1 Introduction
The braking behavior of a passenger car may be deduced from skid marks in a narrow range. When choosing the friction coefficient as well as the deceleration build-up time, the reconstructionist may found on a number of publications. There is not much room left for discussion on that theme in the courtroom (well, at least in Germany). The behavioral pattern of all passenger car drivers is more or less the same: The brake pedal is pushed with exaggerated force, at least until the front wheels lock up. The deceleration build-up is mostly determined by mechanical processes, like the rise of the pressure in the braking system.

For the motorcyclist, emergency braking is a more difficult task. When assigned with the task to reduce speed in the shortest possible distance, he may not rely on the self-stability of his vehicle, as it is based on the gyration of its wheels. The motorcyclist is forced to control his behavior as lock-up of the front wheels will result in immediate tilt.

The rise of the deceleration and its maximum value is not that much determined by mechanical processes but by the braking skill of the driver. Thus the individuality of the driver has a strong impact on the braking performance. This gives reason to the heading of this paper: We should not speak of motorcycle deceleration but of motorcyclists deceleration ability.

Every reconstructionist knows of motorcycle accidents where time distance considerations gave evidence that the defense time of the motorcyclist was considerably long, but the skid marks left by the motorcycle were rather short. For a motorcycle, the breaking distance and length of skid marks is simply not that rigidly coupled as for a non-ABS passenger car.

A longer skid mark always stems from the motorcycle rear wheel, but it would be remote from reality assuming that the motorcyclist exclusively made use of the rear brake. Front brake usage is sometimes proven by a double skid mark left shortly prior to collision, when the motorcyclist at last skipped all mental reservations against font wheel lock-up.

The present paper should help to describe the braking pattern of motorcyclists in a narrower range than possible so far.

2 Conception of the Experiments
In two earlier papers [1, 2] we developed a mathematical description of the motorcyclist’s braking behavior which was based on forty braking experiments. Founding on this findings, we conducted new braking experiments with improved measuring equipment [3].

With a group of 18 drivers using 15 different motorcycles we conducted 74 braking experiments. As these numbers imply, each driver could use his own motorcycle with the exception of three persons. This was the only way to make sure that the driver was fully adapted to the
braking behavior of the motorcycle. The group used for the experiments represents the complete spectrum of possible driving experience (less than 20,000 km up to 130,000 km in total). The experiments were conducted roughly in the mid of the driving season at dry weather on asphalt road surface. The drivers were assigned with the task to brake from an initial speed of some 50 km/h to standstill within the shortest possible distance.

Intentionally, we did not equip the motorcycles with outriggers or support wheels to prevent tilt when breaking. These would suspend the motorcyclist’s mental reservation against front wheel lock-up and thus lead to unrealistic braking behavior.

3 Measuring Equipment
The demand that every motorcyclist should use his own machine called for a mobile measuring equipment, fig. 1. In the driving experiments, the data recorder was located in a back package that the drivers had to carry. The sensors consisted of two accelerometers, a thread potentiometer that measured the dip motion of the fork and a reflex taster that recorded the rotation of the rear wheel. Data recording was triggered automatically by driving through a speed trap. After that point, the drivers could make a free choice on the start point of the braking maneuver.

The fixation points of the accelerometers were changed several times at the beginning. At last, the first was mounted on the fork and the other on the rear wheel pinion right next to its pivot. The accelerometer mounted on the fork was used as a trigger that indicated the start of the braking maneuver, as its measurement was very sensitive to the brake torque applied to the front wheel. The second accelerometer measured the deceleration of the center of mass. Due to the special fixation point, its signal was not much influenced by brake pitch.

Measuring the dip motion of the fork was intended to allow compensation of any gravitational acceleration coupling into the measurements, which later turned out to be obsolete. The reflex taster recording the rotation of the rear wheel allowed to draw conclusions on the driver’s control strategy regarding the rear wheel.

4 Evaluation Technique
The low pass characteristic of the mechanical accelerometer used in the previous experiments [1] resulted in a relatively smooth function plot for the acceleration. The higher resolution of the electronic accelerometer tends to cause confusion at first glance, fig. 2.

When structuring the experimental results, the exponential description derived in [2] proved to be very useful. The recorded acceleration may thus be approximated by

$$a(t) = a_0 \left(1 - e^{-t/T}\right).$$  \hspace{1cm} (1)

The static factor $a_0$ is equivalent to the maximum value of deceleration. The time constant $T$ describes the rising behavior of the deceleration. A large time constant $T$ results in a slow rise of the acceleration, small values result in steep rising behavior.

For each acceleration recording the functional parameters $a_0$ and $T$ of the function pattern eq. 1 were adjusted such that maximum coincidence with the recorded signal was achieved. The term ‘maximum coincidence’ was represented by the minimum of the functional
\[ G(a_0, T) = \left| \int_{0}^{t_e} [a_{\text{meas}}(t) - a(t)] dt \right| \]
\[ = \left| \int_{0}^{t_e} [a_{\text{meas}}(t) - a_0 \left(1 - e^{-\frac{t}{T}}\right)] dt \right| \] (2)

Eq. 2 is often referred to as the 'loss function'. Consciously, we used the simple, linear weighting including the sign of the deviation. This mathematical treatment guarantees that the difference between the actual speed and the speed calculated by the exponential function is minimized for time \( t_e \). As an alternative, we applied the 'classic' square loss functional \([4]\)

\[ G(a_0, T) = \int_{0}^{t_e} [a_{\text{meas}}(t) - a(t)]^2 dt \] (3)

which is more suitable for analytical treatment if the function is linear in respect to the parameters (which is not the case for our function). The difference between the parameter sets \( a_0, T \) estimated by the use of different functionals was only small.

5 Experimental Results

5.1 Rising Behavior and Maximum Deceleration

The shortest braking distance is achieved by a high maximum value combined with a steep rise of the deceleration. But the motorcyclist cannot fulfill both claims at the same time. The individual abilities will limit braking performance such that a rise of the maximum deceleration is always accompanied by a rise of the deceleration build-up time, fig. 3.

For each initial speed, there is one combination of parameters \( a_0 \) and \( T \) which results in the minimum braking distance. Depending on driving experience, the drivers may be assigned to four different groups. Fig. 4 depicts the maximum deceleration value \( a_0 \) depending on driving experience. Each bar group represents the mean values for the best and poorest driver in the according group. In-between, the white bar indicates the mean value for the whole group.

With growing driving experience we may state a rise in the maximum deceleration value achieved. This is accompanied by a leveling of the braking abilities between the drivers, as the span between best and poorest driver also narrows. As each group consisted of four or five drivers, the narrowing may not be assigned to just the size of the group.

To the contrary, the time constant, fig. 5, is nearly independent from driving experience. From the diagram we may draw the conclusion that the time constant first decreases with the driving ex-
experience up to a point where the driver has reached about 100,000 km in total. Afterwards, the time constant rises again in order to gain a higher constant deceleration. This seemed to be the most effective control concept when fulfilling the experimental task. Again, we may state the most scatter of parameter \( T \) in the group with little driving experience.

### 5.2 Rear Wheel Lock-up

When conducting a defensive braking action in a double-track vehicle, the first skid marks will stem from the front wheels as the front axle will lock-up first. The rise of the deceleration may be described with a linear function and the total rising time is comparatively short. German measurements indicate a value of some 0.2 s for deceleration build-up time, i.e. for the time lag between initial touch of the brake pedal and the start of the skid marks.

To the contrary, longer skid marks left by a two-wheeler stem from the rear wheel. Since there are two completely separate braking circles, we have no definite coupling between the deceleration achieved and the start of the skid marks. During the braking maneuver, the dynamic load transfer from rear to front axle is much greater for a two-wheeler than for a normal passenger car. This is due to the shorter wheelbase in combination with the elevated center of mass. As a consequence, higher values of deceleration are almost exclusively achieved by the breaking torque applied to the front wheel.

Skilled motorcyclists therefore rarely use the rear brake in normal day driving; the driver exclusively concentrates on the more powerful and more controllable hand brake. During an emergency brake, the touch of the brake pedal will cause almost immediate lock-up of the rear wheel, as there is nearly no load left on the rear wheel.

Only in extreme situations, the loss of stability caused by rear wheel lock-up will be justified by the small gain in deceleration performance. In safety training courses, tutors therefore instruct the drivers to make use of the rear brake in extreme situations, but this behavior has to be trained systematically.

**Fig. 6** depicts the time lag between the start of the braking maneuver and rear wheel lock-up. While some drivers lock up the rear wheel almost instantly, others traverse the whole distance to stop without locking up the rear wheel. There is a slight tendency that drivers who have passed a security training tend to lock up their rear wheels faster. Again, the group of the most experienced drivers shows less scatter. As can be expected from this, there is no definitive dependency between the length of the skid mark and the initial speed, as depicted by **Fig. 7**.
6 Comparison to Prior Results

For the maximum deceleration value \( a_0 \) our experiments give a (rounded) range of 6.0 – 9.0 m/s\(^2\). The time constant \( T \) falls into a range of 0.15 – 0.30 s. Earlier investigations \([1, 2]\) gave values of 6.8 – 10.0 m/s\(^2\) for the maximum deceleration and 0.32 – 0.60 s for the time constant. The discrepancy between the achieved maximum deceleration may be assigned to the more sophisticated mounting of the accelerometer in the newer experiments. In the earlier experiments, the mechanical accelerometer was mounted on the carrier. Due to braking pitch, the gravitational acceleration coupled in and could not really be compensated.

We consider the different findings for the deceleration build-up time as more severe. In a retrospective view on the earlier experiments, we have to admit that we may have given false instructions to the drivers as we only assigned them with the task to achieve the highest deceleration possible. Fig. 2 shows that the fulfill of such a task will force the drivers into a long deceleration build-up time. The task posed in the new experiments – to achieve the smallest braking distance possible – will yield in the optimal choice of parameter combination \( a_0 \) and \( T \) (at least in the ideal case).

7 Consequences

7.1 Applicability of the Findings

At this point question may rise to what extent the findings are applicable to real world accidents. In the experiments, the drivers could choose the start point of the braking maneuver freely and they were definitively not willing to take any risk in regard to capsizing. Stress was only generated by the exam situation in combination with the ambition to prove good braking skills in concurrence to other participators. To the opposite, the accident situation forces the driver to prove his braking skills in a life-threatening situation.

We would like to point out that stress reaction of the body – as for instance the ejection of adrenaline – is intended to improve performance in extreme situations. While stress may have a negative implication on cognitive skills \([5]\), highly overlearned behavioral patterns may even benefit from stress.

Anyway, there should be few doubt that the experimental findings may be used to calculate the reasonable braking distance out of a certain admitted speed. Adding the distance traversed during reaction will give the stopping distance. If the defense distance of the motorcyclist may be proven to be longer than this distance, the accident is avoidable for him.

7.2 Braking Distance

Strictly speaking, the values \( a_0 \) and \( T \) deduced from the experiments are only applicable in the initial speed range depicted by fig. 7. We assume them to be applicable in a speed range of 30 – 70 km/h. Fig. 8 shows lower and upper values for the braking distance out of different initial speeds. The values were calculated using the approximation by the exponential function eq. 1. and the data for \( a_0 \) and \( T \) given in fig. 8. The proceeding was such that we integrated eq. 1 twice and then applied Excel’s goal seek algorithm to get the values for \( v(t_{stop}) = 0 \).

The mean deceleration was calculated from the initial speed \( v_0 \) and breaking distance \( d \) by

\[
\bar{\alpha} = \frac{v_0^2}{2d}.
\]
The value calculated by this equation differs somewhat from the temporal mean

$$\bar{a} = \frac{v_0}{t_{\text{stop}}}.$$  \hspace{1cm} (5)

As the relationship eq. 4 is common for calculating the breaking distance, the mean value defined by this equation is more suitable for direct comparison to other deceleration values supplied by literature.

Numerical computations show that the braking distances given in fig. 8 may be approximated by

$$s = \frac{v_0^2}{2a^*} + v_0T^*$$  \hspace{1cm} (6)

where $a^*$ and $T^*$ are somewhat modified versions of their counterparts $a_0$ and $T$. Best fit is achieved choosing

<table>
<thead>
<tr>
<th></th>
<th>$a^*$</th>
<th>$T^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skilled</td>
<td>8.94 m/s²</td>
<td>0.137 s</td>
</tr>
<tr>
<td>Novice</td>
<td>5.93 m/s²</td>
<td>0.265 s</td>
</tr>
</tbody>
</table>

These values will reproduce the stopping distance calculated by the original relationship with an accuracy of 5 cm or less.

When calculating the stopping distance for a motorcyclist, one has to keep in mind that our functional description includes the deceleration build-up time. Thus any recommendations on (car) driver reaction time that refer to the start point of the skid marks must be somewhat reduced.

### 7.3 Calculation of Initial Speed

Given a real accident, the reconstructionist will first calculate the collision speed of the motorcycle and then attempt to calculate its initial speed. When fate is smiling at him, he might base this calculation on a skid mark left by the motorcycle rear wheel.

Of course, a skid mark left by the rear wheel gives definite proof only on rear break usage. But it would be remote from reality assuming exclusive use of the rear brake in an emergency situation.

To favor the motorcyclist, the reconstructionist may assume instant rear wheel lock-up at the very beginning of the braking maneuver, i.e. the braking distance not being longer than the skid mark. This implies that the motorcyclist skipped all mental reservations in respect to rear wheel lock-up when encountering the accident situation.

Based on the skid mark, the reconstructionist should calculate the initial speed assuming front brake usage. Having done so, he must cross-check this assumption by time distance considerations.

Adding the reaction time to the braking time will give the total defense time of the motorcyclist in case that the skid mark starts shortly after the beginning of braking. On the other hand, the defense time might be calculated based on the occurrence of the threat. If both values differ much, this either indicates a prolonged reaction time or, more probably, a longer braking time without rear wheel lock-up.

<table>
<thead>
<tr>
<th>Initial speed [km/h]</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breaking time [s]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skilled</td>
<td>1.08</td>
<td>1.38</td>
<td>1.69</td>
<td>2.00</td>
<td>2.31</td>
</tr>
<tr>
<td>Novice</td>
<td>1.69</td>
<td>2.15</td>
<td>2.61</td>
<td>3.08</td>
<td>3.54</td>
</tr>
<tr>
<td>Breaking distance [m]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skilled</td>
<td>5.0</td>
<td>8.4</td>
<td>12.7</td>
<td>17.8</td>
<td>23.8</td>
</tr>
<tr>
<td>Novice</td>
<td>8.0</td>
<td>13.4</td>
<td>20.0</td>
<td>27.9</td>
<td>37.1</td>
</tr>
<tr>
<td>Mean deceleration [m/s²]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skilled</td>
<td>6.9</td>
<td>7.3</td>
<td>7.6</td>
<td>7.8</td>
<td>7.9</td>
</tr>
<tr>
<td>Novice</td>
<td>4.3</td>
<td>4.6</td>
<td>4.8</td>
<td>5.0</td>
<td>5.1</td>
</tr>
</tbody>
</table>

Fig. 8 Upper and lower limits for various initial speeds

Skilled: $a_0 = 9.0$ m/s², $T = 0.15$ s ; Novice: $a_0 = 6.0$ m/s², $T = 0.30$ s
7.4 Application of the Findings

Though the exponential function has proved to be useful for the mathematical description of the experimental results, it is somewhat awkward for normal day use. As it describes the deceleration in terms of elapsed breaking time, the total breaking time has to be calculated first, usually calling for an iterative treatment of the problem.

Another problem that has no definite solution is the speed loss prior to the skid mark. For passenger cars (front wheel) skid marks start when deceleration build-up is almost finished. As the motorcycles have to distinct breaking circuits, rear wheel skid may start at any point of the total breaking maneuver. Assuming exclusive use of the rear brake, deceleration value at the start of rear wheel skid is about 4.0 m/s². Front break usage will elevate this value. Therefore all we know is, that at the start of the skid mark deceleration had at least reached a level of some 4.0 m/s² and that there must have been some speed loss prior to that.

So what can be done to simplify things for normal day use?

If breaking time is long enough that the deceleration ‘reaches’ its final value, i.e. \( t > 5 T \), we may approximately calculate the initial speed by the skid mark assuming constant deceleration \( a_0 \). This will overestimate speed loss over the skid mark (\( \Delta v_+ \)), but neglect the speed loss prior to the skid mark (\( \Delta v_- \)). Fig. 9. Subtracting these terms we get

\[
\Delta v_+ - \Delta v_- = \Delta v = a_0 T (1 - t_s / T) \quad (6)
\]

If the braking time at the start of skid \( t_s \) equals \( T \), these terms balance each other.

Reaching \( a = 4.0 \) m/s² needs 0.33 s (= 1.10 \( T \)) for the novice and 0.09 s (= 0.59 \( T \)) for the skilled driver. Eq. 6 therefore holds in good approximation for the novice driver, whilst the skilled driver is somewhat mistreated by it. Please note that especially for the novice driver, the time elapsed prior to skid and the speed loss of 0.78 m/s achieved during this time should be accounted for.

For shorter total braking times, the following mean deceleration values are achieved:

<table>
<thead>
<tr>
<th>Time [s]</th>
<th>novice</th>
<th>skilled</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 s</td>
<td>3.1 m/s²</td>
<td>6.4 m/s²</td>
</tr>
<tr>
<td>1.0 s</td>
<td>4.3 m/s²</td>
<td>7.7 m/s²</td>
</tr>
<tr>
<td>1.5 s</td>
<td>4.8 m/s²</td>
<td>8.1 m/s²</td>
</tr>
<tr>
<td>2.0 s</td>
<td>5.1 m/s²</td>
<td>8.3 m/s²</td>
</tr>
</tbody>
</table>

If the brake pattern in the accident situation is not too far from that in our experiments, the mean deceleration achieved during short braking maneuvers is considerably low, especially for novice drivers.

Note that there is no contradiction to the approach just mentioned, assuming a mean deceleration of \( a_0 \) over the whole skid. The table lists the mean deceleration for the total breaking time, whilst the mean deceleration of \( a_0 \) was computed dividing the total speed loss by the (shorter) skidding time.

8 Résumé

The experimental results presented in this paper show (again) that motorcyclists’ braking maneuvers may not be described in such a narrow range as for passenger cars. Nevertheless, the experiments narrow the range of motorcyclists’ braking behavior that has to be taken into account. Definitively, the experimental results may be used to calculate the reasonable braking distance out of a certain admitted speed.
It turns out that the mean deceleration achieved by novice drivers is considerably low, especially for short breaking maneuvers.

References


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