Longitudinal and Lateral Accelerations in Normal Day Driving

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Abstract

In most accidents, the driving behaviour prior to reaction is governed by personal habits and not by the urge to protect oneself. In our investigation we instrumented the personal cars of 11 test persons with a bi-axial accelerometer and a speed sensor. During a one hour test drive on normal roads the longitudinal and lateral accelerations were recorded and evaluated statistically.

Introduction

There are several driving manoeuvres where the acceleration chosen by the driver is governed more by personal behaviour than by physical driving limits [A1, B1, B2, B3, S1]:

- starting acceleration
- stopping deceleration
- changing lanes
- negotiating a turn.

The limiting factor – in normal day driving – is probably the static muscle work needed to withstand the accelerating forces, producing a certain discomfort for the driver, whereby lateral accelerations are harder to withstand than longitudinal accelerations, as there is no direct point of support, like the backrest for (longitudinal) accelerations or the steering wheel for decelerations.

A look at the literature [B1, B2, K1] reveals that there has been considerable research by reconstructionists on the "normal" starting acceleration. This is probably due to its essential relevance for time-distance considerations specifically in accidents at road junctions, as it determines the signalling point of the starting car. The lane changing manoeuvre has also gained some interest [S1, S2]: What portion of an overtaking manoeuvre is taken up by the lane change? And at what point in time may an oncoming driver recognise the swerve of his later opponent?

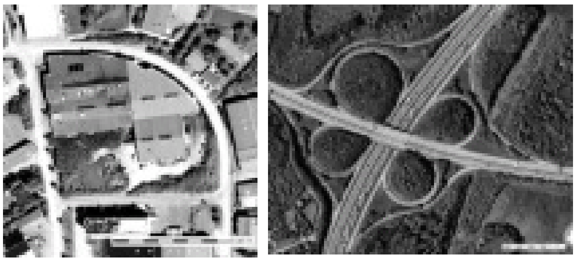
The "normal" lateral acceleration when negotiating a curve has gained less interest. Reconstructionists seem to be mostly interested in the maximum curve speed, defined as the physical driving limit. Other investigations reveal that the maximum curve speed is far beyond the experience of the normal driver [A1, S1] and even test drivers are unable to estimate either the absolute lateral acceleration or the security reserves regarding the physical driving limits [B3].

The average deceleration in normal day driving has gained even less interest by reconstructionists so far. There has been some research work by vehicle manufacturers [K1, L1] aiming at brake assistance systems, as many drivers do not reach the maximum brake pressure at the start of a defensive braking manoeuvre. A braking assistance system has to be "aware" of the range for every day braking decelerations as one parameter to distinguish the defensive action from the normal.

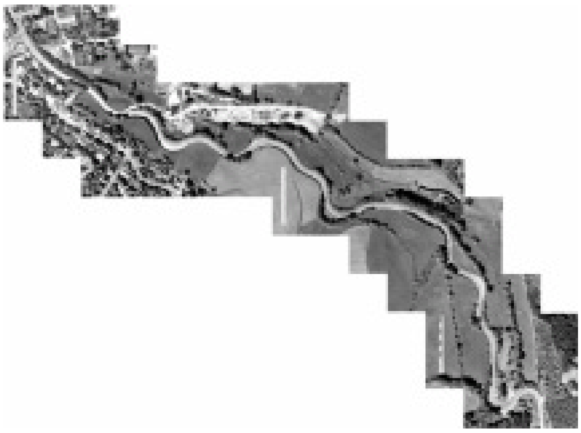
Why bother?

For what reasons should reconstructionists be interested in "normal" accelerations? Well, we should bear in mind that driving behaviour prior to an accident is often guided not by the oncoming threat but by everyday behaviour. Thus, the reconstructionist may have to assign physical values to witness account like: *"Prior to the accident, the driver in front of me was negotiating the curve just normally."*

On the other hand, the reconstructionist may have to assist when it comes to relating some behaviour to the average. This can for instance affect actions required from the



a) Round course b) Highway intersection



c) Country road (excerpt)

Fig. 1: The test drives
(Note the different scales)

driver in order to avoid an accident. As an example, we may assume that the excessive speed was so high that, if the driver had observed the speed limit, he would have needed only a deceleration of 4.5 m/s² to avoid the accident. But how “abnormal” is 4.5 m/s²?

In the same range fall technical deficiencies that manifest themselves only under certain minimum conditions. For instance, one of our case files considered a car with overinflated new tyres that went into oversteer at high centrifugal accelerations. But the claimant stated that he had been negotiating the curve just normally when his vehicle became unstable. In such a case, the reconstructionist should first determine the lateral acceleration at which the car changes its behaviour (which we did by experiments on a test ground). But in a second step he should probably make some remarks on how the driving behaviour needed to reach the region of instability relates to the average.

Another field of application may be case files in which tire marks are sparse, for instance an inner city pedestrian accident some ten metres ahead of a red traffic light (as eye witnesses describe). If the point of collision is fixed – say, a gap between two parking cars where the pedestrian darted out – we may narrow the collision speed by a “normal” deceleration and the known distance from the traffic light.

These examples show that we cannot expect such considerations to give exact answers but they may be the best we can do in certain situations.

Experimental set-up

For the experiment [N1] we used a team of eleven test persons, seven of them with an age of 21 – 29 years, three of them in a range of 37 – 47 years and one man with age of 65. Men were slightly over-represented (7:4). The test persons drove their own cars, mostly VW Golf (Rabbit) II (6 of 11). The cars were equipped with a bi-axial accelerometer and a pulse counter connected to the digital speedometer. The signals were pre-processed by a microprocessor and recorded with a laptop.

The test persons had to drive a given route unknown to most of them. The one hour drive consisted of four portions, **Fig. 1**:

- a round course with three turns of 9 – 11 m radius that was driven clockwise and anti-clockwise
- a country road section of 3 km length with 27 alternating curves with an average slope of 5% that was driven downhill at the beginning and uphill at the end of the test drive. The sharper curves are concentrated in the somewhat steeper portion (first 2 km).

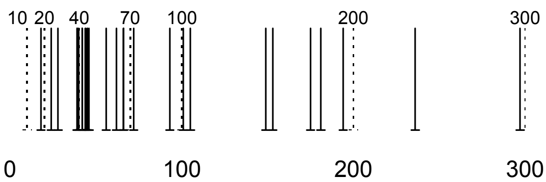


Fig. 2: Distribution of the curve radii on the country road.

- a highway intersection with three drive ramps of 55 m radius and one of 75 m radius
- an inner-city course.

Fig. 2 shows the distribution of the curve radii on the country road section. Each curve is represented by a continuous line, the boundaries of the groups (classes) established for the evaluation are indicated by dashed lines that are labelled at the upper end. The absolute class width increases to the right (10 m, 20 m , 2 × 30 m, 2 × 100 m). The distribution shows a cluster at 50 m, whilst the 200 – 300 m class contains only two curves. The radii were determined by means of the aerial photographs displayed in fig. 1.

The test persons were told to drive normally, ignoring the test situation and keep on their lane during the curves. The aim of the experiment was explained to them: We wanted to record their normal driving behaviour, we were not interested in the limits of their driving ability – as long as it was not their habit to explore these limits...

Evaluation

During post-processing, the signals were levelled by floating average over 1 s and the result of this was used a the basis for signal evaluation. We had no gyro platform, thus due to pitch and roll, the gravitational acceleration coupled into the accelerometer signals and had to be compensated quasi-statically. The accelerometer was mounted in front of the front passenger seat in order to place it as low as possible and avoid dynamic vehicle body accelerations coupling in. Its offset from the centre of gravity proved to be negligible for curve radii larger than 10 m.

The maximum of this levelled acceleration was taken as the centrifugal acceleration at the apex of the curve or as the longitudinal acceleration / deceleration. By means of the recorded driving speed $\boldsymbol{v}$ we were able to calculate the actual driven curve radius $\boldsymbol{r}$ from the centrifugal acceleration $\boldsymbol{a_{cf}}$ via $\boldsymbol{r} = \boldsymbol{v}^2/\boldsymbol{a_{cf}}$.

Lateral accelerations

Country road

Fig. 3 shows all recorded maximum accelerations for the country road, both uphill and downhill, i.e. 594 data points (=2 × 11 × 27). The accelerations are already compensated quasi-statically.

As has been found earlier [S1], the centrifugal acceleration decreases with increasing curve radius, respectively speed. The lowering towards higher speeds cannot be attributed to the speed limit (of 100 km/h) that would roughly result in about 2.5 m/s² even for 300 m radius. The normal driver probably keeps a security margin to the physical driving limits and increases this margin at higher speeds. The decrease in centrifugal acceleration $\boldsymbol{a_{cf}}$ with radius $\boldsymbol{r}$ may be described by the functional approach

$$a_{cf} = a_\infty + (a_0 - a_\infty)\, e^{-r/r_c} \qquad (1)$$

with $\boldsymbol{a_0}$ and $\boldsymbol{a_\infty}$ as the limits for low and high speeds and $\boldsymbol{r_c}$ as a modelling parameter (characteristic radius). Approximating all three parameters by minimising a loss function yielded $\boldsymbol{a_\infty} \approx 0.5$ m/s² for both up- and downhill drives. This value was then fixed in a second step and the two remaining pa-

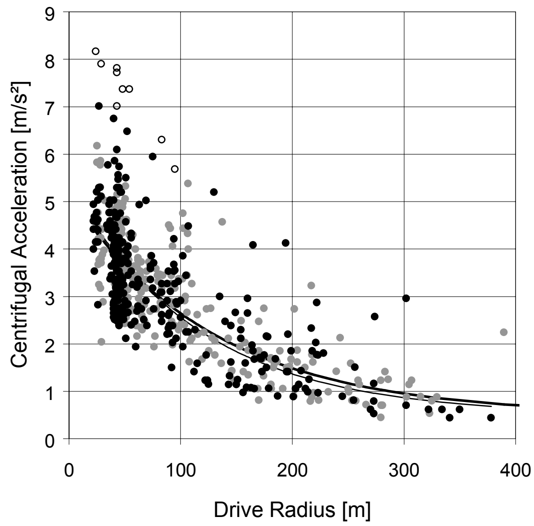


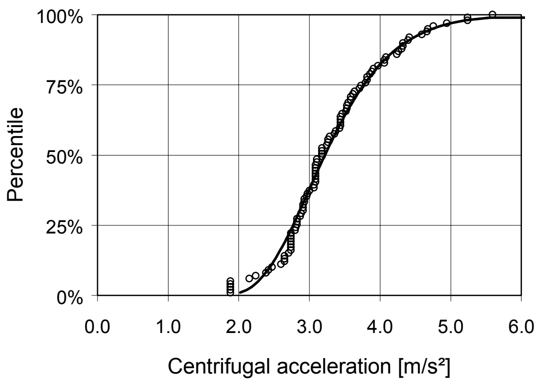
Fig. 3: Measured Centrifugal accelerations by drive radius (not curve radius)
black dots: uphill
grey dots: downhill
hollow dots: Driver DiA

rameters were adapted optimally:

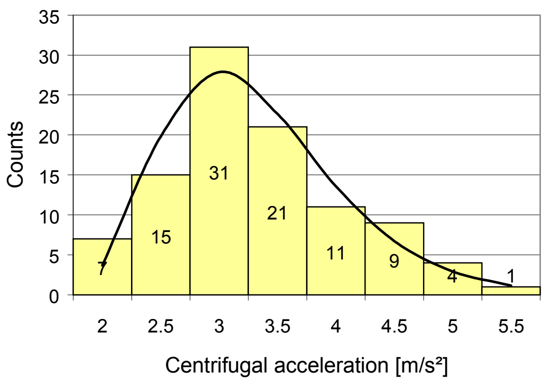
	downhill	Uphill
a_0	5.16 m/s²	5.39 m/s²
r_c	127 m	116 m

This approximation included all data, revealing that the difference between up- and downhill is – in total – not that great, as is suggested by the small number of points away from the curve. The regression curves are included in fig. 3. Driving up or down the hill made a difference especially for those drivers that explore the limits. This effect may partially be attributed to vehicle dynamics, but has probably also psychological reasons as the driver may decelerate his car faster when driving uphill and may therefore take more risks. Especially this produces greater scatter when considering the total spectrum of drivers, the maxima being produced by a few persons who explore the physical driving limits (like driver DiA).

We could not detect any significant differences between left and right turns at any radius (contrary to what we expected). There are several reasons for which the lateral acceleration accepted in right turns might be higher than that accepted for a left turn: The driver can find support at the driver's door; quite often he may use the outer lane to increase his radius (in the absence of oncoming traffic), the right bend is always sharper than the corresponding left bend, etc. None of these good reasons seemed to affect normal driving behaviour to a measurable extend.



a) Summary distribution



b) Distribution and density function

Fig. 4: Distribution for sharp right turns and approximation by shifted Gamma distribution

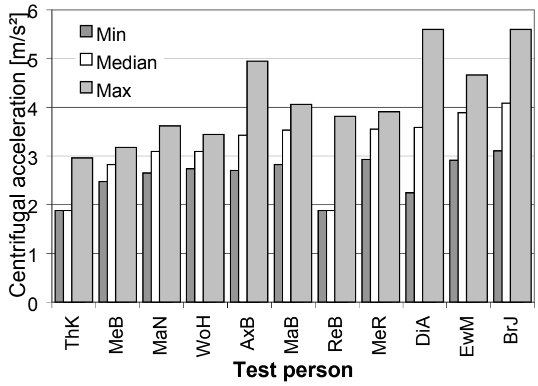


Fig. 5: Centrifugal accelerations achieved by the various test persons

Sharp Turns

While clockwise driving on the round course, all turns had about 10 m radius, with no possibility of "short-cutting", as the kerb was right next to the passenger's side. Parametrising centrifugal accelerations by the radius during the evaluation would therefore not pay, so we pooled all data, getting 99 data points, i.e. 11 test persons, each of them driving the round course three times. **Fig. 4** shows the distribution of the data.

The distribution is slightly left-steep (skew = 0.57). The percentiles are

	10%	50%	90%
a [m/s²]	2.6	3.2	4.3

The total range stretches from 1.9 to 5.6 m/s².

The shifted Gamma distribution

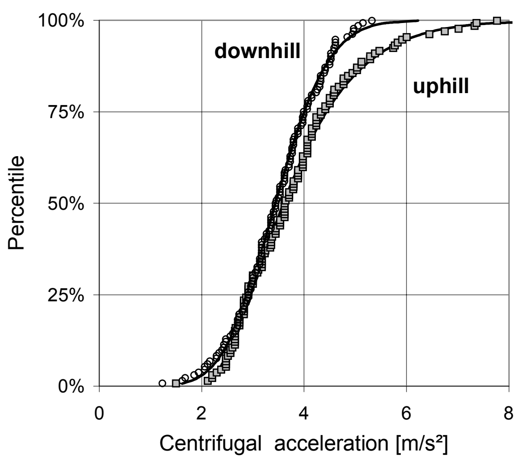


Fig. 6: Percentiles of centrifugal acceleration for curve radii 40 – 70 m, split into downhill and uphill driving. Each distribution consists of 132 data points. Approximation by shifted Gamma distribution.

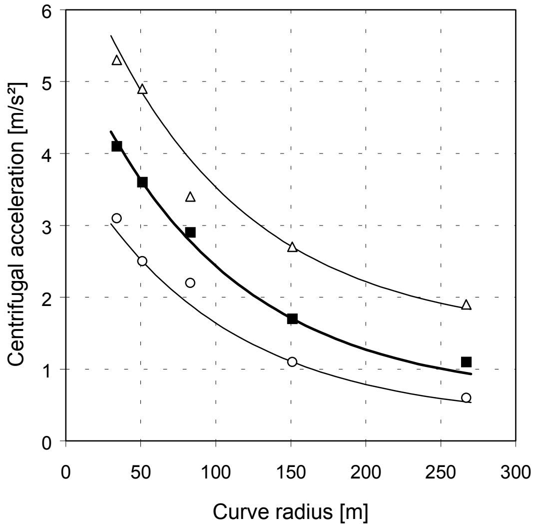


Fig. 7: Percentiles of centrifugal acceleration as a function of curve radius

$$f(a) = \frac{1}{\Gamma(\lambda)\, a_c} \left(\frac{a - a_s}{a_c} \right)^{\lambda - 1} e^{-\left(\frac{a - a_s}{a_c}\right)} \tag{2}$$

had already proven its ability to model experimentally found left-steep distributions [H1] and did a good job in this case, too. The procedure leading to optimal fit of its parameters is rather easy to handle and is described in detail in the cited paper. In eq. (2) $\boldsymbol{a_s}$ represents the shift of the Gamma distribution, $\boldsymbol{a_c}$ is a normation and $\boldsymbol{\lambda}$ a dimensionless parameter. The shifted Gamma distribution models the right "tail" of **fig. 4b** better than the ascent left to the maximum, a characteristic that is also reflected by the summary distribution **fig. 4a**.

Fig. 5 exhibits the intra- and interpersonal differences, displaying the minimum, maximum and median for each individual driver.

Radii [m]	Mean [m]	Count	10% [m/s²]	50% [m/s²]	90% [m/s²]
20 – 40	34	6	3.1	4.1	5.3
40 – 70	51	11	2.5	3.6	4.9
70 – 100	83	2	2.2	2.9	3.4
100 – 200	151	7	1.1	1.7	2.7
150 – 300	267	2	0.6	1.1	1.9

Table 1: Lateral accelerations for different radii

Country road, revisited

We bundled the curve radii of the country road into classes as indicated by fig. 2. For each of these classes we processed the data as exemplified by the proceeding section. The data and diagrams in their entirety may be found on our website [U1]. Here we will concentrate on the most prominent results.

Fig. 6 displays the summary distribution for the 40 – 70 m radius range, split into uphill and downhill driving. As has been said already, the country road was driven downhill at the start and uphill at the end of the test drive, i.e. each curve was driven through both uphill and downhill. Comparable to fig. 3, the distribution shows that when driving uphill, the curves were negotiated somewhat faster in the whole, which affects especially the higher percentiles.

Table 1 lists the most important percentiles for each group of radii, **fig. 7** shows the corresponding graph. The curves were generated by use of the functional approach eq.(1) with the following parameters:

	10%	50%	90%
$\boldsymbol{a_0}$ [m/s²]	3.98	5.60	7.10
$\boldsymbol{a_c}$ [m/s²]	0.29	0.60	1.45
$\boldsymbol{r_c}$ [m]	100	100	100

When evaluating the parameters of the functional approach, we used the true mean of the radii in each group and weighted the groups according to the number of curves falling into that range, see **Table 1**. The round values for r_c are by coincidence.

Sharps turns, revisited

Comparing the lateral accelerations for sharp turns with the smallest curve radius on the country road reveals that the preferred lateral acceleration seems to decrease for very small radii:

Radius [m]	10% [m/s²]	50% [m/s²]	90% [m/s²]
10	2.6	3.2	4.3
20 – 40	3.1	4.1	5.3

This finding has been observed earlier [S1], though the reason for it is not exactly clear. A possible reason may be that you do not gain much time by accepting high centrifugal accelerations in sharp turns of radius $\boldsymbol{r}$ and angle $\boldsymbol{\alpha}$. With the rotational speed $\boldsymbol{\omega}$ you may calculate the time $\boldsymbol{t}$ needed by

$$a_{cf} = \omega^2 \, r = (\alpha \,/\, t)^2 \cdot r \tag{3}$$

or

$$t = \alpha \cdot \sqrt{r \,/\, a_{cf}} \,. \tag{4}$$

For small radii, the acceptance of the discomfort created by high centrifugal accelerations does not gain much time, i.e. it just does not pay enough – which does not mean that high lateral accelerations are impossible in a situation that calls for them, for instance a U-turn on a busy road.

Considering large radii, the limits proposed by table 1 are probably not that flexible for the normal driver, which does not mean that certain experienced drivers may reach speeds far beyond those proposed by the table.

Drive ramps

As we expected, the centrifugal acceleration when passing the drive ramps of the highway intersection was slightly higher than the usual, especially for the lower percentiles:

Radius [m]	10% [m/s²]	50% [m/s²]	90% [m/s²]
40 – 70	2.5	3.6	4.9
55 – 75	3.2	4.2	4.9

We may presume several reasons for this finding: First, the curve angle of 270° is much greater than that of a normal curve of that radius and accepting the discomfort of high lateral accelerations will gain more time than usual. Second, the driver meets a standardised situation, i.e. a mostly constant radius of 55 m. And, last, but not least, driving the ramp will take a good 15 s, thus the driver has enough time get used to the situation.

Decelerations

Decelerations were measured during the round course when approaching one of the turns and during the city drive when approaching traffic lights. Thus we are talking of stops (or near-stops) that could be foreseen, i.e. kind of “planned” by the driver. The values found – 1.3 / 2.2 / 3.3 m/s² for 10%- / 50%- / 90%-percentile – were lower than we expected, but coincide with findings in [C1], where a range of 1.5 – 3.2 m/s² was found for stopping manoeuvres from 25 – 40 km/h. The single value of 2.45 m/s² given in [K2] is reproduced by the median of our measurements.

In Germany, the yellow phase of traffic lights is 3 / 4 / 5 s for 50 / 60 / 70 km/h. Calculating with a reaction time of 1.2 s, this calls for a deceleration of 3.9 / 3.0 / 2.6 m/s² if the traffic light turns yellow exactly at stopping distance. At least for the 50 km/h limit the deceleration called for is significantly higher than the usual, which may be part of the reasons for which people tend to accelerate in such situations (thinking positively about the state of German discipline in traffic).

Accelerations

The accelerations were evaluated during the round course when leaving one of the turns and during the city drive section when starting at a traffic light, giving values of 0.9 / 1.6 / 2.6 m/s² for the percentiles. Again, this coincides with earlier findings that the power limits of the vehicle are, by far, not exploited in normal day traffic.

Conclusions

The maximum curve speed is, by far, not reached in normal day driving. The average driver keeps a significant security margin from the physical driving limit and this margin increases with rising speed, i.e. increasing radius. We could not determine any significant difference regarding the preferred acceleration between left or right turns, but driving uphill seems to rise self-confidence and thereby the centrifugal acceleration accepted.

In very sharp turns, the centrifugal acceleration accepted lessens, because the possible gain in time is rather small. To the contrary, large turning angles, like those of the drive ramps in highway intersections, seem to increase the accepted lateral acceleration.

We pooled the data for every group of radii and refined the data to a summary distribution (function) giving the centrifugal accelerations for all percentiles. The distribution turned out to be left-steep and could be approximated by a shifted Gamma distribution function.

The normal day deceleration for foreseen (near-) stops is only slightly higher than the average starting acceleration, the deceleration claimed by a traffic light turning red possibly being significantly higher. Our results regarding starting accelerations have confirmed well-known earlier results.

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