Trafitec

# Braking distance, friction and behaviour

### Findings, analyses and recommendations based on braking trials


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# 1. Introduction

The Danish Road Directorate has conducted a study designed to shed light on braking behaviour among non professional drivers and their braking distance at different speeds. The study will be included in an assessment of the current values for braking distances recommended in the Danish Road Standards and Guidelines.

The study was planned and carried out by Trafitec, in association with the Danish Road Directorate.

## 1.1 Background and object

Braking distance is applied as a significant basic parameter in e.g. calculations of stopping sight distance.

A vehicle's braking distance depends on a number of factors pertaining to the vehicle, the road and the driver's behaviour. The most important factors are:

- speed of the vehicle
- coefficient of friction between tyres and roadway
- driver's braking behaviour/technique
- vehicle's braking system and condition
- tyre pressure, tyre tread depth and road-holding capability
- road's vertical grade

All these factors affect braking distance to a greater or lesser extent depending on the actual conditions present when decelerating. A general method for determining braking distance at different speeds, which is representative for the composition of cars, drivers and friction, requires knowledge of the significance of the individual factors for overall braking distance. The present Danish Road Standards and Guidelines contain a method for calculating braking distance at different speeds which is essentially based on early American findings.

The purpose of this study is to assess the braking behaviour of non professional drivers, including braking distances under different physical conditions. The findings will be included in an assessment of the present methods for calculating braking distance.

The following describes both the method currently employed in determining braking distances for Denmark, and a few foreign methods.

### 1.1.1 The Danish Road Standards and Guidelines

The present method, as described in the Danish Road Standards and Guidelines [1], is based on measurements of friction values for tyre/roadway and the physical laws of deceleration.

Here the braking distance is obtained from the speed, coefficient of friction and the roadway grade by applying the following formula:

$$l_{brake} = \frac{V^2}{2 \cdot g \cdot (\mu_{brake} + s) \cdot 3.6^2}$$

| | | |
|---|---|---|
| $l_{brake}$ | = | braking distance (m) |
| V | = | speed (km/h) |
| g | = | acceleration due to gravity (9.81 $m/s^2$) |
| $\mu_{brake}$ | = | mean coefficient of friction |
| s | = | roadway grade |

The friction values applied are obtained from measurements on a wet, but clean road surface. As a rule, the coefficient of friction is not constant, in that it increases during braking as speed diminishes. In determining the coefficient of friction, a mean value is therefore applied for the given speed. The coefficient of friction is also dependent on whether the road being driven is curved or straight. The recommended friction values from the Danish Road Standards and Guidelines are shown below.

| Speed (km/h) | Resulting coefficient of friction (straight road) | Braking coefficient of friction (curve) |
|---|---|---|
| 130 | 0.28 | 0.27 |
| 120 | 0.29 | 0.28 |
| 110 | 0.30 | 0.29 |
| 100 | 0.31 | 0.30 |
| 90 | 0.33 | 0.31 |
| 80 | 0.34 | 0.31 |
| 70 | 0.35 | 0.31 |
| 60 | 0.36 | 0.31 |
| 50 | 0.38 | 0.31 |

*Table 1.1 Coefficients of friction from the Danish Road Standards and Guidelines*

For braking in a curve in the road, the right-hand column containing braking coefficients of friction is used, while the resulting coefficients of friction are used for braking on a straight road. Braking in curves produces longer braking distances, as friction has to be “expended” on simultaneously steering the vehicle along the curve.

Applying the values from Table 1.1 in the above formula produces the braking distances for a straight, level road, as shown in Table 1.2.

| Speed (km/h) | Braking distance (m) |
|---|---|
| 80 | 74 |
| 110 | 159 |
| 130 | 234 |

*Table 1.2 Braking distance on a straight, level road.*

### 1.1.2 International methods for determining braking distance

In the latest version of the AASHTO Green Book [2], determination of the braking distance for use in calculating stopping sight distances has been altered from the more traditional calculation method using coefficients of friction (like the Danish) to a calculation method based on behavioural recordings and measurements from braking trials.

Based on the findings of a large-scale measurement programme, the following method has been adopted for calculating braking distance.

The approximate braking distance for a vehicle driving along a level road can be determined by applying the following formula:

$$d = 0.039 \cdot \frac{V^2}{a}$$

where

d = braking distance (m)
V = speed (km/h)
a = deceleration ($m/s^2$)

Braking studies indicate that by far the majority of all motorists brake with a deceleration of more than 4.5 $m/s^2$, when stopping for an unexpected object on the road. Approximately 90% of all motorists brake with a deceleration of more than 3.4 $m/s^2$. This deceleration enables the motorist to keep the vehicle in lane without losing control when braking on a wet roadway. Thus, 3.4 $m/s^2$ is used as the recommended deceleration value in the above formulaic expression. 3.4 $m/s^2$ is also regarded as being a comfortable rate of deceleration for the majority of motorists.

The underlying assumption is thus that the braking system and tyre/roadway friction is actually capable of this rate of deceleration. Measurements indicate that by far the majority of wet roads do indeed provide the necessary friction and that by far the majority of vehicles are fitted with brakes and tyres capable of decelerating at a rate of 3.4 $m/s^2$.

By applying 3.4 $m/s^2$, we obtain braking distances as shown in the table below:

| Speed (km/h) | Braking distance (m) |
|---|---|
| 20 | 5 |
| 30 | 10 |
| 40 | 18 |
| 50 | 29 |
| 60 | 41 |
| 70 | 56 |
| 80 | 73 |
| 90 | 93 |
| 100 | 115 |
| 110 | 139 |
| 120 | 165 |
| 130 | 194 |

*Table 1.3 Design braking distances – Green Book (2001)*

A comparison of braking distances calculated using the Danish Road Standards and Guidelines and the Green Book is shown in figure 1.1.

It should be noted that the Danish Road Standards and Guidelines operate with an extra safety margin of +20 km/h, i.e. the braking distance for e.g. 80 km/h is obtained by using 80+20 km/h. The extra safety margin is not reflected in the values given in Figure 1.1, which would result in appreciably greater differences between the Danish Road Standards and Guidelines and the Green Book.

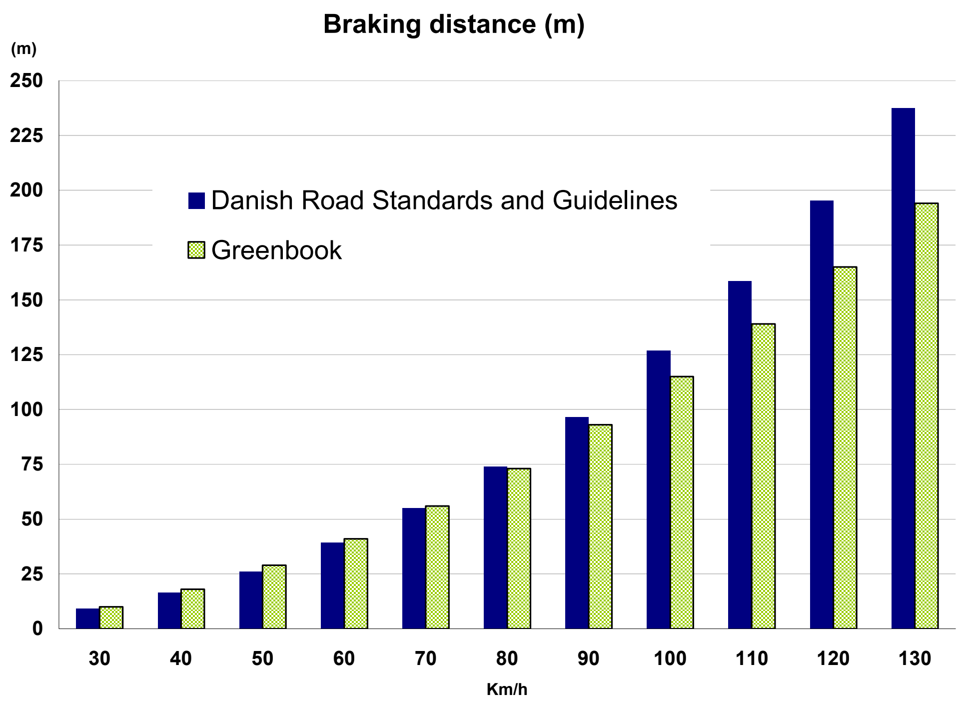



*Figure 1.1 Recommended braking distances from the Danish Road Standrads and Guidelines and the AASHTO Green Book.*

# 2. Measurement programme

In order to assess the present method for calculating braking distances, a series of controlled braking trials were conducted with a total of 22 test drivers.

Two types of braking manoeuvres were trialled. An emergency stop, where the vehicle is brought to a complete standstill as quickly as possible, and a normal braking action, the so-called "comfort braking action", where the vehicle is brought comfortably to a standstill. The main emphasis of the measurement programme was on the emergency stops.

The majority of the 22 test drivers were non professional drivers (ordinary drivers), but among them were also a few selected professional test drivers (total of 6 persons).

The aim was for the emergency stops to be performed under different conditions, that is, different speeds, friction values, road surface (dry/wet), car size and tyre type. The projected influence of the various parameters on driver behaviour is shown in the table below.

| | **Projected influence on braking behaviour** | | |
|---|---|---|---|
| | Slight | Some | Great |
| **Speed** | | | + |
| **Friction** | + | | |
| **Road surface (wet/dry)** | | + | + |
| **Vehicle** | | + | + |
| **Tyre type** | + | + | |

*Table 2.1 Projected influence on braking behaviour*

Speed, road surface and vehicle were projected to have great or some influence on braking behaviour. All combinations of these parameters were thus included in the trials. The friction and tyre type are likely to have somewhat lesser influence on behaviour, which meant that these parameters did not necessarily need to be tested by all test drivers.

The measurement programme was conducted using the following test parameters.

| Test parameter (and number of levels) | | |
|---|---|---|
| Speed | (3) | 80, 110 and 130 km/h |
| Friction | (3) | road sections with friction in the range 0.4 – 0.8 |
| Road surface | (2) | wet and dry roadway |
| Vehicle | (2) | small and medium-sized car (representative of Denmark) |
| Tyre type | (1) | Ordinary new summer tyres |

*Table 2.2 Test parameters in the measurement programme*

The measurement programme was based on braking with only a single tyre type. Testing with 2 different types of tyre was originally planned as a component of the measurement programme, but was excluded from the final programme, since the number of test parameters and combinations would otherwise have been inordinate. It was also decided that findings on the braking capabilities of different tyre types have been fairly well documented in other studies.

All trials were conducted on a level, straight road using vehicles fitted with ABS brakes. During each trial, the test drivers were free to decide when to brake, so the study does not include measurement of driver reaction time.

## 2.1 Measurement equipment

In order to record braking behaviour, a measurement wheel was mounted on the car, a pressure sensor was fitted to the brake pedal, and a notebook PC was installed for data collection.

The measurement wheel was fitted to the car's coupling hook as a trailing wheel. Using a hydraulic system, the wheel is pressed against the road surface in order to ensure constant contact even during hard braking which typically raises the rear end of the car by as much as 20-30 cm.

For each 10 cm, a data line was logged to indicate distance travelled, a time code and the recorded pressure on the brake pedal. Based on these data, it was possible to calculate speed, deceleration, etc.

The time code is stated in seconds to 5 significant figures. The pressure meter on the brake pedal was able to detect changes down to approx. 0.15 kg. In practice this means that the pedal pressure is highly sensitive, which means that the data may include minor variations in pedal pressure, not necessarily due to the driver depressing the pedal. Minor variation may be due to the car juddering due to uneven road or due to sharp acceleration or deceleration of the car.

Fig. 2.1 shows the measurement wheel fitted to one of the measurement cars, and the pressure meter on the brake pedal. Although the pressure meter on the brake pedal may appear obtrusive, actually applying the brake does not feel uncomfortable or unfamiliar. After a few minutes' driving, most test drivers becomes oblivious to its presence. It is therefore not regarded as likely that the pressure meter influences the behaviour of the test drivers.

*Figure 2.1 Test car with fitted measurement wheel and pressure meter on brake pedal.*

The devices are connected to a control box and a notebook PC which collects and stores data for subsequent use; see Figure 2.2. During the braking trials, the test driver is alone in the car. In order to start data recording, the test driver is required to press "start" on a keypad mounted on the passenger seat. Once the test car has driven along the test track, and braking has ceased, the test subject presses "stop" to save the data to the PC. Each braking session is thus saved in a separate file. The file header also saves information about the actual test drive such as date, time of day, etc. In addition, a walkie-talkie is placed in the car to allow the driver to communicate with the measurement team.

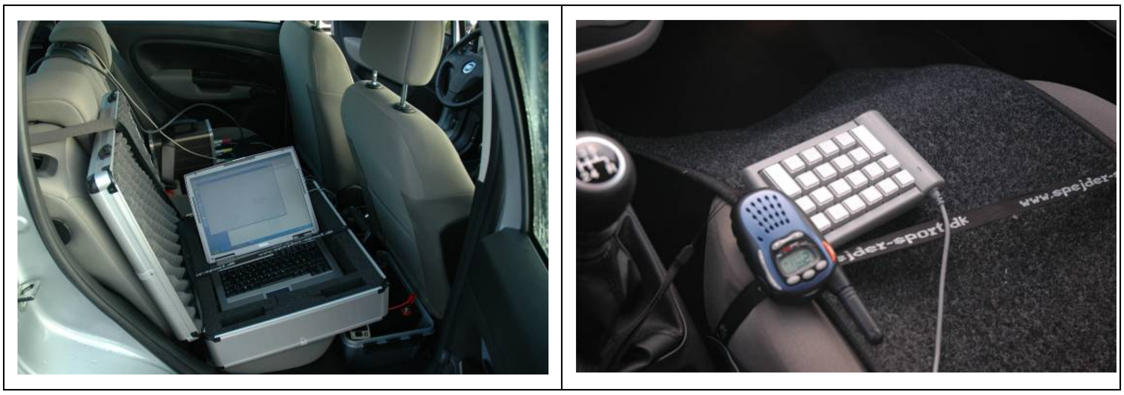


*Figure 2.2 Notebook PC, etc. for data collection and keypad for start/stop.*

## 2.2 Test cars

For the braking trials, two cars were used: a small and a medium-sized car, which were judged to be fairly representative of recent makes of car in Denmark. The cars were a Fiat Grande Punto and an Opel Vectra, see Table 2.3 below.

| **Car1** | | **Car2** | |
|---|---|---|---|
| Make: | Fiat Grande Punto | Make: | Opel Vectra |
| Model: | 1.4 Dynamic | Model: | 1.8 Comfort |
| Year: | 2006 | Year: | 2004 |
| Kilometres clocked: | 350 km | Kilometres clocked: | 29,650 km |
| Kerb weight: | 1,060 kg | Kerb weight: | 1,275 kg |

*Table 2.3 Test cars in the braking trials.*

Both cars feature ABS brakes and manual transmission. Test car 2 (Opel Vectra) also features a so-called “brake assistant” to boost brake pressure for full brake power when hard braking is attempted. Braking systems incorporating a brake assistant, EBD, EPS and the like are standard in many new cars.

The cars were fitted with new summer tyres (Continental EcoContact 3) prior to the first braking trials. The tyres were however ’run in’ by 500 kilometres’ ordinary driving prior to the first measurement day. The tyres used were judged to be average, typical summer tyres with medium to good braking capability (according to the Federation of Danish Motorists’ (FDM) tyre tests [6]). This make of tyre is among the best-sellers on the Danish market.

The same tyres were used for all the braking trials. Tyre tread depth was measured before and after each measurement day. The total wear on the tyres, measured from the first to the last measurement day, was recorded as < 1 mm. This should be seen in the light of the fact that the tread depth from the start was measured as 7-8 mm. However, it should be noted that although tread depth was not reduced significantly as a result of the extensive braking, some wear was detectable on the front tyres especially in the form of a roughened and “flocked” surface.

All braking trials were conducted using the recommended tyre pressure for the test cars. Tyre pressure was checked immediately before each measurement day, and tyre temperature was measured regularly during the braking trials.

In order to ensure that the cars were in as ”uniform technical condition” as possible during all the braking trials, in the intervals between the individual measurement days, they were kept out of service. Both cars were leased through a private car rental firm for a period of 4 months, exclusively for use in these trials.

The other technical specifications for the tyres are presented in Appendix 1.

## 2.3 Test tracks

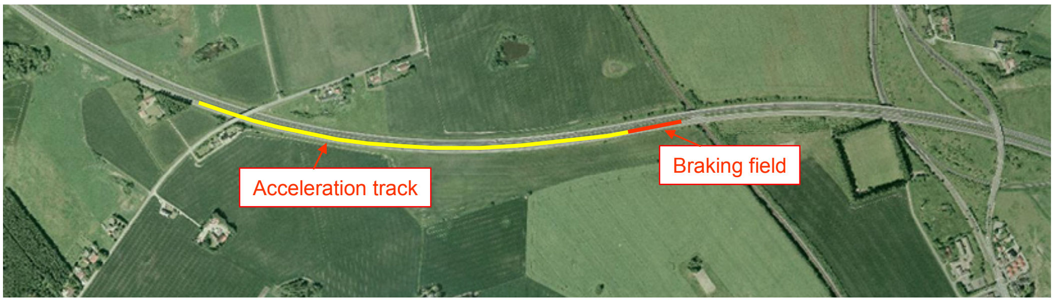
The primary aim was to find 3 locations with as different friction values as possible (range 0.4-0.8). Another important criterion was for it to be feasible and sufficiently safe to conduct the braking trials at speeds of up to 130 km/h. Among other considerations this meant that the test track would have to be closed to all other traffic and otherwise fulfil road safety conditions, i.e. with a broad lane and with no hazardous fixed objects by the roadside. In addition, the total test track had to be approx. 1,200 m in length (sufficient distance to be able to bring the car up to speed well in advance of deceleration), the braking section had to be a straight sub-section (without horizontal curves) and the roadway grade in the braking section had to be 0 degrees (level road). A last, important criterion was for it to be feasible to conduct the braking trials within a period in which the test cars were actually available (July-Oct 2006).

After examining several potential locations, three tracks were selected at Holbæk, Odense and Værløse.

On each test track, the section in which the brake was to be applied was precisely defined and marked with cones during the braking trials. On test track 1 (Holbæk), the same section was used for both dry and wet braking. On test track 2 (Odense) and test track 3 (Værløse), two separate sections were used in immediate extension of each other for dry and wet braking, respectively.

The three test tracks are described in greater detail in the following. Additional photos and layout are provided in Appendix 2.

Test track 1 is located on the Holbæk motorway (M11) between kilometer posts 59.500 km and 61.000 km (left roadside). The braking trials were conducted on 25 July 2006 between the hours of 9:30 am and 4:00 pm, when the motorway was closed to other traffic due to nearby roadworks.

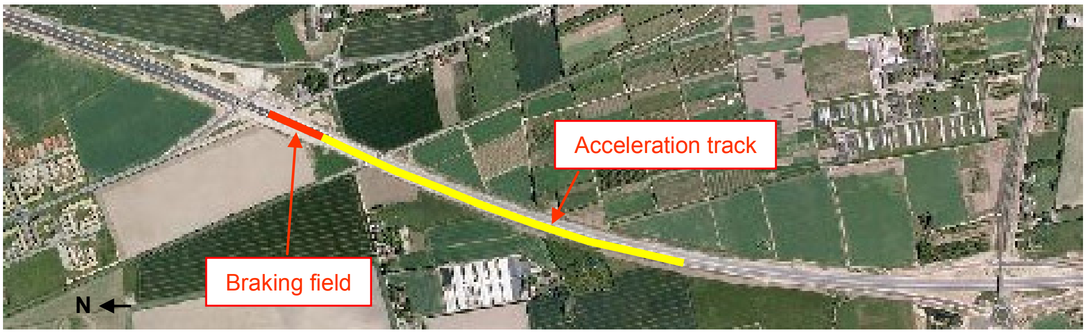



| | |
|---|---|
| **Test track 1 – Holbæk** | |
| M11 Holbæk motorway – left-hand carriageway/right-hand lane | |
| Braking section: | kilometer posts 59.950 – 60.100 |
| Roadway grade in braking section: | + 0.023 |
| Cross (lateral) slope in braking section: | - 0.0083 |
| Time of braking trials: | 25 July 2006 between 9:30 am and 4:00 pm. |
| Weather: | Sunny – fresh breeze |
| Air temp.: | 20 – 28 °C |
| Roadway temp.: | 30 – 45 °C |
| Tyre temp.: | 25 – 50 °C |
| Friction measured at 60 km/h with 20% slip: | |
| Dry-braking section: | 0.49 |
| Wet-braking section: | 0.49 |

*Table 2.4 Test track 1 - Holbæk.*

The actual braking section was 250 m long and marked with cones. The same section was used for both dry and wet braking. See Appendix 2 for photos and layout of the test track.

Test track 2 was located on the new Svendborg motorway at between kilometer posts 4.600 and 6.000 km (right-hand carriageway). The braking trials were conducted on 10 August 2006 between the hours of 10:30 am and 4:00 pm. At that time the motorway was still under construction, but paving work, road marking, and the crash barrier were established and the motorway appeared as “almost” completed. The motorway was opened to traffic 4 weeks after the braking trials were conducted.

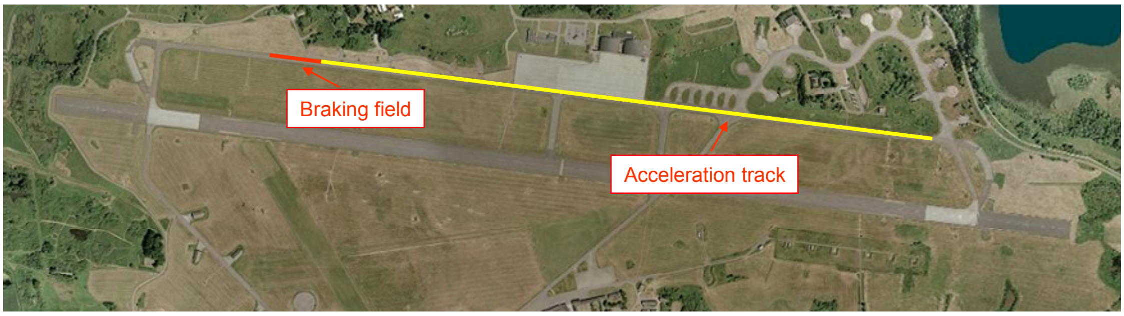



| | |
|---|---|
| **Test track 2 - Odense** | |
| M45 Svendborg motorway – right-hand carriageway / left-hand lane | |
| Braking section: | Kilometer posts 4.600 – 4.900 |
| Roadway grade in braking section: | 0.0 |
| Cross (lateral) slope in braking section: | - 0.02 |
| Time of braking trials: | 10 August from 2006 from 10:30 am to 4:00 pm |
| Weather: | Mixed clouds and sun – gentle breeze |
| Air temp.: | 20 °C |
| Roadway temp.: | 20 – 35 °C |
| Tyre temp.: | 20 – 40 °C |
| Friction measured at 60 km/h with 20% slip: | |
| Dry-braking section: | 0.52 |
| Wet-braking section: | 0.64 |

*Table 2.5 Test track 2 - Odense.*

The actual braking section consisted of a 2 x 150 m section marked with cones. One field for dry-braking and one for wet-braking. See Appendix 2 for photos and layout of the test track

Test track 3 was located at Værløse air field, where the east-west running taxiway parallel with the runway was used. The braking trials here were conducted on 3 and 4 October 2006, on both days between 9:00 am and 4:00 pm.




| | |
|---|---|
| **Test track 3 – Værløse** | |
| Taxiway – south lane | |
| Braking section: | Kilometer posts 0.650 – 1.000 |
| Roadway grade in braking section: | 0.00 |
| Cross (lateral) slope in braking section: | - 0.02 |
| Time of braking trials: | 3 + 4 October from 2006, from 09:00 am to 4:00 pm |
| Weather: | Intermittently overcast, wet spell, light breeze |
| Air temp.: | 12 – 18 °C |
| Roadway temp.: | 10 – 20 °C |
| Tyre temp.: | 20 – 40 °C |
| Friction measured at 60 m/h with 20% slip: | |
| Dry-braking section: | 0.75 |
| Wet-braking section: | 0.74 |

*Table 2.6 Test track 3 - Værløse.*

The actual braking section consisted of a 2 x 150 m section marked with cones. One section for dry-braking and one for wet-braking. See Appendix 2 for photos and layout of the test track.

### 2.3.1 Friction measurement on the test tracks

Friction on the three test tracks was measured by the Danish Road Institute's measurement vehicle, which measured the friction on both lanes in the braking section. Table 2.7 shows the recorded friction values at 60 km/h and 20% slip (standard measurement method). At test tracks 2 and 3, the friction measurements were obtained on the same day as the braking trials, while, for practical reasons, measurements on test track 1 were obtained 17 days after the braking trials.

| | | | Measured Friction Values | | |
|---|---|---|---|---|---|
| | | | 60 km/h – 20% slip | | |
| **Test track** | **Braking section** | **Value** | **Left lane** | **Right lane** | **Av.** |
| 1 - Holbæk | Dry | Mean | 0.49 | 0.49 | **0.49** |
| | | Spread | 0.04 | 0.04 | **-** |
| | Wet | Mean | 0.49 | 0.49 | **0.49** |
| | | Spread | 0.04 | 0.04 | **-** |
| 2 - Odense | Dry | Mean | 0.54 | 0.50 | **0.52** |
| | | Spread | 0.09 | 0.08 | **-** |
| | Wet | Mean | 0.67 | 0.61 | **0.64** |
| | | Spread | 0.07 | 0.08 | **-** |
| 3 – Værløse | Dry | Mean | 0.79 | 0.71 | **0.75** |
| | | Spread | 0.04 | 0.03 | **-** |
| | Wet | Mean | 0.77 | 0.71 | **0.74** |
| | | Spread | 0.03 | 0.04 | - |

*Table 2.7 Recorded friction values for the test tracks.*

Friction on the three test tracks was in the range 0.49 – 0.75. According to Operating Road Regulations in Denmark, the minimum friction requirement is set at 0.4. For new roadways, the requirement is however 0.5; see [13] and [14]. Thus, all the test tracks meet the operating requirements regarding friction.

It should be noted that test track 2 – Odense deviates slightly from the others. As will be noted, the friction in the two braking sections (dry/wet) differs somewhat in spite of the fact that they are in immediate extension of each other. The spread of the friction here is also approx. twice that of the two other test tracks. The reason for the large variation and differences is presumably due to the fact that the wearing course on test track 2 was new and still not 'run in' by traffic. Where the wearing course is new, the top of the road paving will be covered by a bitumen membrane which results in low and somewhat diverse friction values. The bitumen membrane is usually worn off after a few months' traffic.

## 2.4 Practical execution

As stated in the foregoing, the measurement programme was carried out on three test tracks, using a total of 22 test drivers. The following describes how the measurement programme was actually carried out in more detail.

### 2.4.1 Test drivers

On each of the three test tracks, both professional and non professional test drivers performed braking manoeuvres. The professional test drivers were recruited from the Danish traffic police. This police division provides instruction to the Danish Police's own staff in driving technique. They thus have extensive experience of different types of driving trials, including braking at high speed. Unfortunately, it was not possible to include the same professional test drivers on all three test tracks. A total of 6 different professional test drivers were used. All 6 test drivers are trained in and deal daily with the same type of work. The 6 professional test drivers' braking behaviour was judged as likely to be uniform. The results from the professional test drivers were assumed to be able to describe the optimal emergency stop under the given conditions.

The non professional test drivers, mainly recruited from among staff in the Danish Road Directorate, break down by age and gender as shown in Table 2.8 below. The non professional test drivers taking part in the study consist of 11 men and 5 women, mainly in the age-range 25-39. The majority of the test drivers drive on a daily basis, although a few do not own a car and therefore seldom drive. The results from the non professional test drivers are intended to shed light on the individual differences in braking behaviour presented by ordinary drivers.

| | Ages (years) | | | |
|---|---|---|---|---|
| Gender | 25-39 | 40-59 | 60 -> | Total |
| F | 4 | 1 | | 5 |
| M | 6 | 3 | 2 | 11 |
| Total | 10 | 4 | 2 | 16 |

*Table 2.8 Non professional test drivers (ordinary drivers) by gender and age.*

The non professional test drivers only performed braking manoeuvres on one of the three test tracks. Thus, none of the non professional test drivers are represented more than once in the measurement programme. On test tracks 1 and 2, 2 and 4 non professional test drivers, respectively were used, while on test track 3, 10 non professional test drivers were used. Appendix 4 presents an overview of the measurement programme conducted.

### 2.4.2 Measurement procedure

All braking trials were conducted using 2 test drivers at a time. The 2 test drivers started by receiving an oral presentation of what was to happen, an introduction to the cars, the equipment, measurement programme, etc. An index of information given to the test drivers is provided in Appendix 3.

Test driver 1 then started by trying out car 1, taking it for a short test run and then proceeded to perform 1-2 comfort braking manoeuvres, whereby he/she was required to bring the car to a comfortable stop. This was done at 80 or 110 km/h on dry road. After comfort braking, driver 1 proceeded to perform a series of emergency stops on the braking section on dry and wet road. Here, the test driver was required to bring the vehicle to a stop as fast as possible from 80, 110 or 130 km/h. As the test driver were expected to become gradually better and more bold in emergency stops over the course of the measurement programme, two different trial sequences were used, which to some extent would serve to equal out any change in braking behaviour over the course of the measurement programme. The trial sequence was one of the two shown in Table 2.9. Test drivers started out in each case with a stop at 80 km/h on dry road. Each driver performed only one emergency stop for each combination. The choice of trial sequence for the individual test driver was usually governed by practical circumstances involving the water truck that was used to wet the road surface.

| Trial no. | Measurement sequence | |
|---|---|---|
| | I | II |
| 1 | 80 dry | 80 dry |
| 2 | 110 dry | 80 wet |
| 3 | 130 dry | 110 dry |
| 4 | 80 wet | 110 wet |
| 5 | 110 wet | 130 dry |
| 6 | 130 wet | 130 wet |

*Table 2.9 Trial sequence.*

After each braking trial, the car was turned and returned to the starting point, where the test driver was able to recount “how it had gone”, and instructions concerning the next part of the programme could be provided.

Once driver 1 had finished doing emergency stops, driver 2 took over the car to perform the same manoeuvres. The measurement equipment was then transferred to car 2 and the measurements repeated for driver 1 and 2.

Not all test drivers performed emergency stops from 130 km/h. Several drivers did not feel confident performing the manoeuvre at this speed, in which case it was omitted in the measurement programme. The results for 130 km/h for the non professionals test drivers are therefore to some degree skewed among the test drivers. Those drivers who performed the 130 km/h manoeuvre were typically those who were “good” at performing them, and who were generally confident with the situation.

Due to time and technical factors, not all test drivers completed the measurement programme fully. A complete overview of the braking trials performed is provided in Appendix 4. By way of summary, the trials break down is shown in Table 2.10.

| Braking manoeuvre | | Non professionals test drivers | | Prof. test drivers | |
|---|---|---|---|---|---|
| | | dry | wet | dry | wet |
| Emergency | 80 km/h | 29 | 23 | 12 | 12 |
| | 110 km/h | 26 | 23 | 12 | 12 |
| | 130 km/h | 16 | 8 | 12 | 12 |
| | Total | 71 | 54 | 36 | 36 |
| Comfort | 80 km/h | 18 | - | - | - |
| | 110 km/h | 8 | - | - | - |
| | Total | 26 | - | - | - |

*Table 2.10 Number of braking manoeuvres performed.*

### 2.4.3 Water truck for wet surface

As described earlier, the braking trials were conducted on both dry and wet road surfaces. The wet road surface was achieved with the aid of a water truck, which dispersed water onto the braking section immediately before each braking trial.

Photos of the water truck and wet braking section are shown below.


*Figure 2.3 Roadway made wet using a water truck.*

The water truck carried approx. 12,000 litres of water, which was ejected through an array of nozzles at the front of the vehicle. The water was dispersed as the water truck reversed slowly through the braking section. In this way, the dispersed water was not disturbed by the truck itself. The water was dispersed across a width of approx. 3.2 m, and this was done once immediately before each braking trial.

It was not possible to measure the exact water volume on the road surface for the braking trials. Based on the observed volume of water consumed, the number of trials performed and the dispersal area, the calculated volume dispersed by the truck was 1.3-1.6 litres/$m^2$. If the water could be assumed to remain in situ, this equated to a water membrane of 1.3-1.6 mm on the braking section. Due to the road's cross slope, some of the water would naturally have run off the road again before the trial was conducted. Typically it took a couple of minutes from the water truck dispersing the water until the braking trial was performed.

The same water truck and procedure for water dispersal was used at all the locations for all braking trials on wet road surface.

# 3. Data processing

This chapter explains the different phases in the stopping trajectory along with a description of how data from the braking trials was post-processed and analysed.

## 3.1 Simplified stopping process

In simplified terms, a vehicle's stopping process can be broken down in time into several phases as described in the following:

Reaction time ($t_r$)
The reaction time is the time it takes from when the driver sees/registers an obstacle or situation on the road that requires a reaction, until he has actually reacted and moved his foot from accelerator to brake pedal.

Braking initiation time ($t_a$)
In the instant the brake pedal is touched and pedal pressure increases, the pedal will travel a few cm before the brake "engages". The time it takes from the brake pedal being touched to actual deceleration commencing is referred to here as the braking initiation time. The braking initiation time will typically be in the range of approx. 0.1-0.4 seconds, depending on the car's braking system and the speed at which the brake pedal is depressed.

To max. braking time ($t_{b1}$)
To max. braking time is the time it takes from the brake pedal being touched until the brake pedal reaches its maximum depression, which, depending somewhat on behaviour and the braking system, typically takes 0.3-1.0 sec.

Max. braking time ($t_{b2}$)
The max. braking time is the time it takes from the pedal pressure reaching its maximum depression until braking is complete and the car has been brought to a complete stop.

The process can be illustrated as shown in Figure 3.1 where pedal pressure, deceleration, speed and distance traversed are shown as a function of time over the braking trajectory.

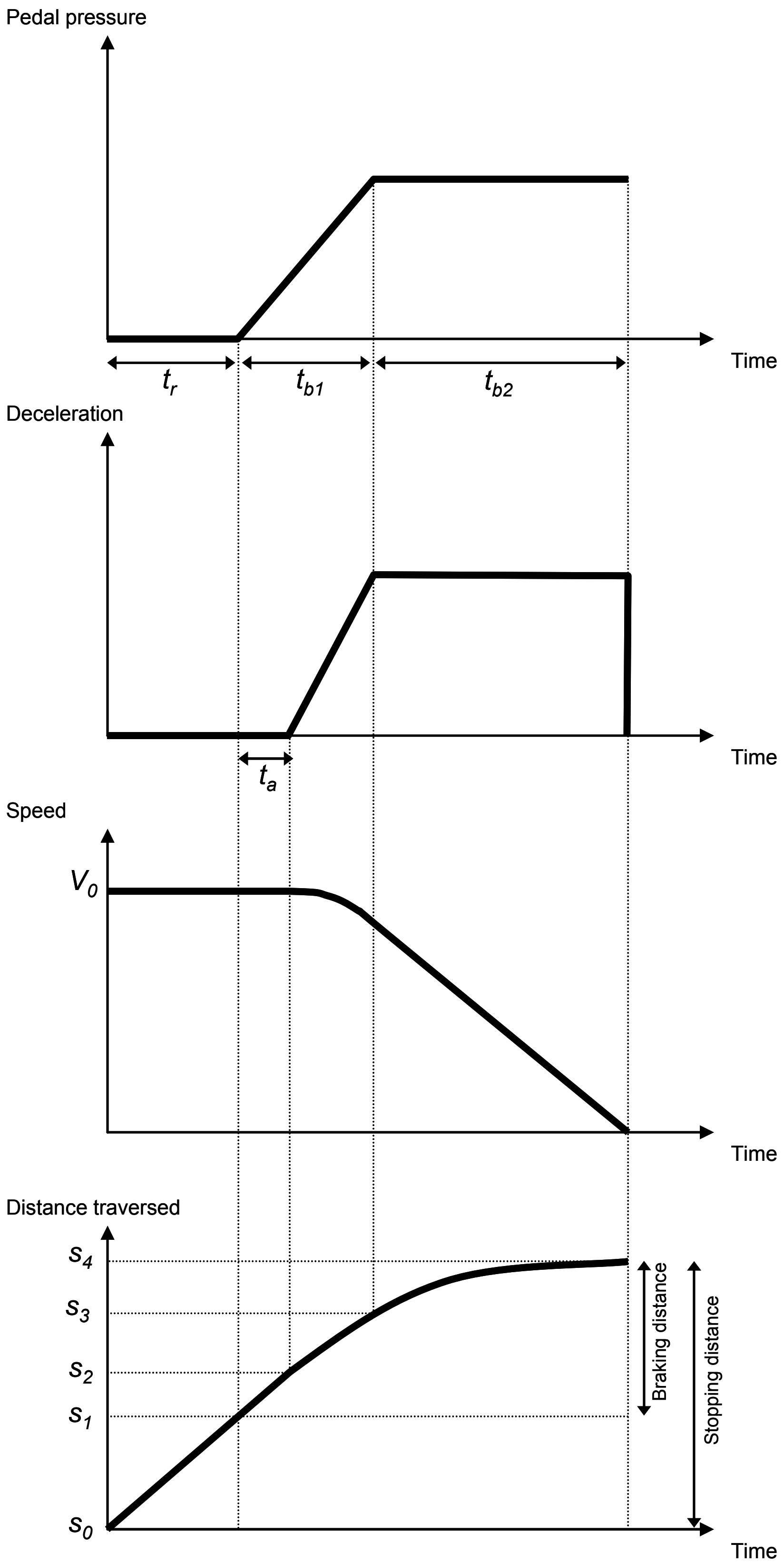



*Figure 3.1 Simplified stopping process*

During the reaction time ($t_r$), the car traverses a distance corresponding to $S_1$-$S_0$.

Distance $S_2$-$S_1$ corresponds to the distance the car traverses from when the pedal is applied and until deceleration itself commences.

Distance S4-$S_1$ is referred to as the braking distance, and is the distance the car traverses from when the brake pedal is applied until the car has come to a complete standstill. This can be termed the behavioural braking distance, since it comprises the time/distance resulting from the braking initiation time.

The purely physical braking distance should in reality be the distance S4-S2, that is, the period in which the car is actually decelerating as a result of brake actuation. A comparison of the measured braking distance applying e.g. theoretical stopping distances (based on the laws of physics) should therefore be based on S4-S2.

In the figure, pedal pressure is assumed to be constant from the maximum level has been attained and until the car comes to a complete standstill. The same applies to the deceleration, which is assumed to be constant in the period. In this way, the speed will be constantly diminishing until the car stops. However, in practice, the braking trajectory is rarely quite so simple. This is due primarily to these factors:

- deceleration starts the instant the accelerator is released (due to rolling resistance, wind resistance, etc.), i.e. even before the brake pedal is touched
- the pedal pressure on the brake typically increases, with cautious braking initially, and as speed is reduced, harder pressure is applied to the brake
- deceleration increases correspondingly over the braking trajectory and is often greatest at speeds of less than 50 km/h.

An example of a recorded braking trail is shown in Figure 3.2. The figure shows the speed, pedal pressure and calculated deceleration as a function of time. The starting speed was 108 km/h. After approx. 61 seconds driving, pressure on the brake pedal is observed, which is gradually increased to approx. 28 kg. Deceleration increases correspondingly and reaches a rate of approx. 9 m/s$^2$. Approx. 3.7 seconds after the brake pedal was actuated, the car has been brought to a complete stop.

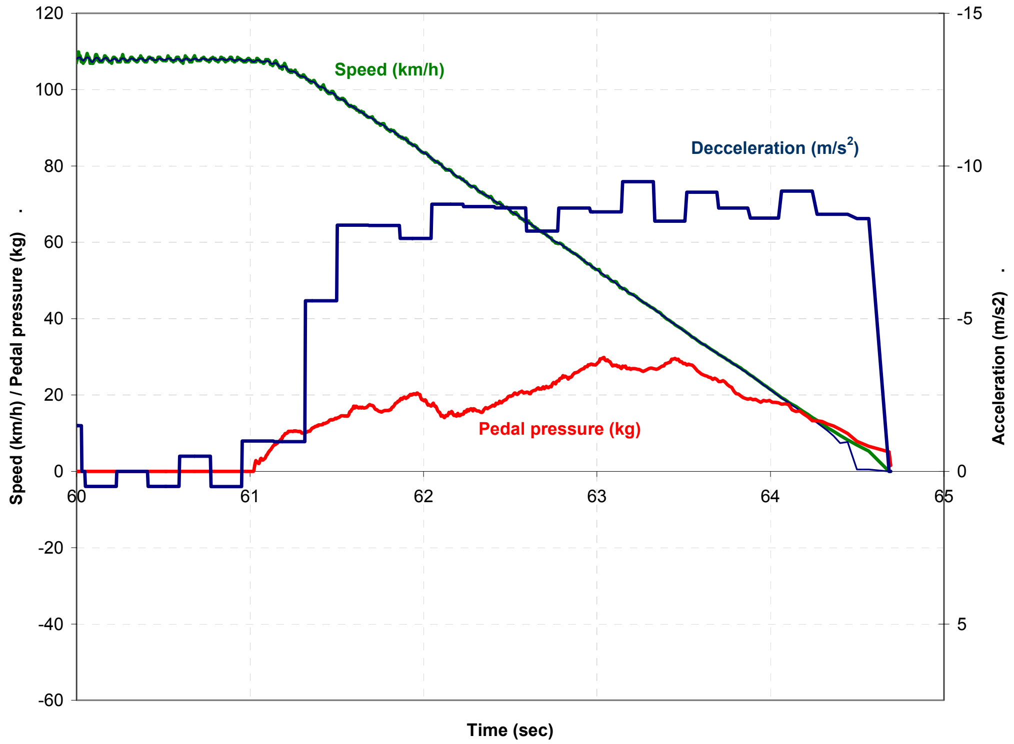



*Figure 3.2 Example of a recorded braking run.*

## 3.2 Description of parameters for use in analyses

In this study, the braking distance was measured from the time the brake pedal was touched until the car had been brought to a complete stop. This braking distance thus equates to distance S4-S1 in Figure 3.1. The measured braking distance is referred to in the following as $L_{brake.}$

In the analysis, the concept $L_{brake\%}$ is used to indicate the percentage difference between $L_{brake}$ for the non professional test driver as compared with $L_{brake}$ for the professional test driver under the same conditions (car, speed, dry/wet, test track). $L_{brake\%}$ is thus used for comparing professional and non professional braking distances. An $L_{brake\%}$ of 30 for example, thus indicates that the non professional test driver has a measured braking distance – $L_{brake}$ – 30% longer than that of the professionals under the same conditions.

### 3.2.1 Correction for initial speed

The test drivers were asked to drive at speeds of 80, 110 or 130 km/h before braking. However, the initial speed before braking was rarely exactly 80, 110 or 130 km/h, so in some analyses, the measured braking distance was corrected using the following formula:

$$L_{brake-corr} = L_{brake-meas} \cdot \frac{V_{desired}^2}{V_{meas}^2}$$

where

$L_{brake-corr}$ = the corrective braking distance
$L_{brake-meas}$ = the measured braking distance during the trial
$V_{desired}$ = the desired speed before braking
$V_{meas}$ = the measured initial speed before braking

The designations $L_{brake80}$, $L_{brake110}$, and $L_{brake130}$ are used hereafter, where:

$L_{brake80}$ designates the corrective braking distance at 80 km/h.
$L_{brake100}$ designates the corrective braking distance at 100 km/h.
$L_{brake130}$ designates the corrective braking distance at 130 km/h.

### 3.2.2 Correction for roadway grade

The roadway grade on test tracks 2 and 3 was measured in the braking section as 0.00, but on test track 1 it was measured as s=0.023. This means that the braking distances obtained on test track 1 are slightly shorter than if they had been obtained on level road. In analyses where measurements are to be cross-compared for the 3 test tracks, it is therefore necessary to correct the measurements from test track 1 so that they are consistent with measurements obtained on the level road.

By using the Danish Road Standards and Guidelines' formula for calculating braking distance (see section 1.1.1) we find that the braking distance from 110 km/h is 159 m on level road, but approx. 11 m shorter where s=0.023.

Measurements of $L_{brake}$ on test track 1 were therefore in some analyses corrected as follows. It is assumed that the deceleration is constant over the entire braking trajectory, which was virtually the case. Acceleration due to gravity will affect the vehicle in the direction of travel with deceleration of 9.81*sin(0.023) = 0.23 $m/s^2$. The actual braking deceleration thus has to be corrected by 0.23 $m/s^2$ to reflect braking on a level road.

A measured $L_{brake}$ of 51.0 m from 105.6 km/h on test track 1 would thus be corrected to 52.4 m, corresponding to braking on level road. The correction is in the order of 2-3%, which is relatively little in relation to the variations otherwise seen in $L_{brake}$.

### 3.2.3 Analyses of speed intervals

Several analyses in this study are based on data from a specific speed interval, e.g., the interval 70-20 km/h. This considers exclusively the subproportion of the braking trajectory that starts when the vehicle is travelling at a speed of 70 km/h, and ends when the vehicle is at a speed of 20 km/h. Data based on a speed interval is interesting in that it offers a ”purer” comparison of different parameters, since the braking trajectory here is less affected by behavioural factors or factors associated with the braking system and braking behaviour at the start of braking.

### 3.2.4 Deceleration

The measured deceleration during breaking is basically calculated using the formula:

$$Dec = \frac{V_1^2 - V_2^2}{2 \cdot (S_1 - S_2)}$$

Where:

$V_1$ and $V_2$ are the start and end speed, respectively (m/sec)
$S_1$ and $S_2$ are respectively the spatial designation (m) for start and end

$Dec_{brake}$ designates the deceleration calculated for the entire braking trajectory, where $V_2$ is obviously equal to 0 and $S_1$-$S_2$ is equal to the braking distance $L_{brake}$

A deceleration calculated for a speed interval, e.g. 70 km/h to 20 km/h, is referred to as $Dec_{70\text{-}20}$

### 3.2.5 Pressure on the brake pedal

Throughout the braking trail, pressure on the brake pedal is measured and expressed in kg. In the analyses, the average pressure on the brake pedal is expressed either for the entire braking trajectory or expressed as a speed interval.

$P_{brake}$ designates the average pressure (kg) on the brake pedal over the entire braking trajectory.

$P_{70\text{-}20}$ designates the average pressure (kg) on the brake pedal in the speed interval 70 km/h to 20 km/h.

T-Pedal$_{>10kg}$ designates the time elapsing from when the brake pedal is applied until the pressure on the brake pedal exceeds 10 kg.

### 3.3 Data omissions

Unfortunately, some braking trials had to be omitted from the subsequent analysis, as the data proved to be unusable. This was the case in a series of 12 measurements for example, in which the measurement equipment for inexplicable reasons lost its calibration. Consequently, data from a measurement series involving professional test drivers on test track 3 (Værløse) in Car 2 regrettably had to be scrapped. Instead, the values for lowest braking distance measured, in Car 2, among the non professional test drivers, was used as a ”professional” measurement. Data from the professionals in Car 1 on test track 3 (Værløse) were not defective and were thus included in the analyses.

Some braking trials were scrapped in instances where the test driver forgot to press the start button or pressed the stop button before the trial was complete. In a few instances, trial drivers kept their foot on the brake for a long time before actually braking. In these instances it was difficult to determine precisely when braking started, and the measurement was therefore scrapped.

Out of a total of 197 emergency stops, 25 measurements were thus omitted. Out of 26 comfort braking manoeuvres, 3 measurements were omitted.

# 4. Findings

In this chapter, the findings obtained from the measurement programme will be presented.

## 4.1 Braking distance in emergency stops

In this section, we deal with the measured $L_{brake}$ for both professional and non professionals test drivers.

Figure 4.1 shows the measured braking distances ($L_{brake}$) for professional test drivers on test track 1 near Holbæk, here by car and dry/wet road. Each point represents a single measurement. A best fit is also shown in the figure.

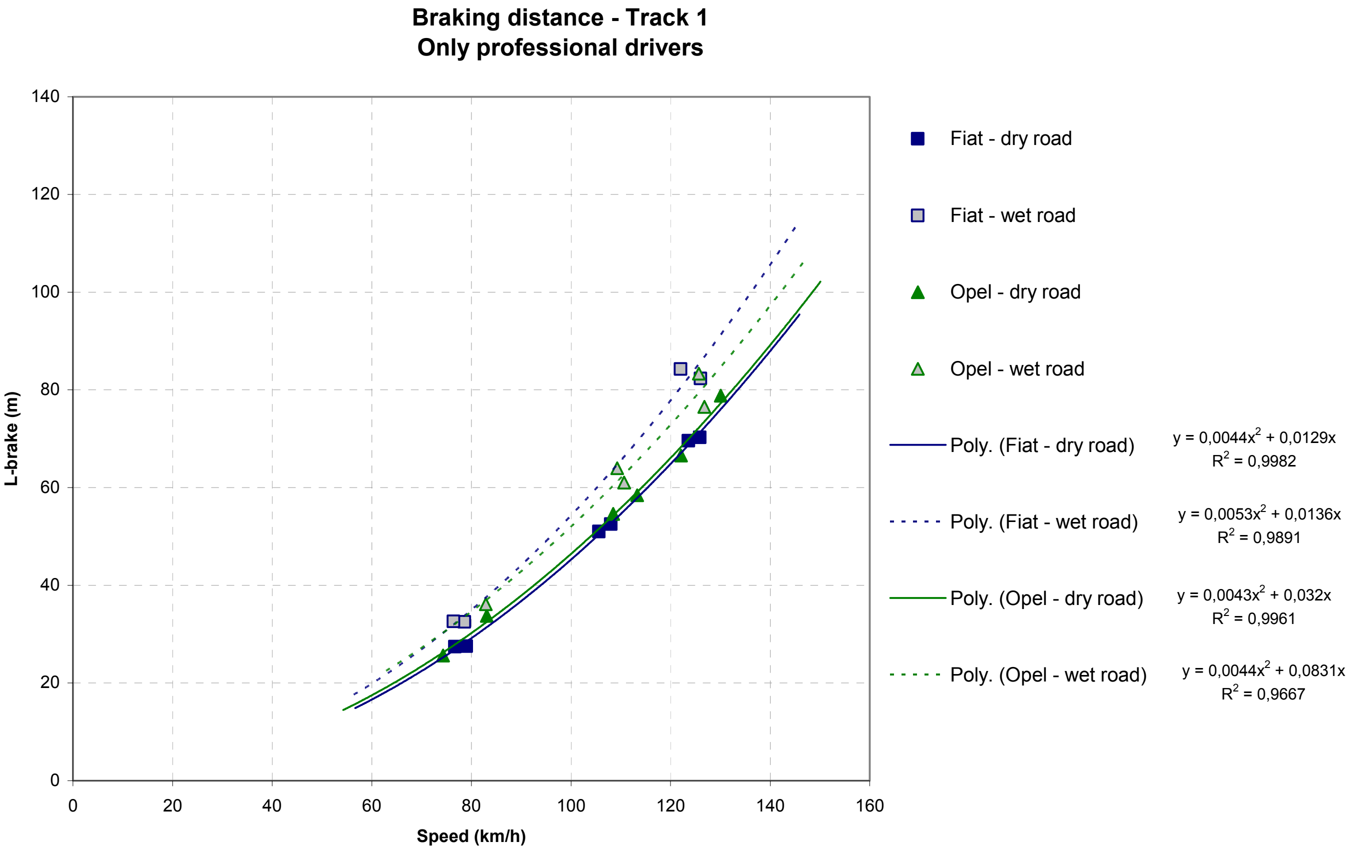



*Figure 4.1 Braking distance ($L_{brake}$) for professional test drivers at test track 1 - Holbæk.*

As illustrated, there is scarcely any difference between Car 1 (Fiat) and Car 2 (Opel) on dry road. Both cars have longer braking distances on wet road compared with dry road. The difference between wet and dry road is greatest for Car 1 (Fiat).

Figure 4.2 shows the measured braking distances ($L_{brake}$) for professional test drivers on test track 2 near Odense, here by car and dry/wet road. Each point represents a single measurement. A best fit is also shown in the figure. As illustrated, there is very little difference between the two cars. The longest braking distances recorded were for wet road.

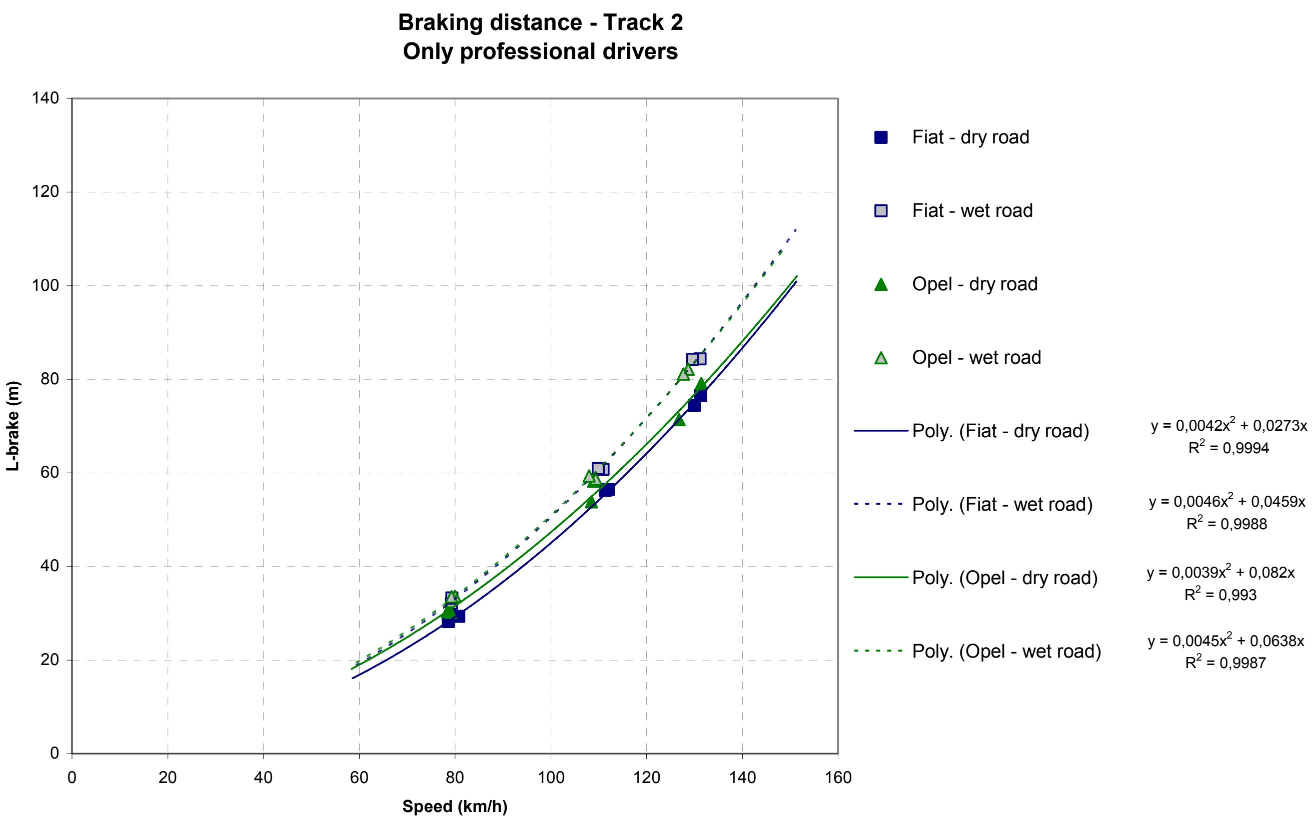



*Figure 4.2 Braking distance ($L_{brake}$) for professional test drivers at test track 2 - Odense.*

Figure 4.3 shows the measured braking distances ($L_{brake}$) for professional test subjects on test track 3 near Værløse, here by car and dry/wet road. Each point represents a single measurement. A best fit is also shown in the figure. As illustrated, there is little difference between the cars, and the difference between wet and dry road is also small.

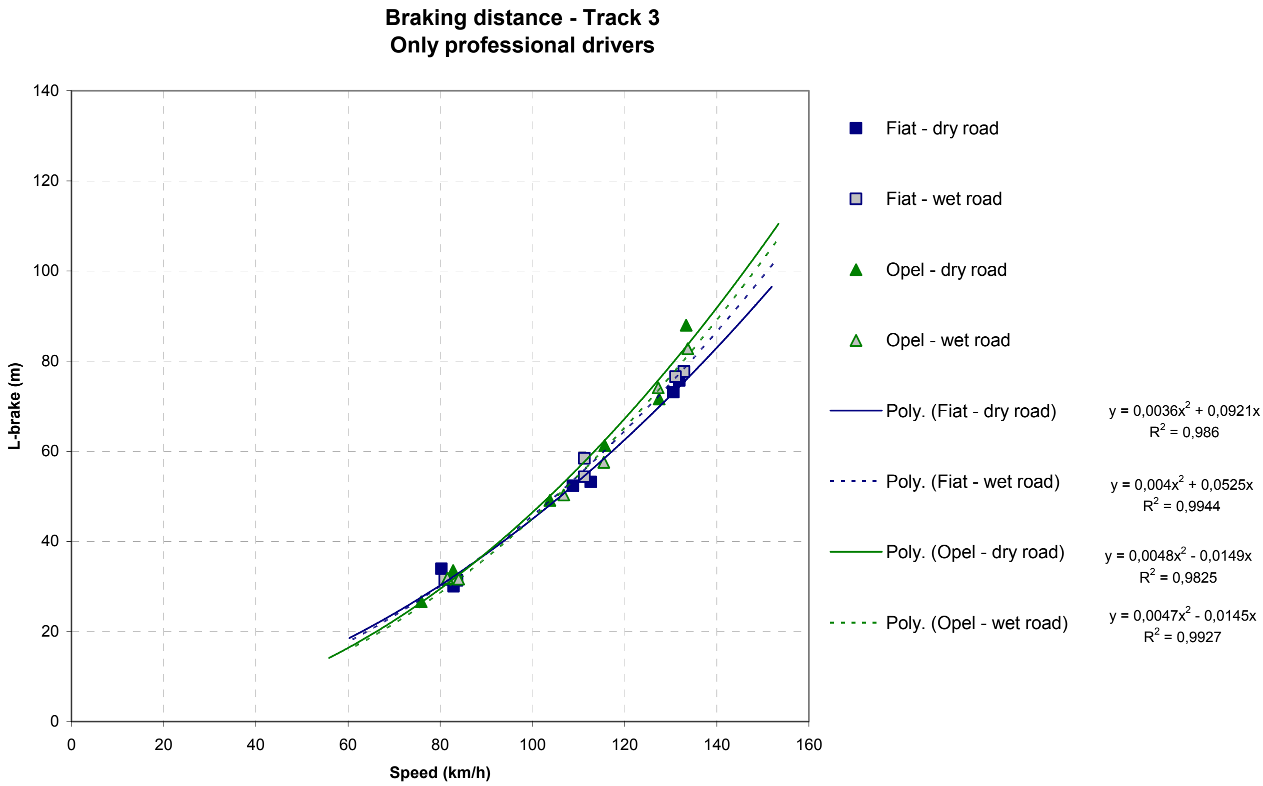



*Figure 4.3 Braking distance ($L_{brake}$) for professional test drivers at test track 3 - Værløse.*

The average braking distances for 80, 110 and 130 km/h on the three test tracks are shown in Table 4.1 (based on regression lines in the figure). Car 1 and Car 2 values are combined. As will be seen, the difference in $L_{brake}$ on dry road is negligible, but for wet road is somewhat larger.

| | 1 - Holbæk | | 2 - Odense | | 3 – Værløse | |
|---|---|---|---|---|---|---|
| **Speed** | **dry** | **wet** | **dry** | **wet** | **dry** | **wet** |
| 80 km/h | 30 m | 35 m | 30 m | 34 m | 30 m | 29 m |
| 110 km/h | 55 m | 64 m | 55 m | 61 m | 55 m | 55 m |
| 130 km/h | 76 m | 88 m | 76 m | 84 m | 76 m | 76 m |

*Table 4.1 Average $L_{brake}$ by speed, test track and dry/wet road surface (professional test drivers only).*

Figures 4.4 – 4.6 illustrate $L_{brake}$ for the non professional test drivers compared with the professionals for each of the 3 test tracks, by dry and wet road. The fully-traced lines are based on the professionals' measurements, while each point represents a non professional test driver.

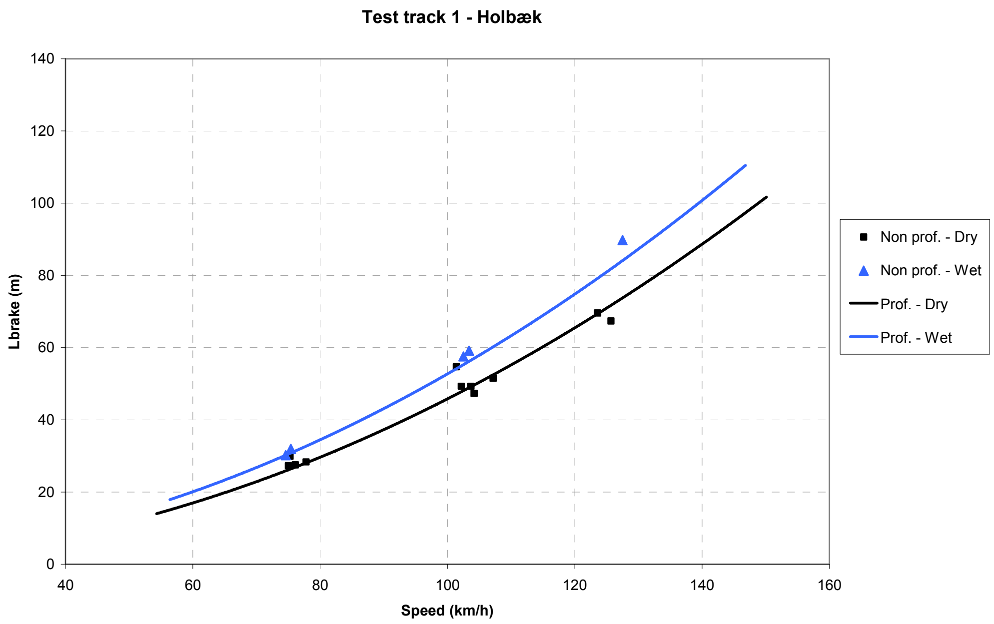



*Figure 4.4 $L_{brake}$ for non professional test drivers compared with professionals. Test track 1 – Holbæk, by dry and wet roadway.*

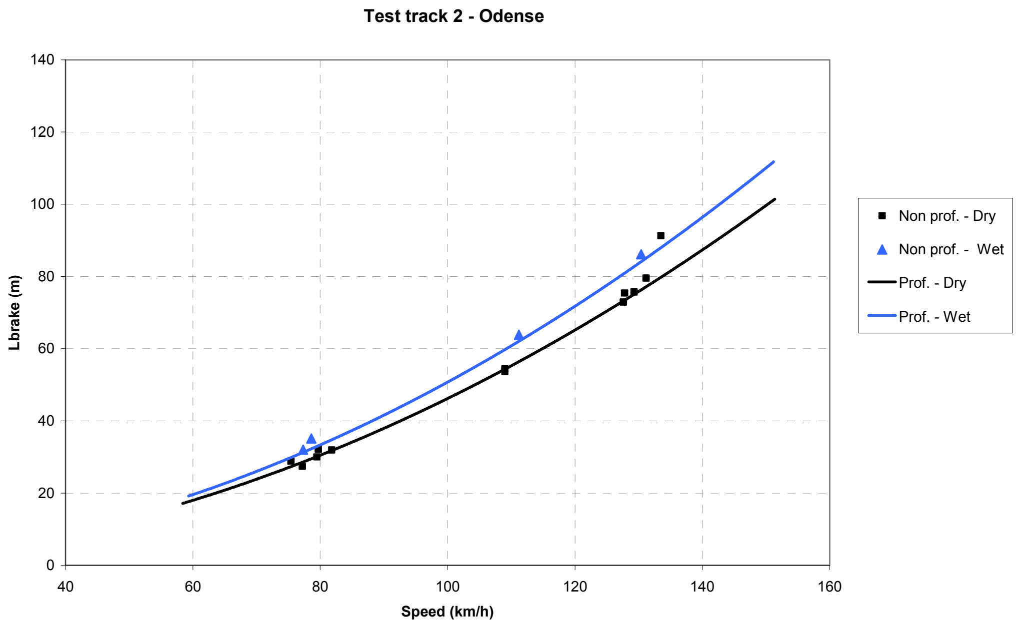



*Figure 4.5 $L_{brake}$ for non professional test drivers compared with professionals. Test track 2 – Odense, by dry and wet roadway.*

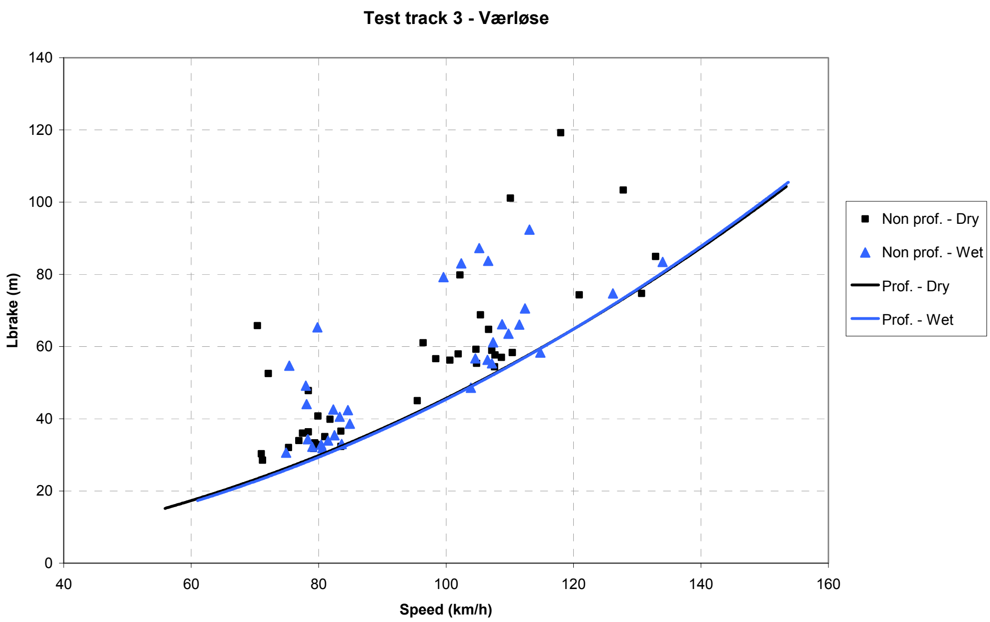



*Figure 4.6 $L_{brake}$ for non professional test drivers compared with professionals. Test track 3 – Værløse, by dry and wet roadway.*

For test tracks 1 and 2, there is no substantial difference in $L_{brake}$, when we compare professional and non professional test drivers. However, here the basis for comparison is modest. For test track 3 (Værløse), the number of non professional test drivers is largest, and this then offers a good impression of the variation in $L_{brake}$ among the non professional test drivers. By far the majority of non professional test drives have an $L_{brake}$ that is a good deal longer than the professionals'.

The findings for all the test tracks can also be illustrated as shown in Figure 4.7. This shows the average $L_{brake80}$, $L_{brake110}$ and $L_{brake130}$, by dry/wet road for the professional and non professional test drivers. Besides the average values, the 15% and 85% fractiles are also expressed.

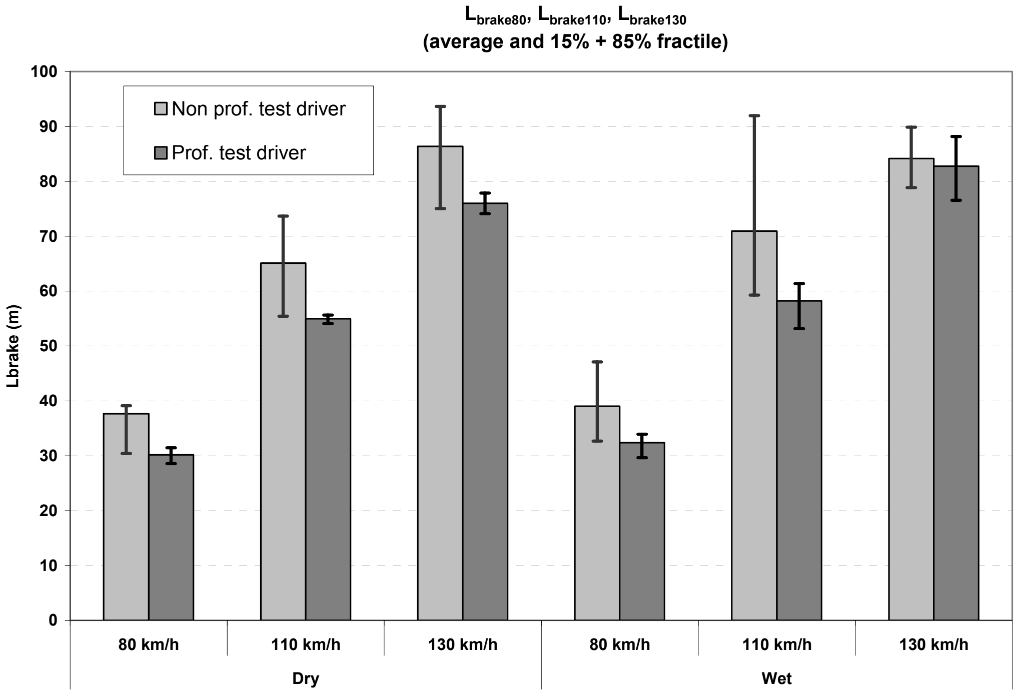



*Figure 4.7 Average values for $L_{brake}$ for professional and non professional test drivers.*

As illustrated, the average $L_{brake}$ for non professional test drivers is greater than the professionals' for all speeds and dry/wet conditions. At the same time, we see a larger spread (here expressed as the difference between the 15 and 85% fractile) for the non professional test drivers. In addition, we find that higher speed produces higher spread for the non professional test drivers. This applies as long as we discount 130 km/h on wet road, which comprises only few recordings. It should be noted that measurements of 130 km/h for the non professional test drivers is based only on those drivers who were sufficiently confident in performing the manoeuvre, which means that these cannot be regarded as being representative of all test drivers.

A more detailed analysis of $L_{brake}$ for the non professional test drivers in relation to the professionals was also carried out. This was done by calculating $L_{brake\%}$, i.e. the percentage difference in $L_{brake}$ for the non professional test driver in relation to $L_{brake}$ for the professional under the same conditions (speed, road surface, test track and car). Overall, the $L_{brake\%}$ is in the order of 20-25%, but the figures hold great variation, as will be discussed in the following. All the measurements at 130 km/h were omitted as they were skewed in their representation of non professional test drivers.

Figure 4.8 shows the individual test subjects' mean value for $L_{brake\%}$. Besides, the mean, the min. and max. values are show. The majority of the test drivers have an $L_{brake\%}$ that averages less than 20%. Several test drivers brake on a par with the professionals, and some even have minimum values that are better than those of the professionals. But there are also test drivers whose average $L_{brake\%}$ is more than 40-50%, and in some cases (max values) exceeds 100% - that is, double the $L_{brake}$ of the professionals.

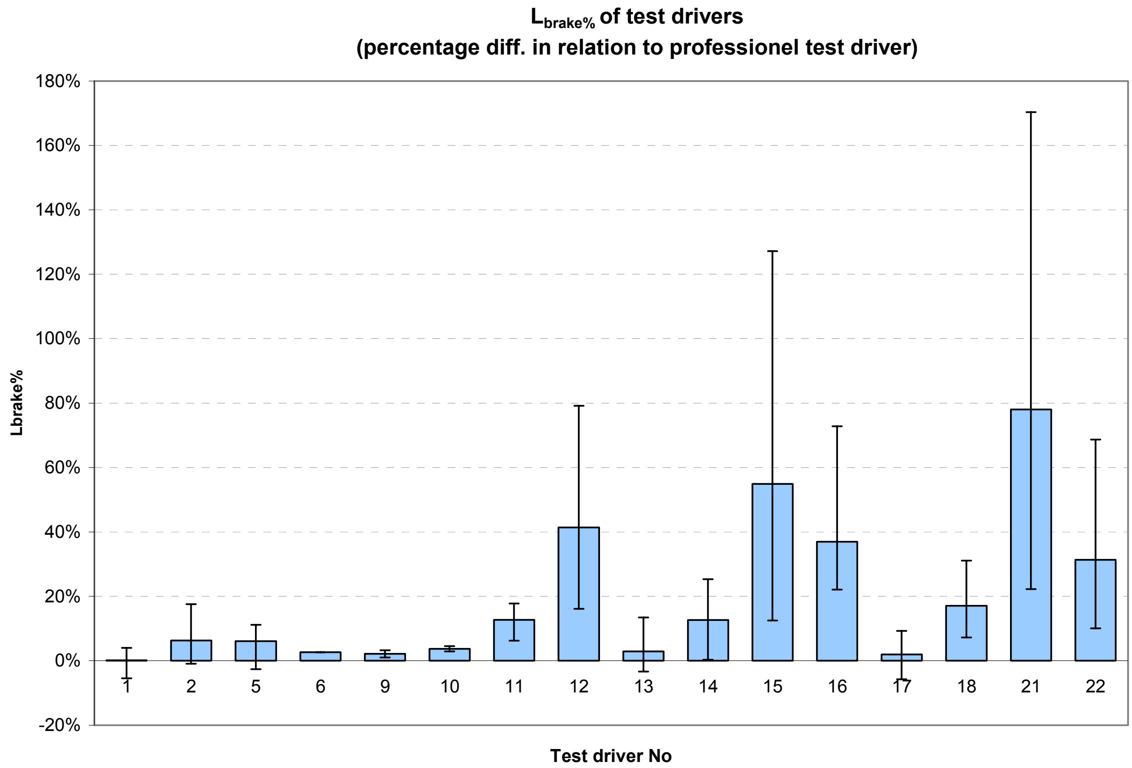



*Figure 4.8 $L_{brake\%}$ for non professional test drivers, expressed as a mean, min. and max. value.*

If we look at the recorded braking distances on wet road at 80 and 110 km/h in isolation, the $L_{brake\%}$ breaks down as shown in Table 4.2. For 14% of all the recorded braking distances on wet road, the $L_{brake\%}$ is negative (i.e. shorter than the professionals'); for 29% the $L_{brake\%}$ is between 0-10, while for 22% the $L_{brake\%}$ is 10-20. By far the majority (80%) of the braking distances have an $L_{brake\%}$ that is less than or equal to 30.

| $L_{brake\%}$ | -10–0 | 0-10 | 10-20 | 20-30 | 30-40 | 40-50 | > 50 | Total |
|---|---|---|---|---|---|---|---|---|
| Number | 13 | 28 | 21 | 14 | 4 | 1 | 13 | 95 |
| % | 14% | 29% | 22% | 15% | 4% | 1% | 14% | 100% |

*Table 4.2. Distribution of $L_{brake\%}$ for wet road at 80 and 110 km/h.*

Table 4.3 shows the $L_{brake\%}$ expressed by speed, dry/wet road and car 1 and car 2. The difference is greatest on wet road and greatest in car 2 (Opel). In addition, a greater difference is seen at 80 km/h as compared with 110 km/h, which can perhaps be explained by the sequence in which the measurements were obtained (see later). Only results for those test drivers who drove both car 1 and car 2 under the same conditions are included in the table.

| | | Car | | |
|---|---|---|---|---|
| Speed | Dry/wet | 1 – Fiat | 2 – Opel | Average |
| 80 | dry | 26 | 24 | 25 |
| | wet | 24 | 29 | 27 |
| 110 | dry | 18 | 17 | 17 |
| | wet | 20 | 30 | 25 |
| Average | | 22 | 25 | 23 |

*Table 4.3 $L_{brake\%}$ expressed by car, speed and wet/dry.*

For the test drivers included in the measurements, men in the age-group 25-50 have the lowest $L_{brake\%}$ (10%). By comparison, women in the same age-group have an $L_{brake\%}$ of 19%. For age-group 50-70 (all men), the $L_{brake\%}$ overall is 41%. The number of test drivers in the study is however, modest, which means that the figures in Table 4.4 barely can be used to generalise.

| | | Age / Gender | | | Average |
|---|---|---|---|---|---|
| | | 25-50 years | | 51-70 years | |
| Speed | Dry/wet | F | M | M | |
| 80 | dry | 17 | 6 | 55 | 25 |
| | wet | 21 | 15 | 48 | 28 |
| 110 | dry | 19 | 3 | 27 | 18 |
| | wet | 20 | 18 | 33 | 24 |
| Average | | 19 | 10 | 41 | 24 |

*Table 4.4 $L_{brake\%}$, by age, gender as well as speed and wet/dry road.*

One of the parameters responsible for great variation in $L_{brake\%}$, is the number of braking trials carried out. The more times the test drivers carried out the manoeuvre, the more effective their braking became. Figure 4.9 shows the $L_{brake\%}$ as a function of the number of braking trials carried out. In the 1st braking trial, which was always at 80 km/h on dry road, the $L_{brake\%}$ averages 23%. In subsequent trials, the $L_{brake\%}$ increases, which is presumably due to the fact that these trials are at higher speeds or on wet road. After 5-6 trials, the majority of test drivers have tried both dry and wet road at different speeds, and begin to feel more confident about the manoeuvre, and the $L_{brake\%}$ falls. Even from the 1st braking trial, the best 15% of the test drivers had a very low $L_{brake\%}$. By far the majority of test drivers carried out 8 braking trials, while a few (typically those who also performed them at 130 km/h) carried out 10-12 braking trials. These drivers generally had a low $L_{brake\%}$ in all braking trials.

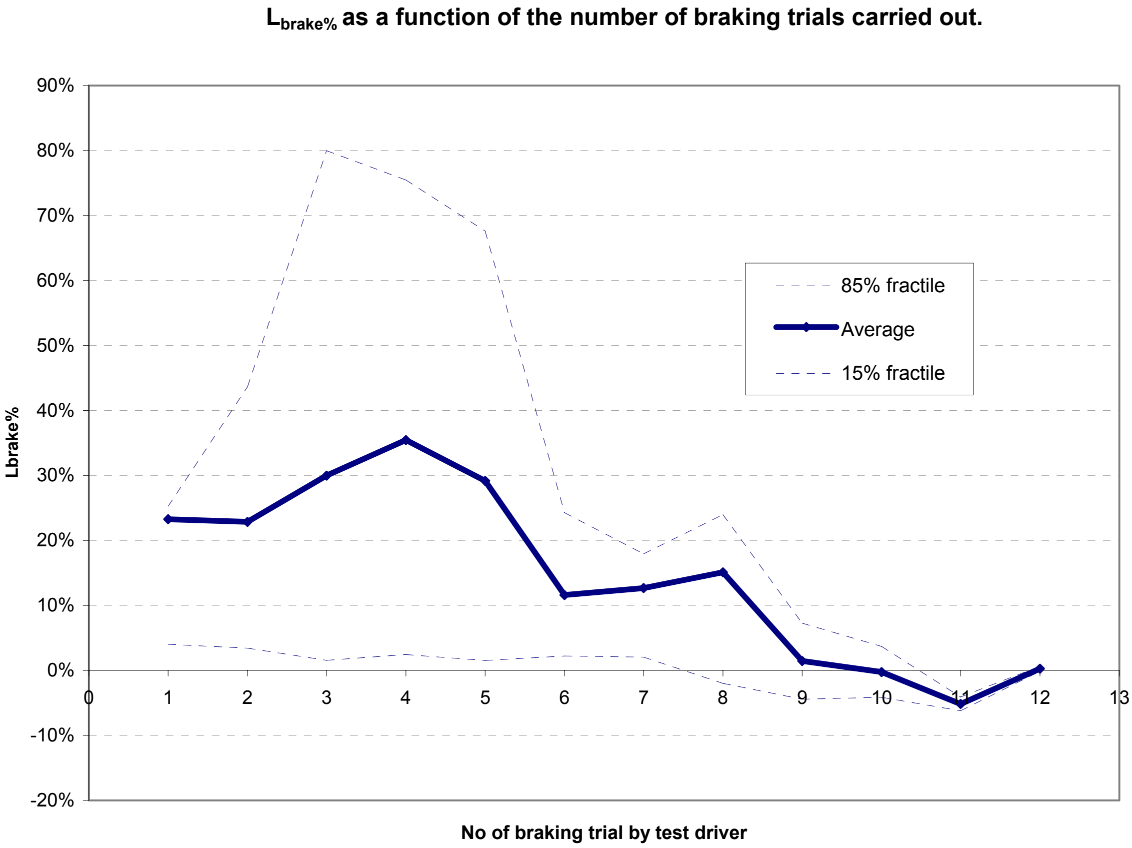



*Figure 4.9 $L_{brake\%}$ as a function of the number of braking trials carried out.*

Appendix 5 provides a complete overview of all the measured breaking distances in terms of $L_{brake}$ and $L_{brake\%}$, by test drivers and braking trial number.

## 4.2 Deceleration in emergency stops

Table 4.5 shows the average deceleration for the professional test drivers, based on the entire braking run ($Dec_{brake}$). Overall, the difference between the two cars was small. $Dec_{brake}$ was measured as 8.4 m/s$^2$ for dry road and 7.9 m/s$^2$ for wet road. The difference between the 3 test tracks must be attributable to differences in friction (discussed later). Further, higher deceleration values are seen at higher speeds, which is due to the fact that braking was more effective at higher speeds, since the braking initiation time accounts for a smaller proportion of the total braking time at higher speeds.

| | | Dry | | Dry Av. | Wet | | Wet Av. |
|---|---|---|---|---|---|---|---|
| | | Fiat | Opel | | Fiat | Opel | |
| | 80 | 8.5 | 8.1 | 8.3 | 7.1 | 7.3 | 7.2 |
| 1 – Holbæk | 110 | 8.5 | 8.4 | 8.4 | - | 7.5 | 7.5 |
| | 130 | 8.6 | 8.5 | 8.5 | 7.1 | 7.7 | 7.4 |
| | 80 | 8.5 | 7.9 | 8.2 | 7.4 | 7.3 | 7.4 |
| 2 – Odense | 110 | 8.6 | 8.1 | 8.3 | 7.7 | 7.7 | 7.7 |
| | 130 | 8.7 | 8.5 | 8.6 | 7.8 | 7.8 | 7.8 |
| | 80 | 8.1 | 8.1 | 8.1 | 8.3 | 8.3 | 8.3 |
| 3 - Værløse | 110 | 9.0 | 8.4 | 8.7 | 8.5 | 8.8 | 8.7 |
| | 130 | 8.9 | 8.3 | 8.6 | 8.7 | 8.4 | 8.5 |
| Average | | 8.6 | 8.3 | 8.4 | 7.8 | 7.9 | 7.9 |

*Table 4.5 Average deceleration values ($m/s^2$) based on the entire braking run. Professional test drivers only.*

Table.4.6 shows the average deceleration values for the non professional test drivers, based on the entire braking run. The values are on average approx. 10% less than those of the professionals. There is only a slight difference between the two cars and the difference between wet and dry road is between 0.1 – 1.0 $m/s^2$.

| | | Dry | | Dry Av. | Wet | | Wet Av. |
|---|---|---|---|---|---|---|---|
| | | Fiat | Opel | | Fiat | Opel | |
| | 80 | 8.0 | 7.8 | 7.9 | 7.0 | - | 7.0 |
| 1 – Holbæk | 110 | 7.8 | 8.5 | 8.3 | 7.0 | - | 7.0 |
| | 130 | - | 8.7 | 8.7 | 7.0 | - | 7.0 |
| | 80 | 8.0 | 7.9 | 8.0 | 7.0 | - | 7.0 |
| 2 – Odense | 110 | 8.5 | - | 8.5 | 7.5 | - | 7.5 |
| | 130 | 8.2 | 8.5 | 8.3 | 7.6 | - | 7.6 |
| | 80 | 6.6 | 6.6 | 6.6 | 6.9 | 6.5 | 6.7 |
| 3 - Værløse | 110 | 7.3 | 6.9 | 7.1 | 7.4 | 6.7 | 7.0 |
| | 130 | 8.4 | 6.9 | 7.4 | 8.3 | 8.4 | 8.3 |
| Total | | 7.5 | 7.2 | 7.4 | 7.2 | 6.8 | 7.0 |

*Table 4.6 Average deceleration values ($m/s^2$) based on the entire braking run. Non professional test drivers only.*

Figure 4.10 shows the average deceleration values for speed intervals 120-100, 100-70, 70-50 and 50-30 km/h for the professional test drivers. The deceleration values are generally higher on dry compared with wet road. Furthermore, the deceleration values are higher within the low speed intervals compared with the high speed intervals. On dry road, $Dec_{50-30}$ was approx. 9.5 m/s$^2$, while $Dec_{100-70}$ was approx. 9.1 m/s$^2$. In addition, there is some difference in the measured deceleration values depending on whether braking started from 130, 110 or 80 km/h. For example, braking from 80 km/h has the poorest $Dec_{50-30}$, while breaking at 110 or 130 km/h is more effective in the shape of higher deceleration values. The reason for this may be that an extended braking trajectory, from e.g. 130 km/h, raises tyre and brake temperature, which in turn boosts braking capability.

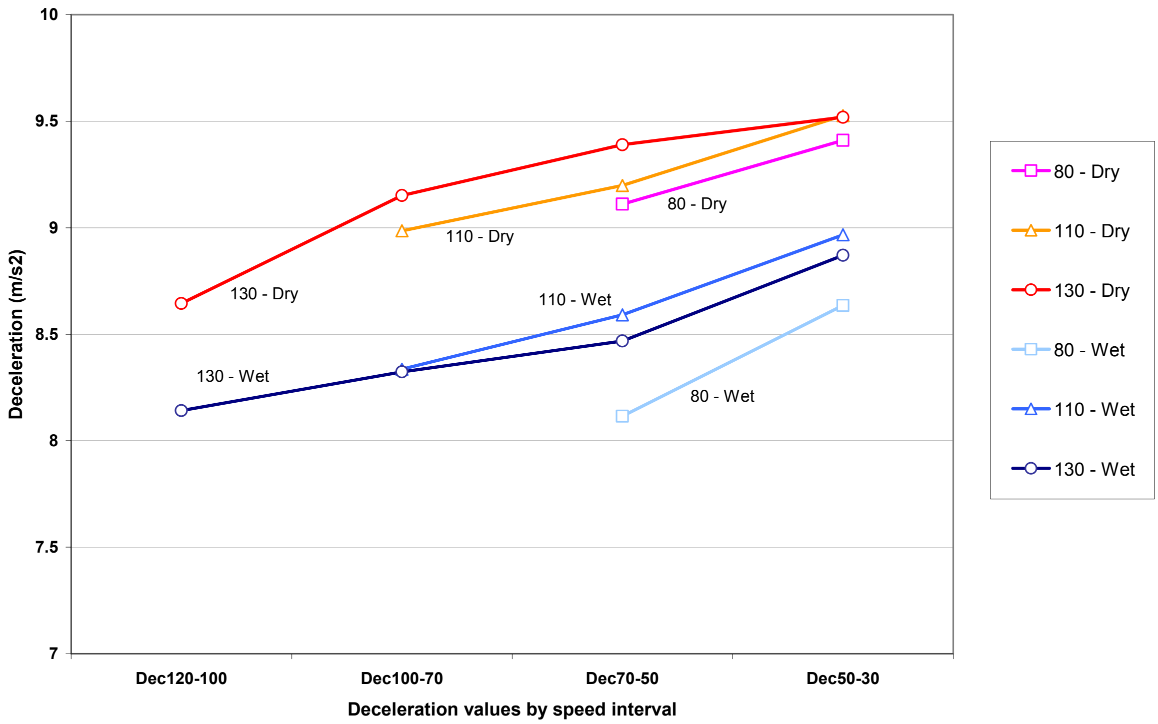



*Figure 4.10 Average deceleration values (m/s$^2$) on dry and wet road, by speed intervals and initial speed. Professional test drivers only.*

A comparison of the professional and non professional test drivers and their deceleration values within different speed intervals is presented in the following figures 4.11 - 4.12. These data derive only from test track 3 – Værløse where there were the most non professional test drivers. For the non professional test drivers, the mean value and 15 and 85% fractiles are shown in the figure.

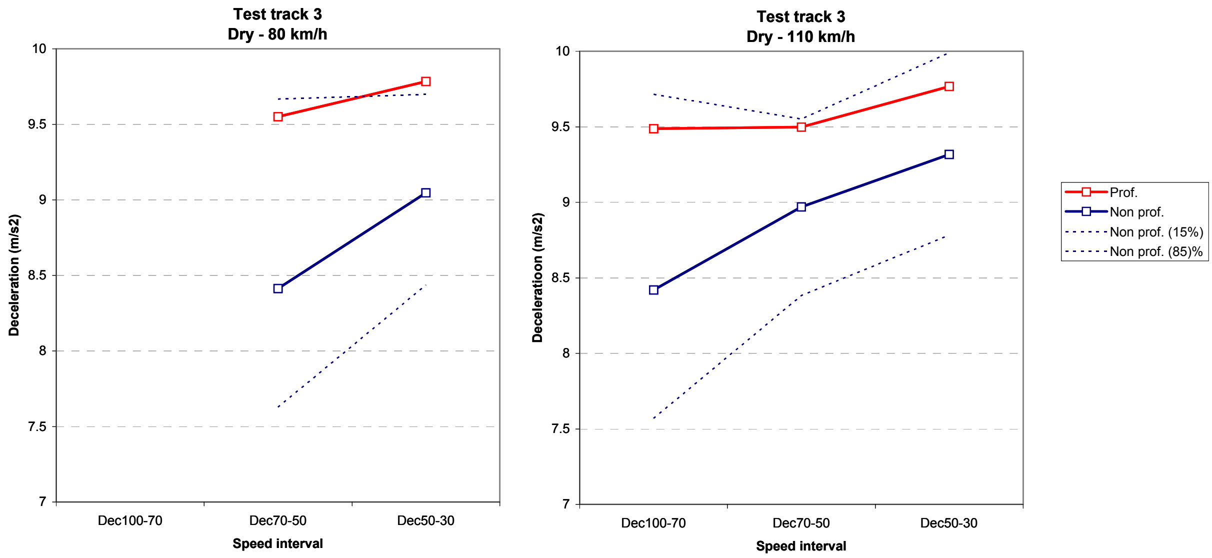



*Figure 4.11 Measured deceleration values (m/s²) from Værløse dry road, by different speed intervals, non prof. and prof. test drivers and initial speed.*

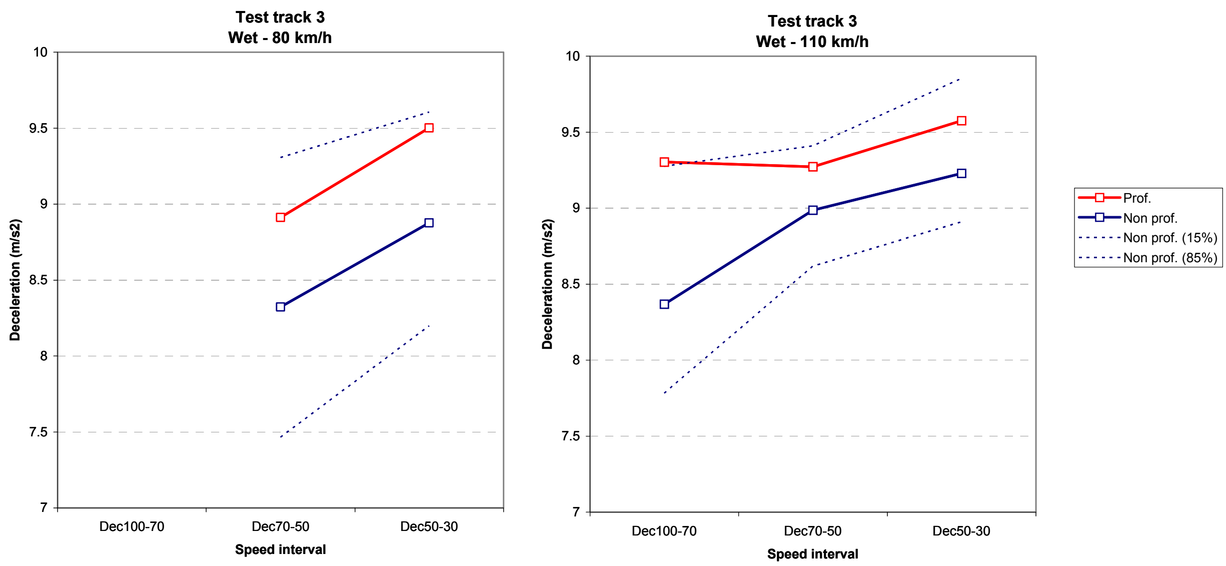



*Figure 4.12 Measured deceleration values (m/s²) from Værløse wet road, by different speed intervals, non prof. and prof. test drivers and original speed.*

As shown in Figure 4.11, the measured values for $Dec_{100-70}$, $Dec_{70-50}$ and $Dec_{50-20}$ are somewhat lower for the non professional test drivers as compared with the professionals, especially for the highest speed intervals. This indicates that it is particularly at the start of the braking trajectory (at the high speeds) that the non professionals test drivers are less effective at braking as compared with the professionals. However, the 15% fractile of the non professional test drivers is generally on a par with the professionals. Figure 4.12 shows the corresponding values from Værløse on wet road. The same trends as on dry road reoccur here.

## 4.3 Brake pedal pressure during braking

As mentioned earlier, the pressure on the brake pedal was measured during the braking trail. In the following, we describe the differences in brake pedal pressure that were observed, and what significance these have for factors such as braking distance and deceleration.

On average, $P_{brake}$ (the average pressure on the brake pedal for the whole of the braking run) was recorded as 34.8 kg for the non professional test drivers and 74.0 kg for the professionals.

And on average, T-$Pedal_{>10kg}$ (the time it takes from the pedal being touched until the pressure reaches at least 10 kg), was recorded as 0.83 sec. for the non professional test drivers and 0.05 sec. for the professionals.

Not surprisingly, the non professional test driver are slower to press the pedal "hard", and overall, pressed the brake only approx. half as firmly as the professionals.

However, there is large variation from one test driver to the next. The best of the non professional test drivers brake just as fast and firmly as the professionals, while others are a great deal more tentative. Table 4.7 shows the average T-$Pedal_{>10kg}$ values for the non professional test drivers. On wet road and at high speeds, the values are highest. This may be interpreted as being situations in which the test drivers brake most tentatively. The table also indicates that Car 2 (Opel) generally had higher T-$Pedal_{>10kg}$ values than Car 1 (Fiat). The same difference is not seen in the professional test subjects. There is thus either a difference in the cars' braking system, which affects the non professional test drivers, or it is an expression of a behavioural difference that means that the pressure on the brake pedal in Car 2 (Opel) does not achieve pressure of min. 10 kg until approx. 0.2-0.3 secs later than in Car 1 (Fiat).

| | Dry | | Wet | | Total |
|---|---|---|---|---|---|
| Car | 80 | 110 | 80 | 110 | |
| Car 1 – Fiat | 0.63 | 0.67 | 0.72 | 0.88 | 0.71 |
| Car 2 – Opel | 0.76 | 0.95 | 0.94 | 1.26 | 0.96 |
| Total | 0.70 | 0.80 | 0.81 | 1.07 | 0.83 |

*Table 4.7 Average T-$Pedal_{>10kg}$ values (sec.) for non professional test subjects.*

Figure 4.13 shows examples of a series of braking runs, in which brake pedal pressure is expressed as a function of time. The figure is based on 19 emergency stops from 110 km/h on wet road on test track 3 – Værløse.

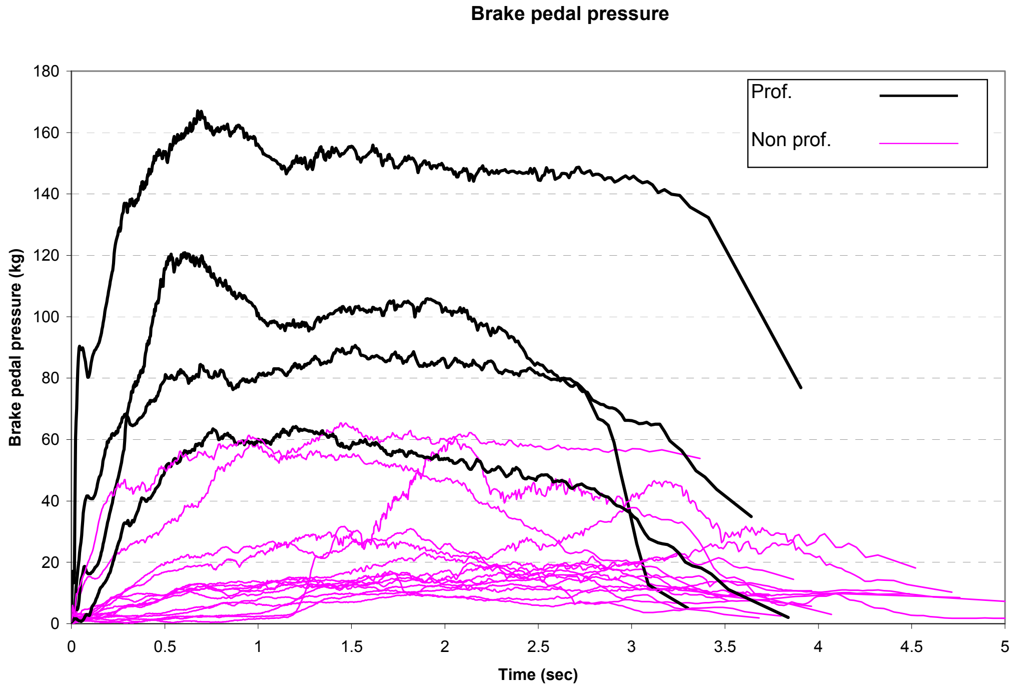



*Figure 4.13 Examples of brake pedal pressure during the braking trajectory by professional and non professional. 110 km/h only, wet road on test track 3 – Værløse.*

The examples in Figure 4.13 reveal that the non professional test drivers' pressure on the brake pedal typically increases slowly up to 15-20 kg, while the professionals achieve faster and firmer pressure on the brake pedal, which in one instance exceeds 160 kg.

The correlation between the measured deceleration and the pressure on the brake pedal was investigated. Figures 4.14 and 4.15 show $Dec_{120-100}$, $Dec_{100-70}$, $Dec_{70-50}$ and $Dec_{50-30}$ as a function of the average pressure on the pedal within the same speed interval. The figures are based on both professional and non professional test subjects.

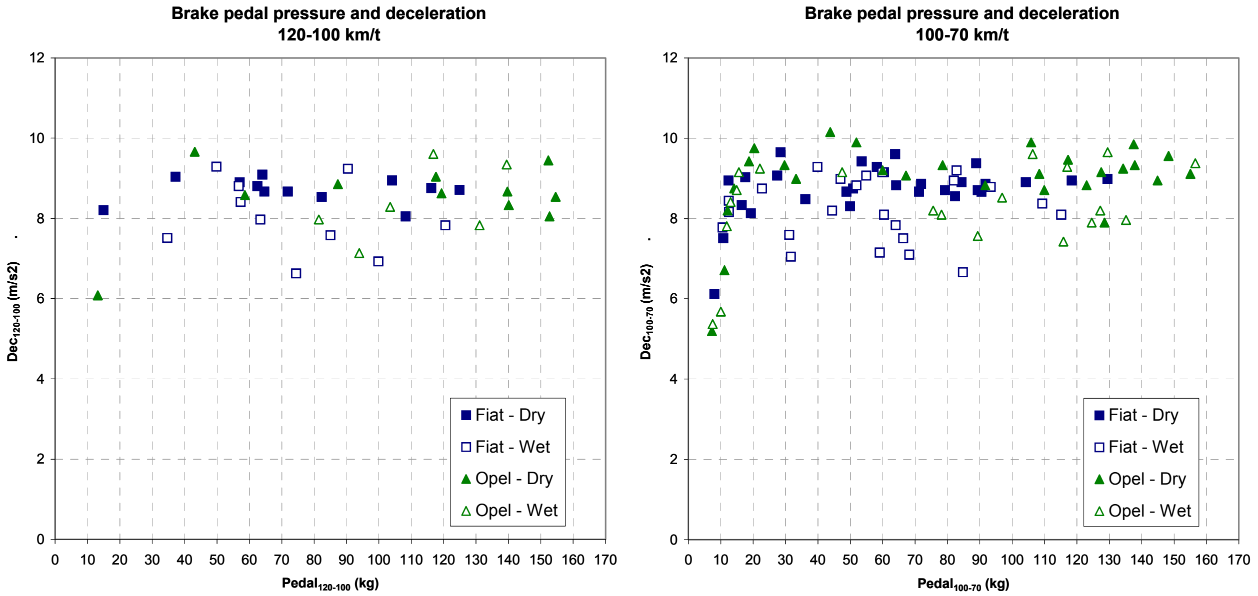



*Figure 4.14 Correlation between deceleration and pressure on the brake pedal within the speed intervals of 120-100 km/h and 100-70 km/h.*

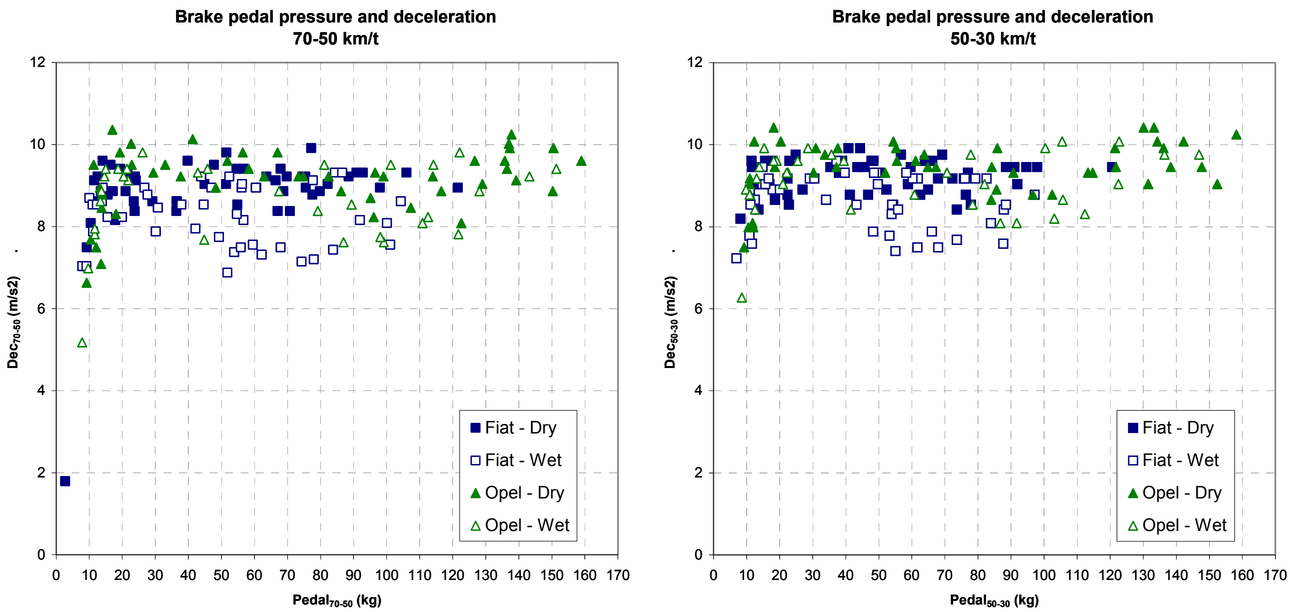



*Figure 4.15 Correlation between deceleration and pressure on the brake pedal within the speed intervals of 70-50 km/h and 50-30 km/h.*

It is the case for all four speed intervals that deceleration drops once the pressure on the brake pedal drops below approx. 10-15 kg. However, there is no consistent difference in deceleration once the pressure exceeds 10-15 kg. Some test drivers applied pressure of up to 150 kg on the brake pedal, but the measured deceleration here is basically the same as if they had applied only 20 kg pressure. This is presumably due to the fact that once the ABS has been activated, additional pressure on the brake pedal does not increase the deceleration.

In sum, an optimal emergency stop with maximum deceleration is achieved through fast and firm pressure on the brake pedal of at least 10-15 kg. The pressure on the brake pedal must then be sustained until the vehicle has come to a complete stop.

## 4.4 Friction and braking distances

As discussed earlier, the road surface friction was measured on the three test tracks. In the following, we compare road surface friction with the recorded braking distances and deceleration values. Only the results from the professional test drivers are included in the comparisons.

It should be noted that the recorded friction values were measured on a wet surface (standard method). The comparisons of braking distance on a dry road surface with recorded friction on a wet road surface involve 2 different states and there is thus not necessarily any immediate correlation.

Figure 4.16 shows the measured braking distances ($L_{brake}$) for 80, 110 and 130 km/h, respectively, on dry and wet road with different friction values. $L_{brake}$ is corrected here for the test track's roadway grade. On dry road, $L_{brake}$ is almost constant for friction values in the range 0.5 – 0.7. On wet road, we see gradually increased braking distances the lower the friction. This is true of all speeds. At 130 km/h, $L_{brake}$ for example, increases from 76 m to 91 m when friction is reduced from 0.75 to 0.5. This corresponds to an increase in $L_{brake}$ of approx. 20%. The same percentage increase in $L_{brake}$ is also seen in the case of the other speeds. It should also be noted that, at high friction, $L_{brake}$ is the same for dry and wet road.

The corresponding values for $Dec_{brake}$ are shown in Figure 4.17. $Dec_{brake}$ for dry road is at 8-8.5 m/s$^2$ irrespective of friction, while for wet road, it drops from approx. 8.5 m/s$^2$ to approx. 7 m/s$^2$, when the friction is reduced from 0.75 to 0.5.

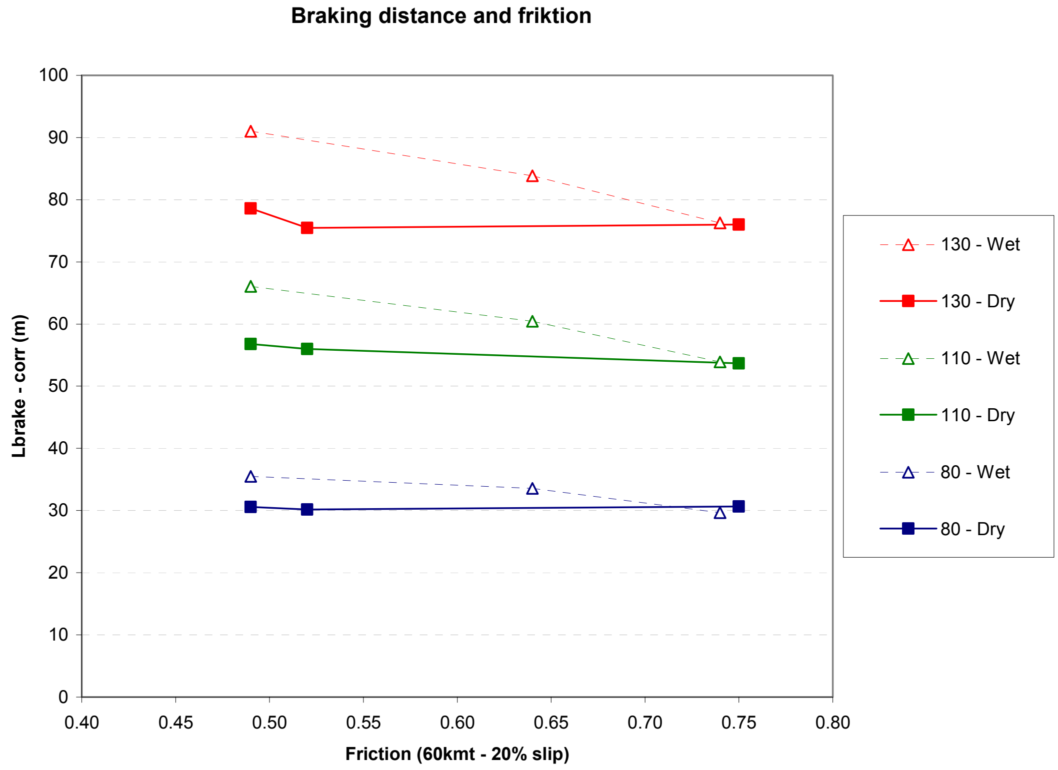



*Figure 4.16 $L_{brake80}$, $L_{brake110}$ and $L_{brake130}$ as a function of friction*

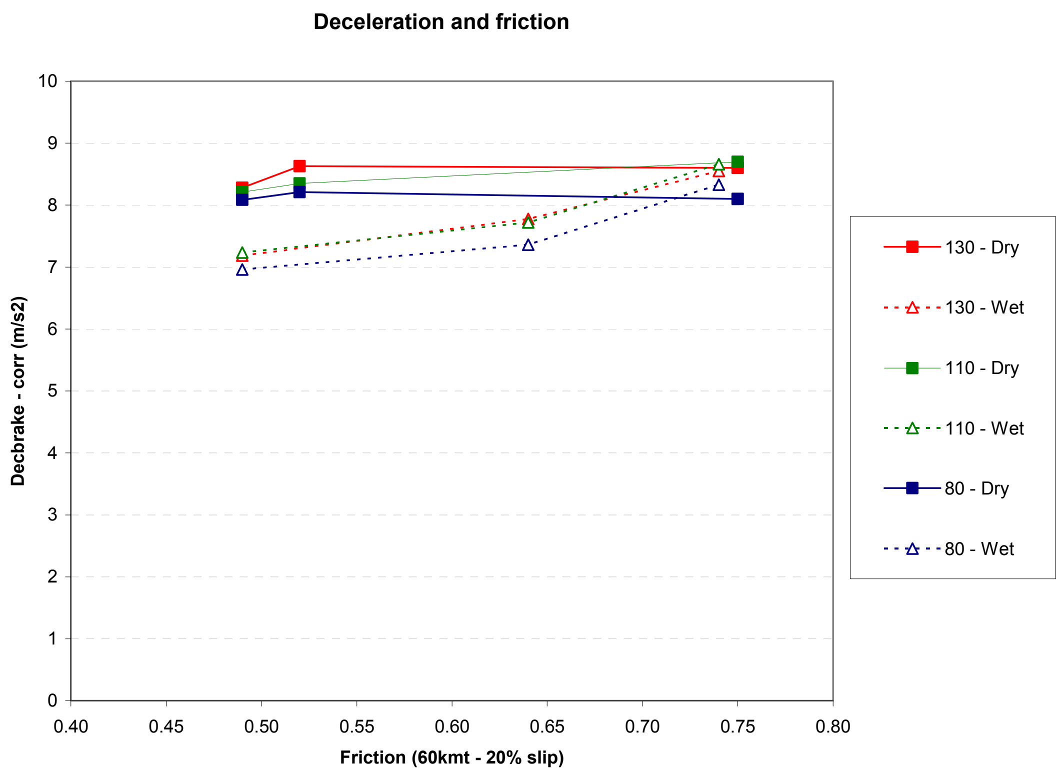



*Figure 4.17 $Dec_{brake80}$, $Dec_{brake110}$ and $Dec_{brake130}$ as a function of friction.*

A regression analysis to describe $Dec_{brake}$ as a function of friction and initial speed was carried out. This was done using the same model as in [3], where deceleration is described using a function in which the square root of the friction is used.

The model is shown below:

$$Dec_{brake} = a \cdot \sqrt{\mu_{fric}} + b \cdot V_0$$

where

$Dec_{brake}$ is the average deceleration for the entire braking run (m/s$^2$)
$\mu_{fric}$ is the recorded friction on the test track at 60 km/h – 20% slip
$V_0$ is the initial speed before braking (m/s)
a and b constants found by regression

For the recorded deceleration values on wet road, the following results were obtained:

$$Dec_{brake} = 8.79 \cdot \sqrt{\mu_{fric}} + 0.028 \cdot V_0 \qquad R^2 = 0.97$$

This allows $L_{brake}$ to be calculated using various friction values by the formula:

$$L_{brake} = \frac{V_0^{\;2}}{2 \cdot Dec_{brake}} = \frac{V_0^{\;2}}{2 \cdot (8.79 \cdot \sqrt{\mu_{fric}} + 0.028 \cdot V_0)}$$

The above formula is illustrated in Figure 4.18, where $L_{brake}$ is shown for friction values in the range 0.4 – 0.8. The actual, recorded values for the professionals' $L_{brake}$ has also been plotted in the figure.

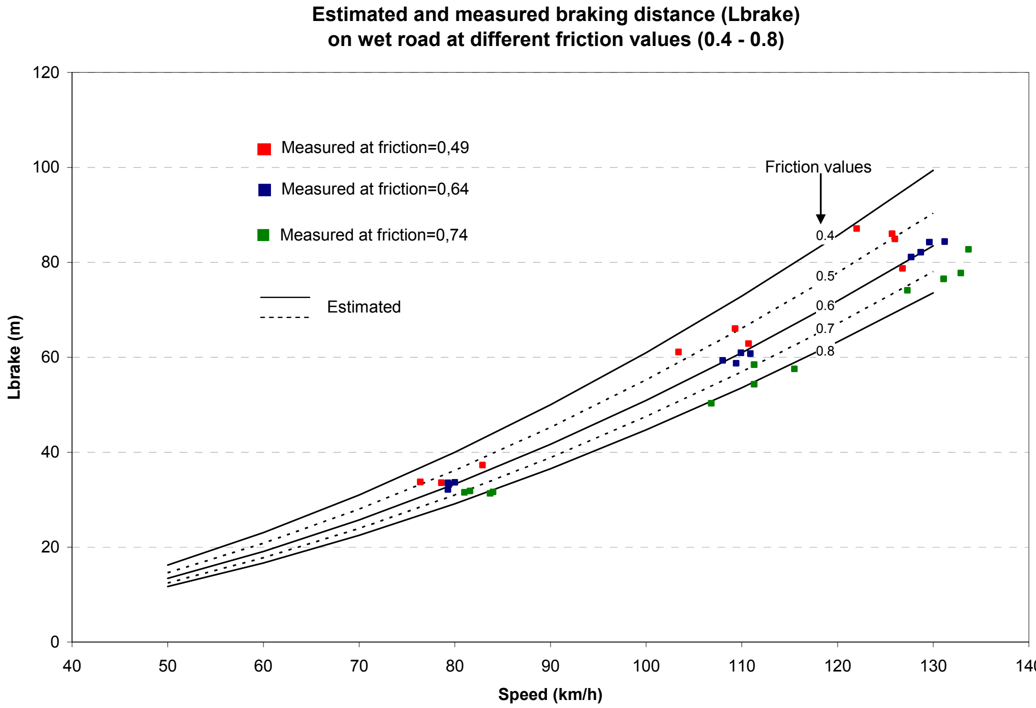



*Figure 4.18 Calculated $L_{brake}$ as a function of friction and speed compared with actual measurements. Wet road only.*

The calculated values for $Dec_{brake}$ and $L_{brake}$ using regression analysis are also shown for 80, 110 and 130 km/h in Table 4.8.

| Friction | 80 km/h | | 110 km/h | | 130 km/h | |
|---|---|---|---|---|---|---|
| | $Dec_{brake}$ (m/s$^2$) | $L_{brake}$ (m) | $Dec_{brake}$ (m/s$^2$) | $L_{brake}$ (m) | $Dec_{brake}$ (m/s$^2$) | $L_{brake}$ (m) |
| 0.4 | 6.2 | 40 | 6.4 | 73 | 6.6 | 99 |
| 0.5 | 6.8 | 36 | 7.1 | 66 | 7.2 | 90 |
| 0.6 | 7.4 | 33 | 7.7 | 61 | 7.8 | 84 |
| 0.7 | 8.0 | 31 | 8.2 | 57 | 8.4 | 78 |
| 0.8 | 8.5 | 29 | 8.7 | 54 | 8.9 | 74 |

*Table 4.8. Estimated deceleration and braking distance for wet road. Based on regression analysis.*

According to the table, a wet road surface with a friction of 0.4 will produce a $Dec_{brake}$ of 6.2-6.6 m/s$^2$ depending on speed. According to the Danish Road Standards and Guidelines, a friction value of 0.4 is the minimum requirement for roads in operation.

## 4.5 Comfort braking

Besides measurements of braking behaviour in emergency stops, a number of trials were conducted on comfort braking. In these trials, the non professional test drivers were required to bring the vehicle to a comfortable stop. The trials were conducted on dry road at 80 km/h and in a few instances at 110 km/h. Both test cars were used. Comfort braking trials were always conducted immediately before the emergency stop trials.

The measurements from two test drivers were excluded from the subsequent analyses, as the test drivers had apparently misunderstood the exercise. The results are therefore based on a total of 23 comfort braking trials, broken down by 11 test drivers (non professional test drivers only).

Overall, the average $Dec_{70\text{-}20}$ was recorded as 3.2 m/s$^2$. Figure 4.19 shows the mean values for $Dec_{70\text{-}20}$, by the individual test driver. The figure also shows the minimum and maximum values for the test driver who carried out several comfort braking trials. As shown, there are some differences between the individual test drivers.

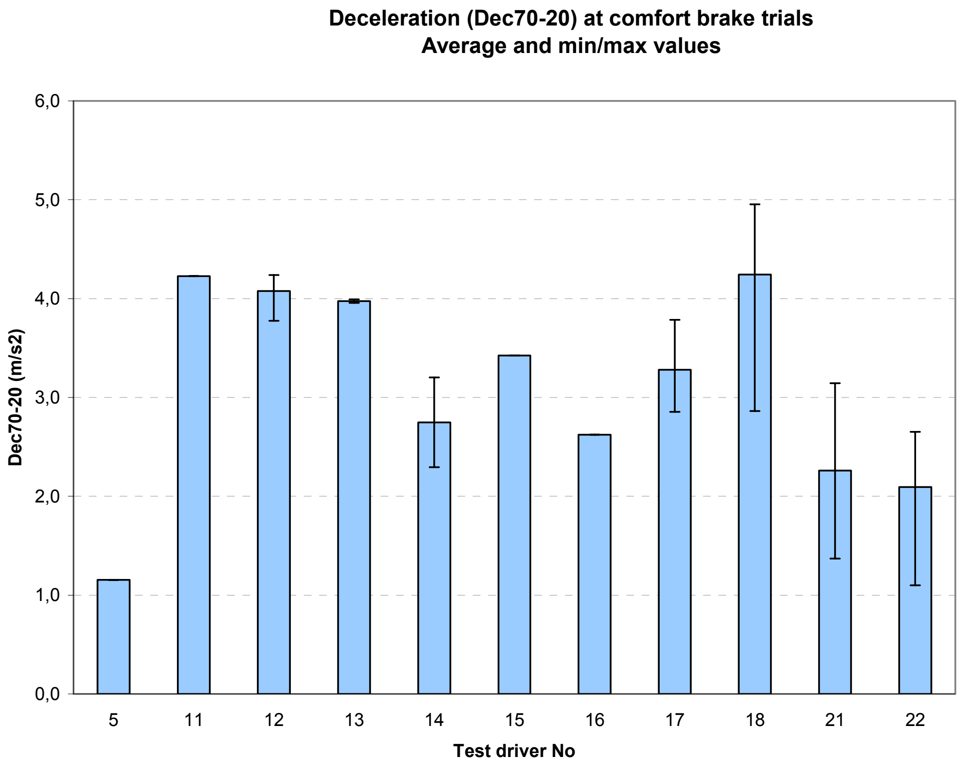



*Figure 4.19 Recorded values for Dec70-20 in comfort-braking trials, by test subject.*

The distribution of the recorded $Dec_{70-20}$ values is shown in Figure 4.20. Most of the recorded $Dec_{70-20}$ values are between 2.5 and 4.0 m/s$^2$.

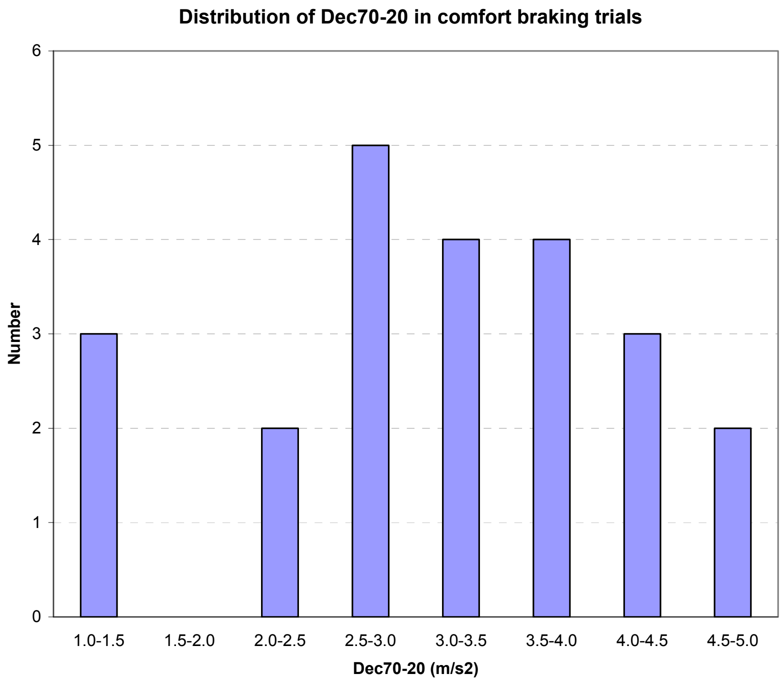



*Figure 4.20 Distribution of $Dec_{70-20}$ in comfort-braking trials.*

The volume of data obtained is too insubstantial to be able to demonstrate differences in the test drivers' choice of deceleration between the two test cars used.

The AASHTO Green Book [2] indicates a deceleration of 3.4 m/s$^2$ as comfortable for the majority of drivers. In the Danish Road Standards and Guidelines for rural roads, comfortable deceleration is set at 2.0 m/s$^2$.

# 5. The significance of other parameters for braking distance

The measurement programme contained a selection of the parameters of significance for braking distance. In this section, we discuss a number of the parameters that were not included in the measurement programme. These are:

- Make of tyre
- Summer tyres versus winter tyres
- Tyre tread depth
- Make of car
- Loaded or non-loaded car
- Wind conditions
- Temperature of tyres and brakes

Information about the significance of the above parameters for braking distance is based on literature found through a small survey of the literature, where the most important sources were scanned for relevant studies. The findings of those studies are cited below.

### Make of tyre

In the measurement programme that was carried out, only one make of tyre was used. The braking capabilities of the tyres used were judged to be better than the average, when compared with other makes of tyre [6]. It should however be noted that the best-selling tyres are typically those that do well in road tests. This means that the tyres used in the measurement programme should be fairly representative of the tyres running on Danish roads.

In [5] reference is made to a German study from 1999 in which the braking distance for ordinary (summer) tyres was recorded for the speed interval 90 km/h to 20 km/h on wet road with a water membrane of 1 mm.

The study comprised 10 different makes of tyre sized 175/70 R13 and 10 different tyre makes sized 195/65 R15. The average braking distance and min. and max. values found by the study are shown in Table 5.1 below.

| | Braking distance (m) | | | |
|---|---|---|---|---|
| Tyre size | Av. | Min | Max | [min., max.] in % |
| 175/70 R13 | 45 m | 42 m | 51 m | [-7% ,+14%] |
| 195/65 R15 | 49 m | 41 m | 49 m | [-9%, +9%] |

*Table 5.1. Recorded braking distances for different tyre makes.*

Compared with the average, the best tyres yield a 9% shorter braking distance, while the poorest yield a 14% longer braking distance.

[11] presents a study of 9 summer tyre braking distances from 80 km/h to 50 km/h on wet road with a 1.5 mm water membrane. The average braking distance was found to be 21.9 m. The min/max values in relation to the average were recorded as [-11%, +10%].

[7] compares different tyre types (summer/winter weather tyres) and tyres of different age, tread depth, etc. The braking friction for the different tyres was recorded by a measurement car travelling at 70 km/h over a 0.5 mm water membrane. For summer tyres with the same tread depth, the min/max values of the braking friction were [-10%, + 8%] compared with the average.

Overall, the finding is that the braking distance for different makes of tyre is within the range [-10% to +10%] compared with the average tyre.

**Summer tyres and winter tyres**

In the measurement programme carried out, all the emergency stops were done on summer tyres. It is well known that the braking capabilities of winter tyres are somewhat weaker compared with summer tyres on wet and dry roads. However, winter tyres are demonstrably better at braking on snow or ice.

[5] summarises the research findings, measurements and knowledge available for summer and winter tyres at different temperatures and for different road surfaces.

The conclusion is that for modern summer and winter tyres, temperature is of no significance for tyre friction on typical road surfaces.

Further, the conclusion is that the increased breaking distance for winter tyres compared with summer tyres is as shown in the table below.

| Road surface | Average | Min/max in % |
|---|---|---|
| Dry | approx. 10% | [0-20%] |
| Wet | approx. 15% | [5-35%] |

*Table 5.2. Increased braking distance in winter tyres compared with summer tyres.*

On dry and wet road surfaces, winter tyres have a braking distance that is on average 10-15% longer than that of summer tyres.

In winter 2006, a survey carried out by RFSD (the Danish Commission on Improved Tyre Safety) found that approx. half of all vehicles in Denmark were fitted with winter tyres [15]. The survey also revealed that it was primarily new cars and company vehicles that were fitted with winter tyres. The total distance covered for vehicles fitted with winter tyres is therefore estimated to amount to more than half of the total number of kilometres driven in winter.

**Tyre tread depth**

The tyre tread depth of the tyres used in the measurement programme was measured as 7-8 mm. The statutory minimum for tread depth is 1.6 mm. The tread depth is primarily of significance for braking capability on wet road.

[7] compares different tyre types (summer/winter tyres) and tyres of different age, tread depth, etc. The braking friction for the different tyres was recorded by a measurement car travelling at 70 km/h over a 0.5 mm water membrane. Among the different tyres (not same make), no correlation was found between tread depth and braking friction provided that the tread depth was in the range 2-4 mm.

In [3], braking distance and deceleration values for tyres with different tread depth were investigated in braking trials. This was done on dry and wet road, with different cars, speed and road-friction values. For cars with ABS, the study did not demonstrate appreciable differences in deceleration in comparisons of tyres with tread depths of 2, 5, 7 and 8 mm. This was the case at 70, 100 and 130 km/h and at different water membrane thicknesses (0.3 mm, 0.7 mm and 1.0 mm).

[9] investigated the braking distance on wet road for 2 different makes of tyre with different tread depths. The average braking distance from 80-0 km/h for the tyres tested is shown in the table below.

| Tread depth | Braking distance |
|---|---|
| 8 mm | 28.8 m |
| 4 mm | 30.3 m |
| 1.6 mm | 37.8 m |

*Table 5.3 Braking distance for different tread depths.*

The braking distance increases from 28.8 m to 37.8 m in comparisons of 8 mm and 1.6 mm tread depths. This equates to approx. 30% longer braking distance. The water volume on the road surface during testing is not stated directly in the study, but was subsequently notified as being approx. 1 mm. The study was carried out by an interest organisation for tyre companies in Finland.

The tyre company Continental refers on its website [10] to an independent testing centre (MIRA), which conducted braking tests of tyres on wet asphalt with different tread depths. According to the study, tyres with a tread depth of 1.6 mm, produce approx. 50% longer braking distance compared with tyres with 8 mm tread depth. For tyres with 4 mm, the braking distance is 22% longer. In the test, the water volume on the road surface was calculated as being between 0.5 and 1.5 mm.

The trend in new cars is for larger and wider tyre sizes, which makes the importance of the tyre tread even more important than previously. Earlier tests performed on smaller tyre sizes were presumably unable to demonstrate the same effect from tread depth as the more recent tests performed on the larger tyre sizes. The tyre industry and independent experts currently recommend drivers to replace tyres when the tread depth is less than 3 mm.

Based on the studies found, the conclusion is that braking distances on wet road are not significantly affected by the tread depth as long as it is at least 4 mm. This is true for water thicknesses of up to 1 mm. At tread depths of less than 3 mm, some studies suggest that the braking distance increases, while other studies demonstrate that this does not happen until the tread depth is less than 2 mm.

The tread depth of cars in Denmark is not known, but a Swedish survey from 2002 [12] reveals that 3% of Swedish cars have a tread depth of less than 1.6 mm, 14% have a tread depth of ≤ 2mm and 32% have a tread depth of ≤ 3mm. One might readily imagine that the situation is similar in Denmark.

In relation to the braking distances recorded in the measurement programme (with 7-8 mm tread depth), the braking distance with a 1.6 mm tread depth could be estimated as being in the order of 0-50% longer. As an average, the effect is set at 25%. This estimate is however somewhat uncertain.

**Make of car**

In the measurement programme, the recorded braking distances for test cars 1 and 2 are almost identical. However, different makes of car with the same type of tyre are known to have different braking distances due to differences in their braking system.

However, it has not been possible to find studies presenting a direct comparison of braking distance and make of car for example. Typically, combinations of car makes and tyres are compared against each other, which means that the differences found cannot be attributed exclusively to the make of car.

It is estimated that the min./max. values for braking distances in relation to an average car are in the range [-10%, +10%]

**Loaded or non-loaded**

All the braking trials in this study were conducted with just a single individual on board (the test driver). The cars were not however loaded with additional dead weight. In an ordinary road situation, car weights will be readily increased by 3-4 persons + luggage (amounting to 300-400 kg) in relation to the car weight during the braking trials.

[3] investigates the braking distance for 3 different cars in loaded and non-loaded states. In the non-loaded state, the car carried only the driver of the car, while in the loaded state, the car was carrying 4 persons + luggage. The braking trials were conducted on wet road at 70, 100 and 130 km/h. For two of the cars, a longer braking distance was recorded in the loaded state. The increased braking distance was recorded as approx. 4%, where deceleration was reduced by approx. 0.5 $m/s^2$. For the last car, no difference was recorded in braking distance.

[4] also investigated the braking distance for 10 cars in loaded and non-loaded state. The 10 vehicles are all typically American, i.e. a mixture of large cars, pick-ups, 4 wheel drives and MPVs. In this study, braking distance was recorded on dry and wet road surfaces at 100 km/h. On average the braking distance is 3-4% longer on wet and dry road in a loaded compared with non-loaded state. There are however some differences from one car to the next. On dry road, a loaded car had a braking distance ranging from -5% to +8% longer compared with non-loaded. On wet road, the difference is greater, in the order of -10% to +15%.

Overall, the finding is that the braking distance for a loaded car is an average 4% longer than for a non-loaded one. The min./max. values are estimated at [-10%, +15%].

**ABS brakes**

In the measurement programme, both test cars were equipped with ABS brakes, which is the case for approx. 90% of cars in Denmark. Since all new cars are equipped with ABS, the percentage will rise year after year. It is well known that cars with ABS (among non professional drivers) have shorter braking distances compared with non-ABS cars. This is true on wet road especially. However, in this study no attempt was made to consider the findings in terms of non-ABS cars.

**Wind conditions**

[4] investigates the significance of various parameters for braking distances. One parameter of interest was whether a strong headwind or strong tailwind would be of decisive significance for car braking distance. The trials offered no indication as to whether wind affected braking distance. Subsequent theoretical calculations based on wind speed, air density and car surface area demonstrated that a headwind of wind strength 10 m/s would be capable of reducing braking distance by approx. 1 m if braking started from 100 km/h (corresponding to 2%). The effect of wind conditions was regarded as insignificant and is not discussed further.

### Temperature of tyres and brakes

[4] investigates the significance of various parameters for braking distance, including the temperature of the brakepad or on the exterior of the brake drum. Braking with a cold brake was found to result in longer braking distances. The same was true of tyre temperature. Hot tyres provided better friction in relation to cold tyres. The differences are so small however, that these factors cannot be addressed in further detail in the present study.

### Summary

A summary of the parameters discussed above is presented in the table below. The table shows the effect on braking distance on wet road for the various parameters compared with either an average state or an altered state.

Winter tyres for example have a braking distance +5% to +35% longer than summer tyres. This puts the average at 15%. In relation to our measurement programme, which was conducted on summer tyres, the braking distance thus has to be increased by an average of 15% to be applicable to vehicles with winter tyres.

| Parameter | Effect in relation to: | [min/max] | Av. | Av. in relation to measure-ment programme |
|---|---|---|---|---|
| Make of tyre | Average tyre | -10% - +10% | +0% | +0% |
| Winter tyre | Summer tyre | +5% - +35% | +15% | +15% |
| Tread depth 1.6 mm | 8 mm | +0% - +50% | +25% | +25% |
| Make of car | Average car | -10% - +10% | +0% | +0% |
| Loaded | Non-loaded | -10% - +15% | +4% | +4% |

*Table 5.4 Effect on braking distance on wet road.*

The question is whether the effects on braking distance can indeed be summed. A poor vehicle with poor tyres that are loaded will, if the effects are summed, risk producing a 10%+35%+50%+10%+15% = 120 % longer braking distance compared with those observed in the measurement programme. In the best case, the braking distance might be 25% shorter. However, the probability of finding a vehicle with these extreme min./max. values is presumably very small. Overall, the conclusion is that a large spread in the braking distance is likely, depending on the listed parameters, if one permits the listed effects to be summed.

A better description of how tyres, brakes, car makes and the interaction of these affect braking distance would require supplementary data or further practical trials.

# 6. New recommended braking distances

An attempt is made in the following to establish a new set of recommended braking distances for use in Denmark. This is done on the basis of the findings from the measurement programme as well as knowledge of the different parameters' influence on braking distance.

As an initial premise it is noted that the Danish Road Standards and Guidelines' recommended braking distances are somewhat greater than the values obtained in this study; see Figure 6.1. The figure shows all the measured braking distances on wet road for both professional and non professional test drivers, compared with the Danish Road Standard and Guidelines' recommendations. At the high speeds especially, the difference are very large (almost factor 3).

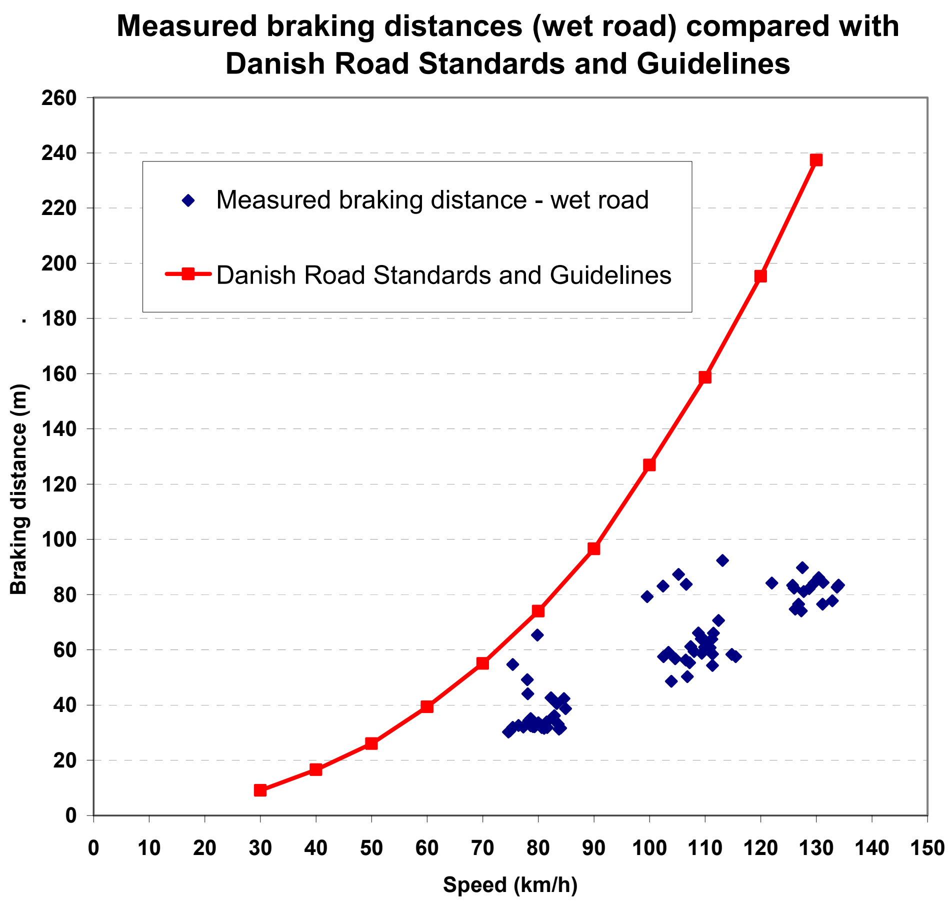



*Figure 6.1. Recommended braking distances from the Danish Road Standards and Guidelines compared with those recorded on wet road. Both professional and non professional test drivers.*

New recommended values for braking distances are provided on the basis of the following considerations:

- the braking distance should reflect worst-case-scenario road conditions, which equate to wet road with low friction. Low friction is set at 0.4, which is consistent with friction requirements for roads in operation. Wet road is assumed to be in the same state as that during the measurement programme, i.e. clean, but with a water membrane of approx. 1 mm.

- the braking distance should reflect the braking capabilities of a vehicle whose braking capabilities are at the weak end of the scale among ordinary cars, but which otherwise conforms to legal brake, tread pattern requirements, etc.

- the braking distance should reflect the braking behaviour found among the worst performing drivers (among non professional) travelling on the roads.

- the braking distance assumes that the vehicle is fitted with ABS brakes.

The braking distance for wet road with friction of 0.4 is determined from the results in Section 4.4. Here we find that a professional test driver is able to achieve a $Dec_{brake}$ of approx. 6.5 m/s$^2$ under these conditions (extrapolated from the recorded data).

By far the majority of the non professional test drivers produced braking distances 0-20% longer than the professionals' (see Section 4.1). It is assumed that the weakest half of the non professional drivers have a braking distance 30% longer than the professionals.

The braking distance for a legal vehicle in which the braking capability is poor due to worn and poor tyres, poor brakes etc. is set (rounded figures) at 45% longer than the observed braking distances for the test cars used in the measurement programme.

Overall, this results in recommended braking distances as shown in the table below.

| | 80 km/h | 110 km/h | 130 km/h |
|---|---|---|---|
| $L_{brake}$ – professional in test car | 40 m | 73 m | 99 m |
| Behavioural increment (+30%) | 12 m | 22 m | 30 m |
| Vehicle increment (+45%) | 18 m | 33 m | 45 m |
| **Recommended $L_{brake}$** | **70 m** | **128 m** | **174 m** |

*Table 6.1. New recommended braking distances. Based on wet and clean road with a friction of 0.4.*

The recommended braking distances correspond to an average $Dec_{brake}$ of 3.7 m/s$^2$.

Figure 6.2 shows the new recommended braking distances compared with the existing ones from the Danish Road Standards and Guidelines and the Green Book, together with those recorded in the measurement programme. The figure shows:

- the recorded values for $L_{brake}$ at friction 0.49, 0.64 and 0.74 (professionals only)
- the calculated $L_{brake}$ for friction 0.4 (extrapolated from data)
- behavioural increment to $L_{brake}$ (+30%)
- vehicle increment to $L_{brake}$ (+45%)
- new recommended braking distances
- recommended braking distances from the Green Book
- current braking distances in the Danish Road Standards and Guidelines
- current braking distances from the Danish Road Standards and Guidelines, incl. safety increment (+20 km/h)

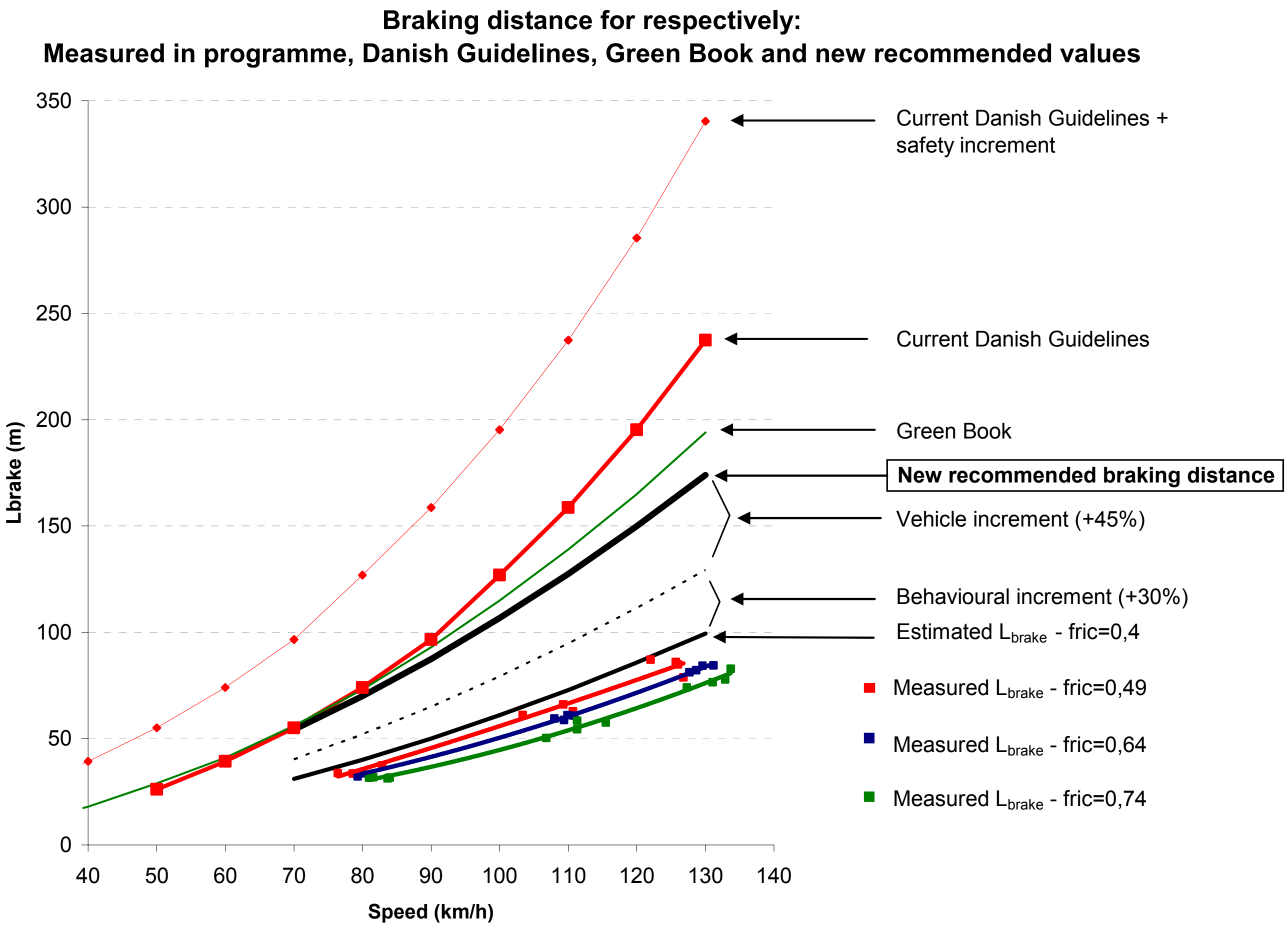



*Figure 6.2. Recorded values for $L_{brake}$ and new and existing recommended braking distances*

As shown by Figure 6.2, the new recommended braking distances are almost identical with the current ones for speeds below 90 km/h. For higher speeds, e.g.

130 km/h, the new recommended braking distances are approx. 25% shorter than the current ones. In relation to the current recommendations, incl. safety increment, the braking distance for 130 km/h is approx. 50% shorter. In relation to the braking distances from the Green Book, the new recommended braking distances are approx. 5-10% shorter.

The method for determining the new recommended braking distances based on the findings of this study calls for a few accompanying remarks:

- The method for determining the vehicle increment of 45% is somewhat uncertain. Section 5 describes the significance of various parameters for braking distances. If these are summed uncritically, we find that a vehicle with better or poorer braking capability (in relation to the test cars) may result in a braking distance that is between -25% shorter or 120% longer than the recorded braking distances. This is a significant variation. The vehicle increment is set at 45%, based on a law of averages combined with what ”would appear fairly reasonable”, but in reality, the vehicle increment is not precisely known.

- It is also debatable whether the recommended braking distance should be based on tyres that are only just compliant with the statutory requirement of 1.6 mm tread depth, or whether stricter requirements for tread depth would be preferable (e.g. 3 mm). The key factor in the vehicle increment is tyre tread depth.

- The vehicle increment is assumed to be independent of speed, i.e. 45% for all speeds. Depending on the vehicle’s technical condition, arguments can be made both for and against the rationale of this.

- In determining new recommended braking distances, the vehicle increment and behavioural increment were summed uncritically. It is debatable whether the recorded braking distance can be translated directly to another vehicle with poor braking capability. One might, for example, imagine that the difference between a professional test driver and a non professional test driver would not be the same if the braking was performed in a vehicle with very poor braking capability. This then would make it incorrect to sum the vehicle increment (45%) and the behavioural increment (30%).

- The behavioural increment is set consistently at a standard 30%, i.e. irrespective of speed. It is debatable whether the behavioural increment should be higher for higher speeds. Against that, the recorded values for the $L_{brake\%}$ are not unequivocally higher at higher speeds, which again might be attributable to the trial sequence in the measurement programme.

Overall, the position is that the new recommended braking distances have been determined somewhat “cautiously” with a good safety margin in relation to the cars and motorists driving on Danish roads.

# 7. Summary

The recommended braking distances in the Danish Road Standards and Guidelines are in the main based on earlier American findings. In order to be able to assess the validity of the recommended braking distances in relation to contemporary vehicles and motorists in Denmark, the Danish Road Directorate has conducted a study designed to shed light on braking behaviour and braking distances among ordinary (non professional) motorists, at different speeds.

This was done through a measurement programme in which 22 test drivers performed braking manoeuvres at different speeds (80, 110 and 130 km/h). The majority of the test drivers who participated were recruited from among non professional drivers. However, 6 out of the 22 test drivers were professional test drivers with extensive experience in advanced driving technique. Two different recent cars with ABS brakes were used as test cars. The braking manoeuvres were carried out on dry and wet road on 3 test tracks with different friction. The majority of the manoeuvres performed were emergency stops, in which the test driver was required to bring the vehicle to a complete standstill as quickly as possible. In addition, a small number of comfort braking manoeuvres were performed in which the test driver was required to bring the vehicle to a comfortable stop.

The main findings of the measurement programme (a total of 172 emergency stops and 23 comfort braking manoeuvres) are presented below in bullet form:

- The non professional test drivers generally have a longer braking distance compared with the professional test drivers. The difference is very individual however. The majority of the non professional test drivers have an average braking distance that is 0-20% longer than that of the professional test drivers. A few non professional test drivers, however, have a significantly longer braking distance.
- The greatest difference between the professional and non professional test drivers is seen on wet road surface.
- Generally, the largest spread in braking distance among the non professional test drivers is seen at high speed and in situations on wet road surface.
- The more times the non professional test drivers performed an emergency stop, the better they became at braking. The difference between the professional and non professional test driver was therefore reduced after 6-7 braking trials.
- The test drivers’ pressure on the brake pedal during braking indicates that the professional test drivers apply far more rapid and generally firmer pressure on the brake pedal than the non professional test drivers.
- The analyses also indicate that the vehicle’s deceleration is independent of brake pedal pressure as long as it simply exceeds 15-20 kg. Where there is less brake pedal pressure, deceleration is reduced significantly.

- The average deceleration values among the professional test drivers are between 8.1 and 8.6 $m/s^2$ on dry road and between 7.2 and 8.5 $m/s^2$ on wet road.
- There is apparently only a small difference between the two test cars used.
- The significance of friction for the braking distance on dry road is negligible. On wet road however, the braking distance increases where friction is lower.
- A good correlation was found between braking distance on wet road, friction and initial speed. This correlation is expressed in a formula obtained from regression analyses.
- The average deceleration in comfort braking manoeuvres was found to be 3.2 $m/s^2$

The completed measurement programme is based on 2 fairly new test cars with new summer tyres. In order to determine the significance of the choice of vehicle and tyre for overall braking distance, the findings of other relevant studies were reviewed. Depending on make of tyre, winter/summer tyres, tread depth, loaded/non-loaded and make of car, great individual differences affect a vehicle's overall braking capability. The condition of the tyres (including tread depth), especially, is highly significant for braking distance on wet road. The finding is that a vehicle with poor braking capabilities will result in a braking distance some 30-60% longer than the test cars used in the measurement programme.

Based on the findings of the measurement programme and the knowledge obtained concerning the significance of other parameters for braking distance (choice of tyre, vehicle, etc.), we have sought to establish a new set of recommended braking distances. These are based on "worst case scenarios", i.e.

- wet road surface with poor friction (friction=0.4 – minimum requirement for roads in operation)
- driver with tentative braking behaviour
- vehicle with poor braking capability

The new recommended braking distances are thus based on calculated braking distances with friction of 0.4 for professional test drivers in the test cars used. In addition, we added a behavioural increment of 30% to reflect the tentative driver, and to this we added a vehicle increment of 45% to reflect a vehicle with poor braking capability. The new recommended braking distances for speeds of 80, 110 and 130 km/h are shown in Table 7.1. The braking distances are assessed as somewhat "cautiously determined" with a good safety margin in relation to the cars and motorists driving on Danish roads.

| Speed | New recommended braking distances |
|---|---|
| 80 km/h | 70 m |
| 110 km/h | 128 m |
| 130 km/h | 174 m |

*Table 7.1. New recommended braking distances for 80, 110 and 130 km/h.*

For speeds below 90 km/h, the new recommended braking distances are almost identical with the existing ones in the Danish Road Standards and Guidelines. At greater speeds, e.g. 130 km/h, the new recommended braking distances are approx. 25% shorter than the existing ones (see Figure 6.2 page 63).

# 8. References

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[10] *Continental's website* http://www.conti-online.co.uk/generator/www/uk/en/continental/portal/general/safety/3mmtread_en.html (seen February 2007)

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Obtained from www.daeksikkerhed.dk (seen April 2007)

# Appendix 1 – Technical specifications for test cars

**Car 1.**

| | |
|---|---|
| Make: | Fiat Grande Punto |
| Model: | Dynamic, 1.4 8v |
| Reg. year | May 2006 |
| Kilometres clocked (July 2006) | 333 km |

**Dimensions**

| | |
|---|---|
| Axle distance (mm) | 2,510 |
| Track width front/rear (mm) | 1,473 / 1,466 |
| Length (mm) | 4,030 |

**Weight**

| | |
|---|---|
| Kerb weight: | 1,060 kg |
| Fuel tank capacity | 45 litres |

**Tyres**

| | |
|---|---|
| Size | 175/65 R15 |
| Make | Continental EcoContact 3 |
| Recommended tyre pressure (bar) | Front/rear 2.2 / 2.1 |

**Brakes**

| | |
|---|---|
| Front | Discs (257 mm dia.) |
| Rear | Drums (228 mm dia.) |
| ABS | Yes |
| Brake assistant | No |

**Car 2.**

| | |
|---|---|
| Make | Opel Vectra |
| Model | 1.8 16v Comfort |
| Reg. year | July 2004 |
| Kilometres clocked (July 2006) | 29,665 |

**Dimensions**

| | |
|---|---|
| Axle distance (mm) | 2,700 |
| Track width front/rear (mm) | |
| Length (mm) | 4,596 |

**Weight**

| | |
|---|---|
| Kerb weight / total weight | 1,275 kg / 1,875 kg |
| Fuel tank capacity | 61 litres |

**Tyres**

| | |
|---|---|
| Size | 195/65 R15 |
| Make | Continental EcoContact 3 |
| Recommended tyre pressure (bar) | Front/rear 2.0 / 2.2 |

**Brakes**

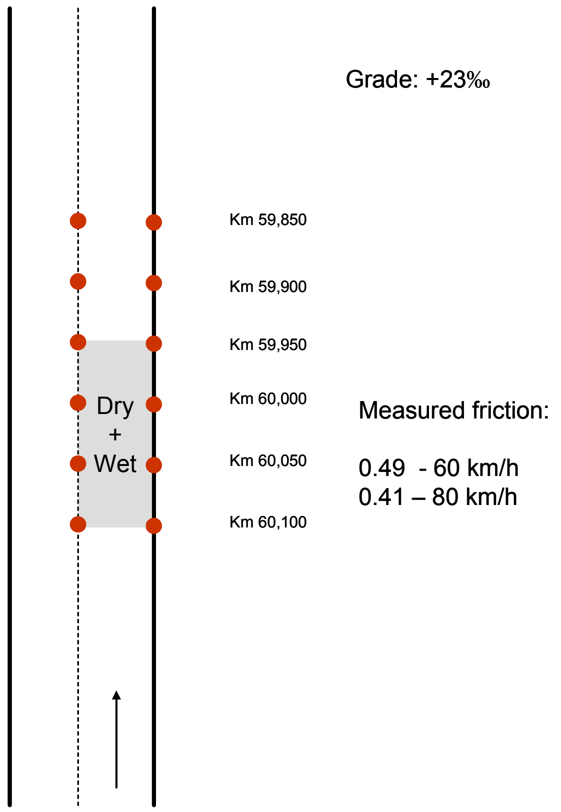
| | |
|---|---|
| Front | Disc brake |
| Rear | Disc brake |
| ABS | Yes |
| Brake assistant | Yes |

# Appendix 2 – Test tracks

Photos from the test tracks and layouts setting out precisely the braking sections for braking on dry and wet road, respectively.

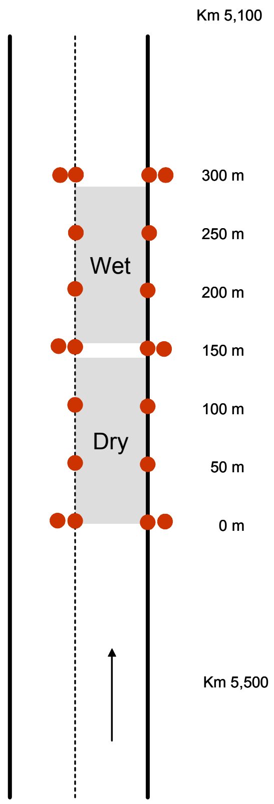
## Test track 1 – Holbæk

**Track 1 Holbæk**
**M11 – left carriageway / right lane**




# Test track 2 - Odense

**Track 2 Odense**
**M45 – right carriageway / left lane**



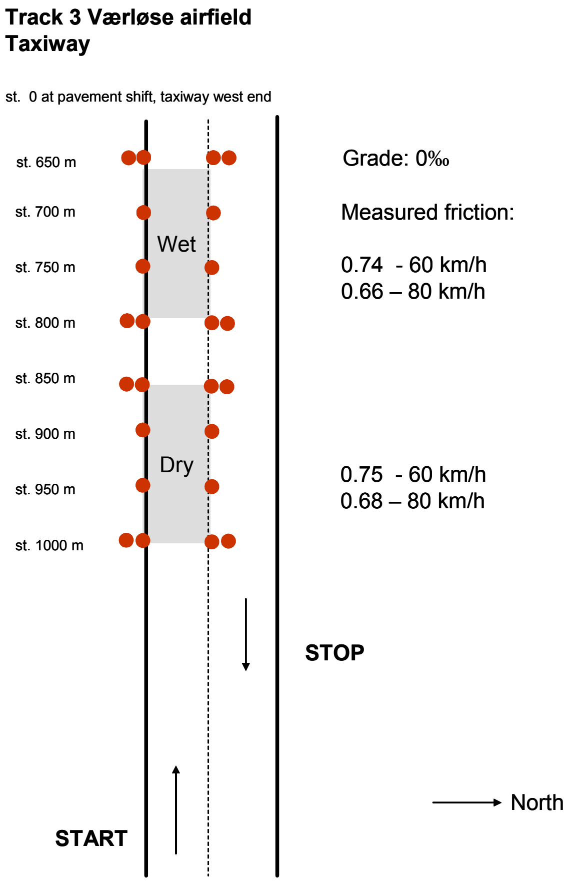

Grade: 0‰

Measured friction:

0.64 - 60 km/h
0.59 - 80 km/h

0.52 - 60 km/h
0.43 – 80 km/h

# Test track 3 - Værløse




# Appendix 3 – Information given to test drivers

**Oral information for test drivers – keywords (only for non professionals)**

- The Danish Road Directorate is currently investigating the behaviour of motorists in performing various driving manoeuvres. To that end, the aim is to carry out a series of braking trials designed to shed light on how motorists brake at different speeds.
- As a test driver, you are required to drive 2 different cars and brake at 80, 110 and 130 km/h on dry and wet road (130 only if you feel confident doing so).
- We will be conducting the trials as shown on this layout (cones indicate braking section).
- Use of START and STOP button on keypad – brake in braking section.
- First you will have an opportunity to take the car for a drive to familiarise yourself with it. You will then be asked to brake comfortably from 80 (and 110) km/h.
- The trial itself, in which you will be carrying out the braking manoeuvre, will then commence.
- Intro to car (no reversing due to recording equipment)!!!!! (important)
- Intro to recording equipment (press start at one end of the lane – press stop when you have reached the bottom of the other end)
- Intro to walkie-talkie
- Intro to speedometer – incorrect display !! - Add 3+4 km/h to the desired speed.
- Do not place your foot on the brake until you want to start braking (firm brake actuation)
- Once the car has come to a standstill after braking, wait 3-5 secs (so the equipment can register it) – and turn the car and drive back to the start.
- When braking on wet road – await “go” via walkie-talkie, as the water truck needs to be completely finished and out of the way before you start.

**Comfort measurement**

- In these trials you are asked to drive at either 80 or 110 km/h. This trial is performed only on dry road. Drive at the desired speed and adjust your braking so that the car has come to a complete stop at the first cone (show on layout)

- Imagine for example that you are driving entirely alone on a rural road (with no other traffic) where you have to stop the car at a red traffic light.

**Emergency stop**

- In these trials you are asked to drive at either 80, 110 or (130) km/h. This trial will be done on both wet and dry road. Once you have attained the required speed and are within the braking section and feel ready, then bring the vehicle to a complete stop as quickly as possible. You decide where in the braking section you want to brake.

- Do not place your foot on the brake until you want to start braking (firm brake actuation)

- Imagine that a large lorry is blocking the road and you have no way of avoiding it. – Then brake like you’ve never braked before!

- You must brake while driving straight ahead (do not start turning/switching lane while braking)

- All manoeuvres are at your own risk. Carry out the manoeuvres only if you feel confident doing so.

# Appendix 4 – Measurements obtained

Table containing values for the emergency stops performed. Cells with grey background are braking trials carried out by professional test drivers.

| | | 1 - Holbæk | | | | 2 – Odense | | | | 3 – Værløse | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | fiat | | opel | | fiat | | opel | | fiat | | opel | |
| Test driver | Speed | dry | wet | dry | wet | dry | wet | dry | wet | dry | wet | dry | wet |
| 1 | 80 | 1 | 1 | 1 | | | | | | | | | |
| | 110 | 1 | 1 | 1 | | | | | | | | | |
| | 130 | | | 1 | | | | | | | | | |
| 2 | 80 | 1 | 1 | 1 | | | | | | | | | |
| | 110 | 1 | 1 | 1 | | | | | | | | | |
| | 130 | 1 | 1 | 1 | | | | | | | | | |
| 3 | 80 | 1 | 1 | 1 | 1 | | | | | | | | |
| | 110 | 1 | 1 | 1 | 1 | | | | | | | | |
| | 130 | 1 | 1 | 1 | 1 | | | | | | | | |
| 4 | 80 | 1 | 1 | 1 | 1 | | | | | | | | |
| | 110 | 1 | 1 | 1 | 1 | | | | | | | | |
| | 130 | 1 | 1 | 1 | 1 | | | | | | | | |
| 5 | 80 | | | | | 1 | 1 | 1 | | | | | |
| | 110 | | | | | 1 | 1 | | | | | | |
| | 130 | | | | | 1 | 1 | 1 | | | | | |
| 6 | 80 | | | | | 1 | 1 | 1 | | | | | |
| | 110 | | | | | 1 | 1 | | | | | | |
| | 130 | | | | | 1 | 1 | 1 | | | | | |
| 7 | 80 | | | | | 1 | 1 | 1 | 1 | | | | |
| | 110 | | | | | 1 | 1 | 1 | 1 | | | | |
| | 130 | | | | | 1 | 1 | 1 | 1 | | | | |
| 8 | 80 | | | | | 1 | 1 | 1 | 1 | | | | |
| | 110 | | | | | 1 | 1 | 1 | 1 | | | | |
| | 130 | | | | | 1 | 1 | 1 | 1 | | | | |
| 9 | 80 | | | | | 1 | 1 | | | | | | |
| | 110 | | | | | 1 | 1 | | | | | | |
| | 130 | | | | | 1 | 1 | | | | | | |
| 10 | 80 | | | | | 1 | | | | | | | |
| | 110 | | | | | 1 | | | | | | | |
| | 130 | | | | | 1 | | | | | | | |
| 11 | 80 | | | | | | | | | 1 | 1 | 1 | 1 |
| | 110 | | | | | | | | | 1 | 1 | | 1 |
| | 130 | | | | | | | | | | | | |
| 12 | 80 | | | | | | | | | 1 | 1 | 1 | 1 |
| | 110 | | | | | | | | | 1 | 1 | 1 | 1 |

| | | 1 - Holbæk | | | | 2 – Odense | | | | 3 – Værløse | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | fiat | | opel | | fiat | | opel | | fiat | | opel | |
| Test driver | Speed | dry | wet | dry | wet | dry | wet | dry | wet | dry | wet | dry | wet |
| | 130 | | | | | | | | | | | | |
| 13 | 80 | | | | | | | | | 1 | 1 | 1 | 1 |
| | 110 | | | | | | | | | 1 | 1 | 1 | 1 |
| | 130 | | | | | | | | | 1 | 1 | 1 | 1 |
| 14 | 80 | | | | | | | | | 1 | 1 | 1 | |
| | 110 | | | | | | | | | 1 | 1 | 1 | 1 |
| | 130 | | | | | | | | | | | | |
| 15 | 80 | | | | | | | | | 1 | | 1 | 1 |
| | 110 | | | | | | | | | 1 | | 1 | 1 |
| | 130 | | | | | | | | | | | 1 | |
| 16 | 80 | | | | | | | | | | 1 | 1 | 1 |
| | 110 | | | | | | | | | | | 1 | 1 |
| | 130 | | | | | | | | | | | 1 | |
| 17 | 80 | | | | | | | | | 1 | 1 | 1 | 1 |
| | 110 | | | | | | | | | 1 | 1 | 1 | 1 |
| | 130 | | | | | | | | | 1 | 1 | 1 | 1 |
| 18 | 80 | | | | | | | | | 1 | 1 | 1 | 1 |
| | 110 | | | | | | | | | 1 | 1 | 1 | 1 |
| | 130 | | | | | | | | | | | 1 | |
| 19 | 80 | | | | | | | | | 1 | 1 | 1 | 1 |
| | 110 | | | | | | | | | 1 | 1 | 1 | 1 |
| | 130 | | | | | | | | | 1 | 1 | 1 | 1 |
| 20 | 80 | | | | | | | | | 1 | 1 | 1 | 1 |
| | 110 | | | | | | | | | 1 | 1 | 1 | 1 |
| | 130 | | | | | | | | | 1 | 1 | 1 | 1 |
| 21 | 80 | | | | | | | | | 1 | 1 | 1 | 1 |
| | 110 | | | | | | | | | 1 | 1 | 1 | 1 |
| | 130 | | | | | | | | | | | | |
| 22 | 80 | | | | | | | | | 1 | 1 | 1 | 1 |
| | 110 | | | | | | | | | 1 | 1 | 1 | 1 |
| | 130 | | | | | | | | | | | | |

# Appendix 5 – Recorded braking distances

Recorded braking distances ($L_{brake}$) and percentage difference from professionals under same conditions ($L_{brake\%}$).

Cells with grey background are braking trials carried out by professional test drivers. Figures in blue are for wet road.

| Location | Test driver | Brake no. | Car | Dry/wet | 80/110/130 km/h | Lbrake (m) | $L_{brake\%}$ |
|---|---|---|---|---|---|---|---|
| 1 - Holbæk | 1 | 1 | fiat | dry | 80 | 27.5 | 4% |
| | | 2 | fiat | dry | 110 | 49.3 | 1% |
| | | 5 | fiat | wet | 80 | 31.9 | 2% |
| | | 6 | fiat | wet | 110 | 59.1 | 2% |
| | | 7 | fiat | wet | 130 | 89.8 | 2% |
| | | 8 | opel | dry | 80 | 28.3 | -1% |
| | | 9 | opel | dry | 110 | 51.5 | -3% |
| | | 10 | opel | dry | 110 | 47.3 | -5% |
| | | 11 | opel | dry | 130 | 67.4 | -6% |
| 1 – Holbæk | 2 | 1 | fiat | dry | 80 | 27.3 | 6% |
| | | 2 | fiat | dry | 110 | 54.7 | 18% |
| | | 3 | fiat | wet | 80 | 30.2 | -1% |
| | | 4 | fiat | wet | 110 | 57.5 | 1% |
| | | 5 | opel | dry | 80 | 29.9 | 12% |
| | | 6 | opel | dry | 110 | 49.3 | 2% |
| | | 7 | opel | dry | 130 | 69.6 | 0% |
| 1 – Holbæk | 3 | 1 | opel | dry | 80 | 25.6 | -2% |
| | | 2 | opel | dry | 110 | 54.6 | 1% |
| | | 3 | opel | dry | 130 | 78.8 | 2% |
| | | 4 | fiat | dry | 80 | 27.4 | 2% |
| | | 5 | fiat | dry | 110 | 51.0 | 1% |
| | | 6 | fiat | dry | 130 | 69.6 | 1% |
| | | 7 | fiat | wet | 80 | 32.6 | 2% |
| | | 8 | fiat | wet | 130 | 84.2 | 5% |
| | | 9 | opel | wet | 110 | 64.0 | 4% |
| | | 10 | opel | wet | 130 | 83.3 | 4% |
| 1 - Holbæk | 4 | 1 | opel | dry | 80 | 33.7 | 4% |
| | | 2 | opel | dry | 110 | 58.4 | -1% |
| | | 3 | opel | dry | 130 | 66.6 | -2% |
| | | 4 | fiat | dry | 80 | 27.5 | -3% |
| | | 5 | fiat | dry | 110 | 52.5 | 0% |
| | | 6 | fiat | dry | 130 | 70.3 | -2% |
| | | 7 | fiat | wet | 80 | 32.5 | -4% |
| | | 8 | fiat | wet | 130 | 82.3 | -4% |
| | | 9 | opel | wet | 80 | 36.1 | -3% |
| | | 10 | opel | wet | 110 | 61.0 | -3% |
| | | 11 | opel | wet | 130 | 76.5 | -6% |

| Location | Test driver | Brake no. | Car | Dry/wet | 80/110/130 km/h | Lbrake (m) | $L_{brake\%}$ |
|---|---|---|---|---|---|---|---|
| 2 – Odense | 5 | 1 | fiat | dry | 80 | 28.8 | 11% |
| | | 2 | fiat | wet | 80 | 35.1 | 10% |
| | | 5 | fiat | dry | 130 | 72.9 | 1% |
| | | 7 | opel | dry | 80 | 31.9 | -3% |
| | | 8 | opel | dry | 130 | 75.7 | 0% |
| 2 – Odense | 6 | 5 | fiat | dry | 130 | 91.3 | 16% |
| | | 7 | opel | dry | 80 | 32.1 | 3% |
| 2 – Odense | 7 | 1 | opel | dry | 80 | 30.4 | 0% |
| | | 2 | opel | wet | 80 | 33.6 | -1% |
| | | 3 | opel | dry | 110 | 58.2 | 6% |
| | | 4 | opel | wet | 110 | 58.7 | -3% |
| | | 5 | opel | dry | 130 | 79.1 | 1% |
| | | 6 | opel | wet | 130 | 82.1 | -1% |
| | | 7 | fiat | dry | 80 | 29.3 | -1% |
| | | 8 | fiat | wet | 80 | 32.1 | -1% |
| | | 9 | fiat | dry | 110 | 56.4 | 1% |
| | | 10 | fiat | wet | 110 | 60.7 | -1% |
| | | 11 | fiat | dry | 130 | 76.5 | 1% |
| | | 12 | fiat | wet | 130 | 84.3 | -1% |
| 2 – Odense | 8 | 1 | opel | dry | 80 | 30.2 | -2% |
| | | 2 | opel | wet | 80 | 33.5 | 1% |
| | | 3 | opel | dry | 110 | 53.8 | -2% |
| | | 4 | opel | wet | 110 | 59.3 | 0% |
| | | 5 | opel | dry | 130 | 71.4 | -2% |
| | | 6 | opel | wet | 130 | 81.1 | 0% |
| | | 7 | fiat | dry | 80 | 28.2 | 0% |
| | | 8 | fiat | wet | 80 | 33.2 | 2% |
| | | 9 | fiat | dry | 110 | 56.2 | 2% |
| | | 10 | fiat | wet | 110 | 60.9 | 1% |
| | | 11 | fiat | dry | 130 | 74.4 | 0% |
| | | 12 | fiat | wet | 130 | 84.2 | 1% |
| 2 – Odense | 9 | 1 | fiat | dry | 80 | 27.4 | 1% |
| | | 2 | fiat | wet | 80 | 32.0 | 3% |
| | | 3 | fiat | dry | 110 | 53.6 | 1% |
| | | 4 | fiat | wet | 110 | 63.9 | 3% |
| | | 5 | fiat | dry | 130 | 75.4 | 5% |
| | | 6 | fiat | wet | 130 | 86.1 | 2% |
| 2 – Odense | 10 | 1 | fiat | dry | 80 | 30.0 | 5% |
| | | 2 | fiat | dry | 110 | 54.4 | 3% |
| | | 3 | fiat | dry | 130 | 79.5 | 5% |
| 3 – Værløse | 11 | 1 | opel | dry | 80 | 33.3 | 15% |
| | | 2 | opel | wet | 80 | 35.4 | 15% |
| | | 3 | opel | wet | 110 | 56.7 | 14% |
| | | 4 | fiat | dry | 80 | 31.7 | 6% |
| | | 5 | fiat | dry | 110 | 57.6 | 12% |
| | | 6 | fiat | wet | 80 | 33.9 | 10% |
| | | 7 | fiat | wet | 110 | 63.6 | 18% |

| Location | Test driver | Brake no. | Car | Dry/wet | 80/110/130 km/h | Lbrake (m) | $L_{brake\%}$ |
|---|---|---|---|---|---|---|---|
| 3 - Værløse | 12 | 1 | opel | dry | 80 | 32.0 | 23% |
| | | 2 | opel | dry | 110 | 79.8 | 64% |
| | | 3 | opel | wet | 80 | 49.2 | 79% |
| | | 4 | opel | wet | 110 | 83.0 | 74% |
| | | 5 | fiat | dry | 80 | 40.8 | 34% |
| | | 6 | fiat | dry | 110 | 56.2 | 23% |
| | | 7 | fiat | wet | 80 | 38.7 | 16% |
| | | 8 | fiat | wet | 110 | 61.1 | 18% |
| 3 - Værløse | 13 | 1 | fiat | dry | 80 | 32.3 | -1% |
| | | 2 | fiat | dry | 110 | 54.4 | 5% |
| | | 3 | fiat | dry | 130 | 74.7 | 2% |
| | | 4 | fiat | wet | 80 | 31.8 | 5% |
| | | 5 | fiat | wet | 110 | 48.6 | 0% |
| | | 6 | fiat | wet | 130 | 74.7 | 6% |
| | | 7 | opel | dry | 80 | 36.5 | 13% |
| | | 8 | opel | dry | 110 | 49.1 | -2% |
| | | 9 | opel | dry | 130 | 71.6 | -6% |
| | | 10 | opel | wet | 80 | 31.8 | 6% |
| | | 11 | opel | wet | 110 | 50.3 | -3% |
| | | 12 | opel | wet | 130 | 74.1 | 0% |
| 3 – Værløse | 14 | 1 | fiat | dry | 80 | 36.0 | 25% |
| | | 2 | fiat | dry | 110 | 45.0 | 8% |
| | | 3 | fiat | wet | 80 | 30.6 | 16% |
| | | 5 | opel | dry | 80 | 26.6 | 0% |
| | | 6 | opel | dry | 110 | 57.0 | 4% |
| | | 7 | opel | wet | 110 | 66.2 | 22% |
| 3 – Værløse | 15 | 1 | opel | dry | 80 | 39.9 | 29% |
| | | 2 | opel | dry | 110 | 101.1 | 79% |
| | | 3 | opel | dry | 130 | 103.3 | 35% |
| | | 4 | opel | wet | 80 | 65.4 | 127% |
| | | 5 | opel | wet | 110 | 92.4 | 58% |
| | | 6 | fiat | dry | 80 | 36.3 | 24% |
| | | 7 | fiat | dry | 110 | 55.3 | 12% |
| 3 – Værløse | 16 | 1 | opel | dry | 80 | 33.9 | 25% |
| | | 2 | opel | dry | 110 | 64.8 | 22% |
| | | 3 | opel | dry | 130 | 119.2 | 83% |
| | | 4 | opel | wet | 80 | 42.6 | 39% |
| | | 5 | opel | wet | 110 | 87.3 | 73% |
| | | 6 | fiat | wet | 80 | 40.6 | 26% |
| 3 – Værløse | 17 | 1 | fiat | dry | 80 | 32.9 | 9% |
| | | 2 | fiat | dry | 110 | 58.3 | 8% |
| | | 3 | fiat | dry | 130 | 84.9 | 12% |
| | | 4 | fiat | wet | 80 | 33.0 | 2% |
| | | 5 | fiat | wet | 110 | 58.3 | -1% |
| | | 6 | fiat | wet | 130 | 83.4 | 6% |
| | | 7 | opel | dry | 80 | 33.5 | 6% |
| | | 8 | opel | dry | 110 | 61.2 | -2% |

| Location | Test driver | Brake no. | Car | Dry/wet | 80/110/130 km/h | Lbrake (m) | $L_{brake\%}$ |
|---|---|---|---|---|---|---|---|
| | | 9 | opel | dry | 130 | 88.0 | 5% |
| | | 10 | opel | wet | 80 | 31.6 | -1% |
| | | 11 | opel | wet | 110 | 57.5 | -6% |
| | | 12 | opel | wet | 130 | 82.7 | 1% |
| 3 – Værløse | 18 | 1 | fiat | dry | 80 | 28.5 | 15% |
| | | 2 | fiat | dry | 110 | 57.9 | 24% |
| | | 3 | fiat | wet | 80 | 32.2 | 11% |
| | | 4 | fiat | wet | 110 | 55.3 | 7% |
| | | 5 | opel | dry | 80 | 30.3 | 31% |
| | | 6 | opel | dry | 110 | 59.2 | 16% |
| | | 7 | opel | dry | 130 | 74.3 | 9% |
| | | 8 | opel | wet | 80 | 34.3 | 24% |
| | | 9 | opel | wet | 110 | 56.3 | 9% |
| 3 - Værløse | 19 | 7 | fiat | dry | 80 | 33.9 | 11% |
| | | 8 | fiat | wet | 80 | 31.5 | 3% |
| | | 9 | fiat | dry | 110 | 52.3 | -1% |
| | | 10 | fiat | wet | 110 | 58.4 | 5% |
| | | 11 | fiat | dry | 130 | 75.7 | 1% |
| | | 12 | fiat | wet | 130 | 77.7 | 0% |
| 3 - Værløse | 20 | 7 | fiat | dry | 80 | 30.0 | -7% |
| | | 8 | fiat | wet | 80 | 31.3 | -3% |
| | | 9 | fiat | dry | 110 | 53.2 | -5% |
| | | 10 | fiat | wet | 110 | 54.3 | -2% |
| | | 11 | fiat | dry | 130 | 73.1 | 0% |
| | | 12 | fiat | wet | 130 | 76.5 | 1% |
| 3 - Værløse | 21 | 1 | fiat | dry | 80 | 65.8 | 170% |
| | | 2 | fiat | dry | 110 | 61.0 | 44% |
| | | 3 | fiat | wet | 80 | 54.7 | 105% |
| | | 4 | fiat | wet | 110 | 79.2 | 76% |
| | | 5 | opel | dry | 80 | 52.5 | 120% |
| | | 6 | opel | dry | 110 | 56.6 | 26% |
| | | 7 | opel | wet | 80 | 44.1 | 60% |
| | | 8 | opel | wet | 110 | 70.6 | 22% |
| 3 - Værløse | 22 | 1 | fiat | dry | 80 | 35.0 | 13% |
| | | 2 | fiat | dry | 110 | 68.8 | 38% |
| | | 3 | fiat | wet | 80 | 42.4 | 28% |
| | | 4 | fiat | wet | 110 | 66.1 | 19% |
| | | 5 | opel | dry | 80 | 47.8 | 69% |
| | | 6 | opel | dry | 110 | 58.9 | 10% |
| | | 7 | opel | wet | 80 | 32.8 | 12% |
| | | 8 | opel | wet | 110 | 83.7 | 61% |