Determination of braking distance and driver behaviour based on braking trials

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Outline

• Introduction and background
• Measurement programme
• Results from braking trials
• Effects from parameters not included in programme
• New recommended braking distances
Braking distance

One of the most important road design parameters

Braking distance - the most important factors:

• speed
• coefficient of friction between tyres and roadway
• driver’s braking behaviour/technique
• vehicle’s braking system and condition
• tyre condition
• road’s vertical grade
Present method in Danish Road Standards and Guidelines

\[ L_{\text{brake}} = \frac{V^2}{2 \cdot g \cdot (\mu_{\text{brake}} + s) \cdot 3.6^2} \]

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

<table>
<thead>
<tr>
<th>Speed (km/h)</th>
<th>( \mu_{\text{brake}} )</th>
<th>( L_{\text{brake}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>0.34</td>
<td>74 m</td>
</tr>
<tr>
<td>110</td>
<td>0.30</td>
<td>159 m</td>
</tr>
<tr>
<td>130</td>
<td>0.28</td>
<td>237 m</td>
</tr>
</tbody>
</table>
Programming

Study initiated by the Danish Road Directorate

Main purpose:

• to study the braking behaviour among non professional drivers

• to study braking distances at different physical conditions (speed, vehicle, road surface)

• to study relation between braking distance and friction
## Parametres in programme

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Levels</th>
<th>Levels Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>speed</td>
<td>3</td>
<td>80, 110 and 130 km/h</td>
</tr>
<tr>
<td>friction</td>
<td>3</td>
<td>road sections with friction in range 0.4-0.8</td>
</tr>
<tr>
<td>road surface</td>
<td>2</td>
<td>wet and dry road surface</td>
</tr>
<tr>
<td>vehicle</td>
<td>2</td>
<td>small + medium sized passenger car</td>
</tr>
<tr>
<td>tyre type</td>
<td>1</td>
<td>ordinary summer tyres</td>
</tr>
</tbody>
</table>
Measurement programme

2 professional test drivers on each test track
- all combinations (vehicle/speed/road surface)

A total of 72 braking trials

16 non professional test drivers (spread on 3 test tracks)
- almost all combinations (vehicle/speed/road surface)

A total of 115 braking trials

In addition: 30 comfort braking manoeuvres
Non professional test drivers

<table>
<thead>
<tr>
<th>Sex</th>
<th>Age</th>
<th></th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25-39</td>
<td>40-59</td>
<td>60-&gt;</td>
</tr>
<tr>
<td>Female</td>
<td>4</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>6</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Total</td>
<td>10</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>
Test cars

Make: Opel Vectra  
Model: 1.8 Comfort  
Year: 2004  
Weight: 1275 kg

Make: Fiat Grande Punto  
Model: 1.4 Dynamic  
Year: 2006  
Weight: 1060 kg
Measurement equipment
Tests tracks - Friction values

<table>
<thead>
<tr>
<th>Test track</th>
<th>Friction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry-section</td>
</tr>
<tr>
<td>1 Existing free-way</td>
<td>0.49</td>
</tr>
<tr>
<td>2 New free-way</td>
<td>0.52</td>
</tr>
<tr>
<td>3 Air field</td>
<td>0.75</td>
</tr>
</tbody>
</table>

Start approx. 1100 m before braking area

Driving direction

Dry

Wet
Wet road surface

Approx. 1.0 – 1.2 mm water layer
Results – professional test drivers

Test track 1

- Car1 - dry road
- Car1 - wet road
- Car2 - dry road
- Car2 - wet road
Results – professional test drivers

Test track 2

- **Car1 - dry road**
- **Car1 - wet road**
- **Car2 - dry road**
- **Car2 - wet road**

Graph showing L-brake (m) vs. Speed (km/h) for different conditions and cars.
Results – professional test drivers

Test track 3

- Car1 - dry road
- Car1 - wet road
- Car2 - dry road
- Car2 - wet road

L-brake (m) vs Speed (km/h)
# Deceleration values

<table>
<thead>
<tr>
<th>Dec\textsubscript{brake} (m/s\textsuperscript{2})</th>
<th>120-100 km/h</th>
<th>100-70 km/h</th>
<th>70-50 km/h</th>
<th>50-30 km/h</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dry</strong></td>
<td>8.4</td>
<td>8.6</td>
<td>9.1</td>
<td>9.2</td>
</tr>
<tr>
<td><strong>Wet</strong></td>
<td>7.8</td>
<td>8.1</td>
<td>8.3</td>
<td>8.4</td>
</tr>
</tbody>
</table>

\textbf{Dec\textsubscript{brake} (m/s\textsuperscript{2}) in speed interval 70-50 km/h}

<table>
<thead>
<tr>
<th>Initial speed</th>
<th>80 km/h</th>
<th>110 km/h</th>
<th>130 km/h</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dry</strong></td>
<td>9.1</td>
<td>9.2</td>
<td>9.4</td>
</tr>
<tr>
<td><strong>Wet</strong></td>
<td>8.1</td>
<td>8.6</td>
<td>8.5</td>
</tr>
</tbody>
</table>
Braking distance and friction

Dry road

Friction

Lbrake (m)

- 130 km/h - Dry
- 110 km/h - Dry
- 80 km/h - Dry
Braking distance and friction

Wet road

Friction vs. Lbrake (m)

- 130 km/h - Wet
- 110 km/h - Wet
- 80 km/h - Wet
Relation between deceleration, friction and initial speed (only wet road)

\[ \text{Dec}_{\text{brake}} = a \cdot \sqrt{\mu_{\text{fric}}} + b \cdot V_0 \]

where:
- \( \text{Dec}_{\text{brake}} \) is the average deceleration for the entire braking run (m/s\(^2\))
- \( \mu_{\text{fric}} \) is the recorded friction on the test track
- \( V_0 \) is the initial speed before braking (m/s)

For the recorded deceleration values on wet road (33 observations), the following results were obtained:

\[ \text{Dec}_{\text{brake}} = 8.79 \cdot \sqrt{\mu_{\text{fric}}} + 0.028 \cdot V_0 \quad R^2 = 0.97 \]
Estimated $L_{\text{brake}}$

$$L_{\text{brake}} = \frac{V_0^2}{2 \cdot Dec_{\text{brake}}} = \frac{V_0^2}{2 \cdot (8.79 \cdot \sqrt{\mu_{\text{fric}}} + 0.028 \cdot V_0)}$$
Estimated and measured braking distance ($L_{\text{brake}}$) on wet road at different friction values (0.4 - 0.8)

- Measured $L_{\text{brake}}$ at friction=0.49
- Measured $L_{\text{brake}}$ at friction=0.64
- Measured $L_{\text{brake}}$ at friction=0.74

Friction values
Non-professional test driver

Example:
Braking distance for prof. and non prof. test drivers
(car1+car2, only wet, test track 3)
Non-professional test driver – result cont.

- learning effect - better braking after 5-6 trials
- male test drivers have shorter $L_{\text{brake}}$ compared to female
- age group 50-70 years have the longest $L_{\text{brake}}$
- high speed combined with wet road conditions
  -> cautious braking behaviour
- in general - little difference between car 1 and car 2
- comfortable braking – deceleration $\approx 3.2 \text{ m/s}^2$
# Brake pedal pressure

<table>
<thead>
<tr>
<th>Test driver</th>
<th>$P_{\text{brake}}$</th>
<th>Time $P_{\text{brake}} &gt; 10$ kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non professional</td>
<td>35 kg</td>
<td>0.83 sec</td>
</tr>
<tr>
<td>Professional</td>
<td>74 kg</td>
<td>0.05 sec</td>
</tr>
</tbody>
</table>
Example:
Brake pedal pressure during braking (110 km/h. wet. test track 3)
Example:
Brake pedal pressure and deceleration values 100-70 km/h
(only car 1, prof. and non prof., all test tracks)

- $P_{\text{brake}} > 10$-15 kg – no difference in deceleration
- $P_{\text{brake}} < 10$-15 kg – deceleration decrease significant
Results from measurement programme

Recommended braking distance
Effect from parameters not included in the measurement programme

- based on a literature review
- only wet road

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Effect in relation to:</th>
<th>[min/max]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Make of tyre</td>
<td>Average tyre</td>
<td>-10% - +10%</td>
</tr>
<tr>
<td>Winter tyre</td>
<td>Summer tyre</td>
<td>+5% - +35%</td>
</tr>
<tr>
<td>Tread depth 1.6 mm</td>
<td>8 mm</td>
<td>+0% - +50%</td>
</tr>
<tr>
<td>Make of car</td>
<td>Average car</td>
<td>-10% - +10%</td>
</tr>
<tr>
<td>Loaded</td>
<td>Non-loaded</td>
<td>-10% - +15%</td>
</tr>
</tbody>
</table>

Vehicle with poor braking capability have 30-60% longer braking distance compared to test cars used in program.
New recommended braking distance

The braking distance should reflect:

- worst-case-scenario road conditions (wet road, friction = 0.4)  
  Estimated – based on prof. test drivers

- vehicle with poor braking capabilities (little tread depth, winter tyres, loaded. …)  
  Vehicle increment: +45%

- braking behaviour among the worst performing drivers  
  Behavioural increment: +30%
New recommended braking distances

<table>
<thead>
<tr>
<th></th>
<th>80 km/h</th>
<th>110 km/h</th>
<th>130 km/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{\text{brake}}$ – professional in test car</td>
<td>40 m</td>
<td>73 m</td>
<td>99 m</td>
</tr>
<tr>
<td>Behavioural increment: (+30%)</td>
<td>12 m</td>
<td>22 m</td>
<td>30 m</td>
</tr>
<tr>
<td>Vehicle increment: (+45%)</td>
<td>18 m</td>
<td>33 m</td>
<td>45 m</td>
</tr>
<tr>
<td><strong>Recommended $L_{\text{brake}}$</strong></td>
<td>70 m</td>
<td>128 m</td>
<td>174 m</td>
</tr>
</tbody>
</table>

$L_{\text{brake}}$  ->  Decc. $\sim 3.7$ m/s$^2$
Braking distance for respectively:
Measured in programme, Danish Guidelines, Green Book and new recommended values

- Measured L\textsubscript{brake} - fric=0.49
- Measured L\textsubscript{brake} - fric=0.64
- Measured L\textsubscript{brake} - fric=0.74
Braking distance for respectively:
Measured in programme, Danish Guidelines, Green Book and new recommended values

<table>
<thead>
<tr>
<th>Speed (km/h)</th>
<th>Measured $L_{brake}$ - fric=0.49</th>
<th>Measured $L_{brake}$ - fric=0.64</th>
<th>Measured $L_{brake}$ - fric=0.74</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>150</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>250</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>350</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Braking distance for respectively:
Measured in programme, Danish Guidelines, Green Book and new recommended values

- Measured $L_{\text{brake}}$ - fric=0.49
- Measured $L_{\text{brake}}$ - fric=0.64
- Measured $L_{\text{brake}}$ - fric=0.74
- Estimated $L_{\text{brake}}$ - fric=0.4
Braking distance for respectively:
Measured in programme, Danish Guidelines, Green Book and new recommended values
Braking distance for respectively:
Measured in programme, Danish Guidelines, Green Book and new recommended values

- Measured $L_{\text{brake}}$ - fric=0.49
- Measured $L_{\text{brake}}$ - fric=0.64
- Measured $L_{\text{brake}}$ - fric=0.74
- Estimated $L_{\text{brake}}$ - fric=0.4
- Behavioural increment (+30%)
- Vehicle increment (+45%)
Braking distance for respectively:
Measured in programme, Danish Guidelines, Green Book and new recommended values

<table>
<thead>
<tr>
<th>Speed (km/h)</th>
<th>Lbrake (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Measured Lbrake - fric=0.49</td>
</tr>
<tr>
<td>50</td>
<td>Measured Lbrake - fric=0.64</td>
</tr>
<tr>
<td>100</td>
<td>Measured Lbrake - fric=0.74</td>
</tr>
<tr>
<td>150</td>
<td>Estimated L_{brake} - fric=0.4</td>
</tr>
<tr>
<td>200</td>
<td>Behavioural increment (+30%)</td>
</tr>
<tr>
<td>250</td>
<td>Vehicle increment (+45%)</td>
</tr>
<tr>
<td>300</td>
<td>New recommended braking distance</td>
</tr>
</tbody>
</table>

- Measured L_{brake} - fric=0.49
- Measured L_{brake} - fric=0.64
- Measured L_{brake} - fric=0.74
- Estimated L_{brake} - fric=0.4
- Behavioural increment (+30%)
- Vehicle increment (+45%)
- New recommended braking distance
Braking distance for respectively:
Measured in programme, Danish Guidelines, Green Book and new recommended values

- Measured L\textsubscript{brake} - fric=0.49
- Measured L\textsubscript{brake} - fric=0.64
- Measured L\textsubscript{brake} - fric=0.74
- Estimated L\textsubscript{brake} - fric=0.4
- Behavioural increment (+30%)
- Vehicle increment (+45%)
- New recommended braking distance
- Green Book

Speed (km/h)

L\textsubscript{brake} (m)
Braking distance for respectively:
Measured in programme, Danish Guidelines, Green Book and new recommended values

- Current Danish Guidelines + safety increment
- Current Danish Guidelines
- Green Book
- New recommended braking distance
- Vehicle increment (+45%)
- Behavioural increment (+30%)
- Estimated $L_{brake} - \text{fric}=0.4$
- Measured $L_{brake} - \text{fric}=0.49$
- Measured $L_{brake} - \text{fric}=0.64$
- Measured $L_{brake} - \text{fric}=0.74$
Braking distance - international values

- UK
- DK - current guidelines
- USA - Green book
- DK - study
- Germany
- UK - "One step down"
- Sweden
- Norway