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Winter braking tests with 66 drivers, different tyres and disconnectable ABS

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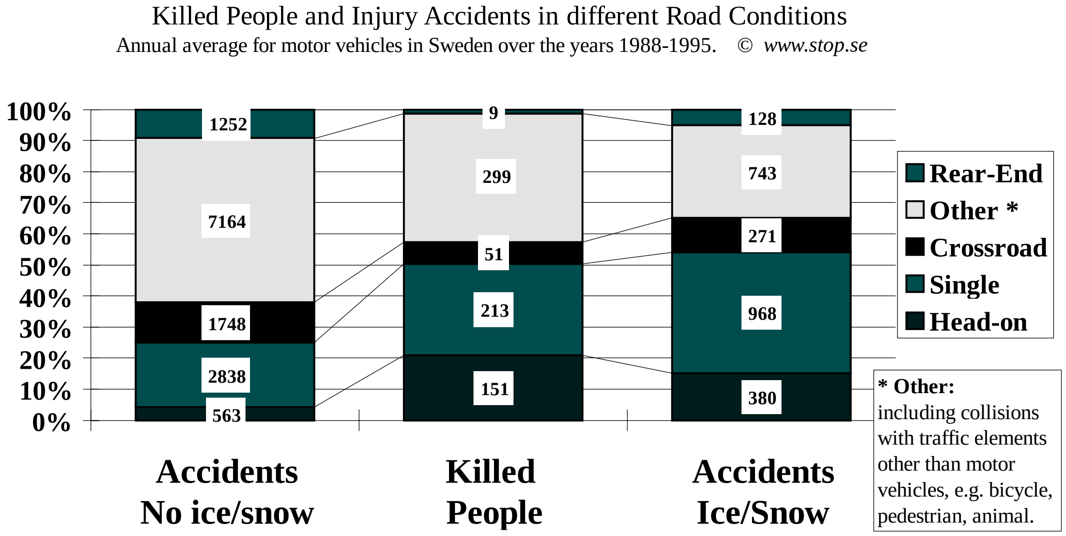
1. Introduction

Reduced braking performance: It is well known that braking performance is substantially reduced in winter, when roads are covered with ice and snow. The deceleration capacity may decrease by more than 90% from dry road conditions. Consequently, the braking distance may become more than ten times as long, when the road surface switches from dry to icy.

Reduced stability: In addition, stability and steerability may be lost on ice during normal speed adjustments or steering manoeuvres with minor horizontal accelerations. Since braking 'consumes' adhesion, cornering forces may easily become too small, particularly if the wheel locks up.

This is demonstrated by official statistics of Sweden, where icy road conditions are significantly over-represented in head-on collisions; see Strandberg (1989)[1]. Statistics reveal a similar over-involvement of single vehicle accidents on icy roads. Together with head-on collisions they cause about 50% of all motor vehicle fatalities in Sweden. See Fig.1.


Killed People and Injury Accidents in different Road Conditions
Annual average for motor vehicles in Sweden over the years 1988-1995. © *www.stop.se*

*** Other:**
including collisions with traffic elements other than motor vehicles, e.g. bicycle, pedestrian, animal.

Fig.1 Killed people and number of police reported accidents with personal injuries in Sweden distributed between accident types and road surface conditions. Data from SCB (1989-1996)[2].

The overrepresentation of slipperiness corresponds to how vehicles move in head-on and single vehicle accidents. Diminishing tyre-road adhesion means less critical speed and reduced directional stability (Strandberg et al, 1982)[3], which may trigger these types of accidents.

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In accident investigations, the difference between front and rear axle tyres should be carefully examined, since it is decisive of stability. This recommendation applies to any accident with evidence of skidding, irrespective of road condition. A survey[1] of fatal hydroplaning accidents in four summer weeks, revealed that nine of ten people were killed in crashes where the deviating car had a much deeper tread pattern at the front tyres than at the rear ones. If the lateral adhesion is greater at the front axle, stability is threatened. The phenomenon may be illustrated by simplified force diagrams, such as Fig.2 and quantified in differential equations[3] resulting in expressions, e.g. for critical speed like the one below.

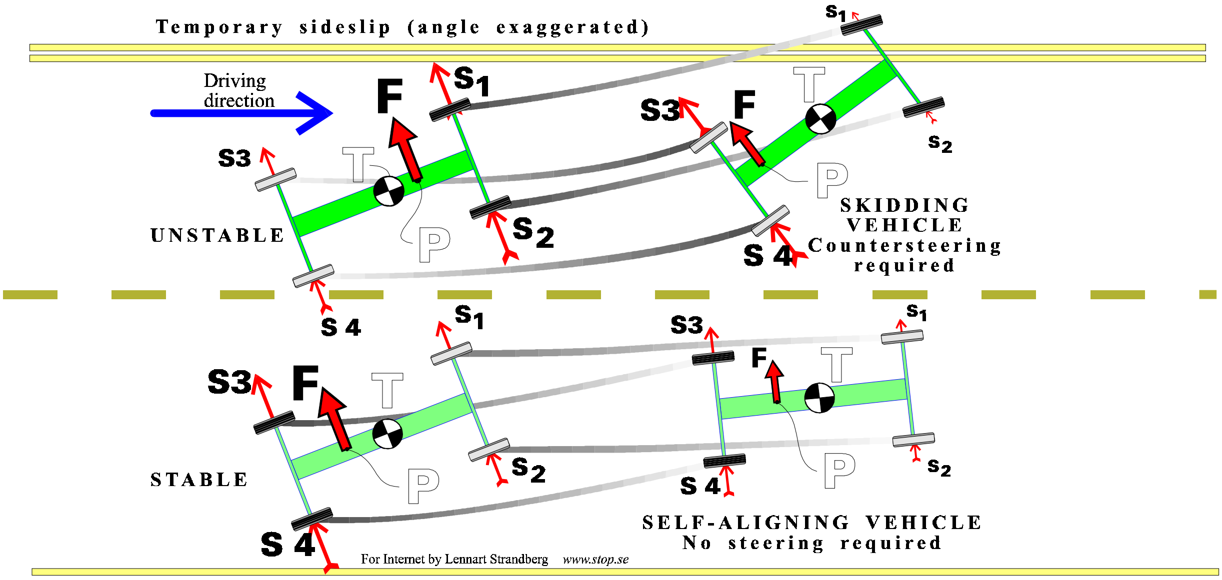

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Fig.2 Simplified illustration of how stability may be lost, if the cornering stiffness coefficient, $K=S/\alpha/N$ (Side force per sideslip αngle unit divided by Normal force), is superior at the *front* tyres. **Figure notation**: Side forces (**S**), their resultant (**F**) and the position (**P**) of its application point in relation to the mass centre (**T**).

Nevertheless, yaw stability is more likely to be lost on slippery roads. Consider the linear approximation of critical speed (v_c)

$$v_c = \sqrt{\frac{K_{12} \cdot K_{34}}{K_{12} - K_{34}} \cdot L \cdot g} \qquad (1)$$

where L is the vehicle wheel-base, g is the acceleration of gravity (9.8 m/s^2) and K is the cornering stiffness coefficient of front (index 12) and rear tyres (index 34) respectively. The quantity K is dimension-less (side Force per normal Force per Radian sideslip angle) but very sensitive to longitudinal (tractive or braking) forces according to the so called friction circle.

Assume that $Lg = 25$ m^2/s^2 and that $K_{34} = 0.9\,K_{12}$ at two different 'adhesion' levels ($K_{12} = 5$ and $K_{12} = 1$ representing wet and icy roads respectively). Though the front/rear coefficient ratio is the same, lowering the overall 'adhesion' level by 80% will result in a reduction of the critical speed from 33.5 m/s (121 km/h) for the wet road to 15 m/s (54 km/h) for the icy road. In practice, the front/rear ratio varies more on icy roads due to longitudinal forces.

The importance of stability and the advantage of ABS was confirmed in an experimental study on a frozen lake by Strandberg (1991)[4]. In a double lane change manoeuvre without braking, loss of control occurred in 40% of the tests with over-steering properties (superior tyres at the front). When tyres were shifted between front and rear axles, the loss of control ratio decreased to 20% of the tests.

In other braking tests within the same study, ABS gave significant improvements both of deceleration performance and of directional stability. Lane marks were hit in 30 of 208 braking tests without ABS, but in only one (1) of 208 tests with ABS. Since a frozen lake lacks inclinations and is slightly concave, the braking tests were combined with a smooth lane change manoeuvre. Still, these tests may have been too easy for drivers to carry out, in comparison with emergency braking in real traffic on uneven, convex and inclined road surfaces. Therefore, more road-like surfaces were selected for the tests reported below.

Variation in braking performance: Less well-known than the *reduction*, however, is the great *variation* in individual braking performance between cars, tyres and drivers on slippery winter roads. While poor tyres and sub-optimal brake force distribution may require some tenths (10%) longer braking distance than a well performing vehicle on dry or wet roads, extensions of several times (100%) are typical on ice and snow. Even greater differences appear, if car and tyre variation are combined with the variance in drivers' skill, particularly when directional stability is considered to be a component of the braking performance quality.

Except of the hazards due to unpredicted shifts in properties within one vehicle, differences between vehicles in braking performance are responsible of many rear end crashes and whiplash injuries. A vehicle with inferior brakes and tyres must be driven a much longer distance behind superior vehicles on slippery winter roads.

Assume that the leading car (index 1) in a queue is braking from cruising speed $\boldsymbol{v_0}$ with constant deceleration $\boldsymbol{d_1}$ to standing still in a distance of $\boldsymbol{S_1}$. If the following car (index 2) starts braking simultaneously (driver reaction time neglected) with a smaller deceleration $\boldsymbol{d_2}$, it needs a distance lag ($\boldsymbol{L}$), which may be determined from its braking distance $\boldsymbol{S_2}$ ($>S_1$) as follows

$$L \equiv S_2 - S_1 = v_0^2\left(\frac{1}{2d_2} - \frac{1}{2d_1}\right) = \frac{v_0^2 \cdot (d_1 - d_2)}{2 \cdot d_1 \cdot d_2} \tag{2}$$

Since both cars were driven at the same speed before braking, the minimum time lag ($\boldsymbol{T}$) is

$$T \equiv \frac{L}{v_0} = \frac{v_0 \cdot (d_1 - d_2)}{2 \cdot d_1 \cdot d_2} \tag{3}$$

In order to arrive at units used in driver education, v in m/s is substituted by $\boldsymbol{H}$ in km/h and d in m/s^2 by $\boldsymbol{R}$ in g-units (1g=9.8m/s^2). Then, the last expression yields

$$T = \frac{H_0 \cdot (R_1 - R_2)}{7.2 \cdot g \cdot R_1 \cdot R_2} \tag{4}$$

With $C_d=R_1/R_2=d_1/d_2$ (>1) denoting the deceleration performance ratio, multiplication of the initial speed (km/h) and time lag coefficient ($\boldsymbol{\tau_H}$) in the expression below will determine the minimum time lag (in seconds) to avoid collision

$$\tau_H \equiv \frac{T}{H_0} = \frac{(C_d - 1)}{7.2 \cdot g \cdot R_1} \tag{5}$$

Equation (5) is the basis of Fig.3, where the time lag coefficient (τ_H) is plotted versus leading vehicle deceleration (R_1) for five values of C_d. Differences in deceleration performance that seem common today, require extreme time lags at low adhesion levels.

Example: Consider two cars with deceleration capacities of R_1=0.2g and R_2=0.1g (C_d=2 - upper dashed line in Fig.3). Car no.2 follows car no.1, both at a speed of 100km/h. If driver no.1 begins emergency braking, a time lag of at least 7 seconds is required by driver no.2 in the following car to stay behind.

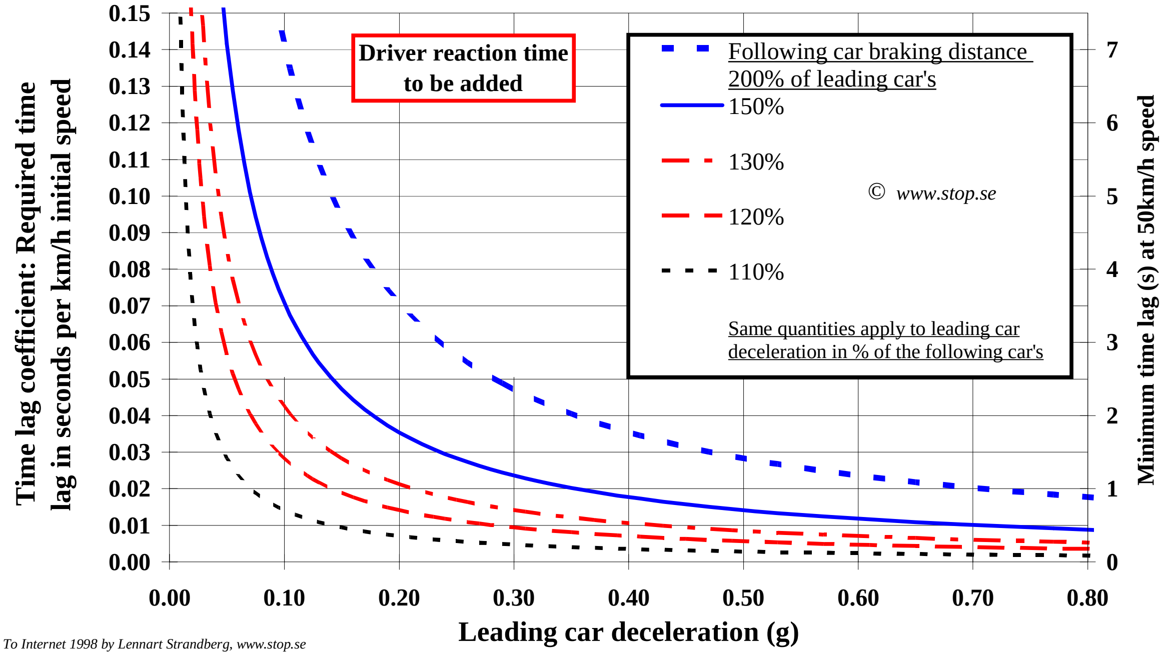


Fig.3 Minimum time lag to avoid rear end collision, when a leading car is braking at a greater deceleration than the following car.

2. Methods

To quantify the problems mentioned above, braking tests were carried out with ordinary drivers on icy and snowy surfaces for three winter weeks. In 22 test sessions, three drivers each participated by driving four test cars with disconnectable ABS and different types of tyre.

The driver subjects were instructed to brake the car from suburban cruising speed to a full stop within the marked lane and using a braking distance as short as possible. The deceleration was computed from the differences among three speed sensor values (stationary light barriers crossing the test lanes). A session took about 3-4 hours including plenary instructions.

Calendar time, project stages and considered sessions: The first recorded tests took place on Monday, 13 February, and the last regular session was completed on Sunday, 5 March 1995. Though 31 sessions were recorded, only 22 sessions have been used in this evaluation. In the remaining 9 sessions, weather and technical problems resulted in missing data, which may cause bias in the results. The 3-week test period was split into three stages:

Stage a) Session no.1-15 (SS no.1-6 & no.11 excluded). **8 sessions evaluated**;
Stage b) Sessions no.16-25 (SS no.18 & no.19 excluded). **8 sessions evaluated**;
Stage c) Sessions no.26-31 (all of them included). **6 sessions evaluated**.

Car individuals and tyre types were shifted between stages; see the Vehicle & Tyre paragraphs.

Location: The test site was located in the northern mountain area of the Swedish province Dalarna (Dalecarlia), where many people go for winter vacation and downhill skiing. Equipment installations and other arrangements were made at a private airport between Saelen and Roerbaecksnaes.

Test lanes: Three straight and parallel but slightly inclined test lanes were prepared.
A) varying snow/ice surface (snow removed only when layer was considerably thick);
B) ice surface being polished, since no studded tyres were allowed (snow removed promptly);
C) ice surface made harsh by studded tyres (snow removed promptly).

The width of the B&C lanes was 3.5 m. During sessions no.7-10 the A-lane width was 3.5 m, but it was increased to 5.0 m in the remaining 18 sessions. The borders were marked by red plastic tubes on both sides at each 10 m of length. In lane B&C the sensitivity to directional deviations was increased by a 'centre line' of rubber rings (diameter 0.2m) put between each pair of red tubes. Any test with hits of centre rings or edge tubes was considered off-lane in the records (cf. Fig.15). The lanes were marked like this along a distance of at least 180 m.

Vehicles: Free of charge, Volvo Car Corporation contributed six Volvo 850 cars with four-wheel antilock (ABS) brakes. The cars were equipped with an optional switch on the dashboard, where the antilock function could be switched on or off by the driver and the instructor passenger. The cars were of the four-door sedan type, 1992 year model, and front wheel driven with 5-shifted manual gear-box. The driver subject and the instructor (front seat) passenger were the only occupants.

The brake systems were checked and adjusted by Volvo in Gothenburg before delivery to the test site. Only four cars were used simultaneously in the braking tests. The same type of tyres was mounted on all four wheels for several test sessions. However, certain tyres were shifted a few times among all six cars. This tyre permutation aimed at neutralising the effect of unknown car differences on tyre related results. Therefore, results are distinguished between types of tyre, but not between car individuals

Tyres: Free of charge, two European tyre manufacturers contributed sets of 4 wheels with various types of tyre. Nine types were used and distributed between the stages abc as follows. All makes are European except one type (a2) from Asia. Two different sets of New Studded M+S tyres (a4 & b4=c4)are distinguished by their ID no, as well as the New Friction tyres (a2 & c2). The name 'Friction' tyre may be inadequate in English. It stems from the Swedish name for tyres with high "hysteresis" (inner damping) rubber, which creates friction forces when sliding on harsh road surfaces.

a1) New Summer tyres - Reference type (same four wheel individuals as b1 & c1).
a2) New 'Friction' tyres. Hysteresis rubber for ice & snow adhesion. Asian makes. ID no.6.
a3) New unstudded M+S tyres. Made for studding but without studs.
a4) New Studded tyres. 105 studs per tyre. Same make and type as above (a3). ID no.8.

b1) New Summer tyres - Reference type (same four wheel individuals as a1 & c1).
b2) Worn Friction tyres. 5 years old. Tread pattern depth 5mm.
b3) Worn Summer tyres. 5 years old. Tread pattern depth 3-5mm.
b4) New Studded tyres. 110 studs per tyre. Same four wheel individuals as c4. ID no.9.

c1) New Summer tyres - Reference type (same four wheel individuals as a1 & b1).
c2) New 'Friction' tyres. Hysteresis rubber for ice & snow adhesion. European. ID no.5.
c3) Worn Studded tyres. 5 years old. Tread pattern depth 5mm.
c4) New Studded tyres. 110 studs per tyre. Same four wheel individuals as b4. ID no.9.

Stud protrusion: The distance between tyre wear surface and tip of stud is decisive of ice adhesion. Therefore, stud protrusion was measured after tests with computerised equipment (by Sven-Ake Lindén). Data for individual studs have been reduced to the statistics below.

	Type of Tyre	Number of studs per tyre (Average)	Protrusion (mm) 4 tyre Average	Protrusion (mm) 4 tyre Std.Dev.
a4)	**New Studded (ID8)**	105 (=419/4)	1.6	0.15
b4,c4)	**New Studded (ID9)**	110 (=439/4)	1.8	0.21
c3)	**Worn Studded**	105 (=420/4)	1.1	0.22

Drivers and testing order: In the 22 evaluated sessions, 66 drivers (24 women and 42 men) participated voluntarily without salary after having responded to announcements at hotels, shops and places of work in the Saelen winter tourism area. Their age varied between 19 and 70 years with average 35 and median 31 years. The testing order was varied between drivers, to distribute changes in road surface conditions and in driver capability between the different types of tyres and ABS-configurations. No person participated as a driver subject more than once.

Driving instructions: Drivers were instructed to stop the car from suburban cruising speed on a distance as short as possible without hitting the marks or leaving the lane. All sessions were preceded by detailed oral instructions and a few drive-through demonstrations of the test lanes.

The instructors gave completing information on demand, but no 'teaching' of braking techniques was allowed until the half-session break. Then, drivers were informed why they should depress the brake pedal heavily when ABS was in function. They were also told that deceleration might increase in lane A if they steer away from the tracks, where most cars have been driven.

Drivers were asked to check the tyres themselves, when moving from one test car to another. The instructors did not tell the drivers anything about the tyres or their past results on the three lane surfaces. On the other hand, drivers were carefully informed on the ABS function, when the instructor switched it on and off. In addition the ABS-indicator lamp lit when ABS was switched off.

> The complete instructions in Swedish may be downloaded from an Internet web-page in a more recent report by Strandberg (1998)[5]. There, concealed speed recordings has been evaluated: After each test, the driver returned in the opposite direction by lane A, where unprotected people from the test team were preparing the following test run. To avoid bias in their spontaneous speed selection, drivers were not told that speed was recorded also on their way back from one test to another.

Measurements and recorded data from braking tests: To assess the emergency braking performance, directional deviations were observed and recorded as lane marker hits via intercom. The mean deceleration was determined afterwards by computer processing of recorded stopping position ($\boldsymbol{X_S}$) and speed values. The speed was measured in three different positions along the lanes. These speed sensors were located at $\boldsymbol{X_1} = 12.5$ m, $\boldsymbol{X_2} = 53.5$ m and $\boldsymbol{X_3} = 103.5$ m after the lane entrance ($X = 0$).

Corresponding index convention for the recorded speeds, *v*, and mean decelerations, *d*, yields

$$d_{12} = \frac{v_1^{\;2} - v_2^2}{2S_{12}} \qquad d_{13} = \frac{v_1^{\;2} - v_3^2}{2S_{13}} \qquad d_{23} = \frac{v_2^{\;2} - v_3^{\;2}}{2S_{23}} \qquad (6)$$

where $\boldsymbol{S_{12}}$ denotes the distance between speed sensors no.1 and 2, etc.

$$S_{ij} = X_j - X_i \tag{7}$$

$$d_{1S} = \frac{v_1^2}{2S_{1S}} \qquad d_{2S} = \frac{v_2^2}{2S_{2S}} \qquad d_{3S} = \frac{v_3^2}{2S_{3S}} \tag{8}$$

where $\boldsymbol{S_{iS}}$ is the driven distance from speed sensor *i* to the 'car centre' stopping position (X_S)

$$S_{iS} = X_S - X_i + f_{mp} \tag{9}$$

In Eq (9) f_{mp}= 2.48m is an estimate of the distance in the test cars from its centre (C-pillars) to the front bumper which was the first part of the car reaching the speed sensor light barriers.

To reduce the influence of errors in the speed records (mostly due to 'light barrier false alarms') all evaluations have been based on the deceleration median:

$$R_m = Median(R_{12}, R_{13}, R_{23}, R_{1S}, R_{2S}, R_{3S}) \tag{10}$$

where R (=d/g) denotes the deceleration in g-units.

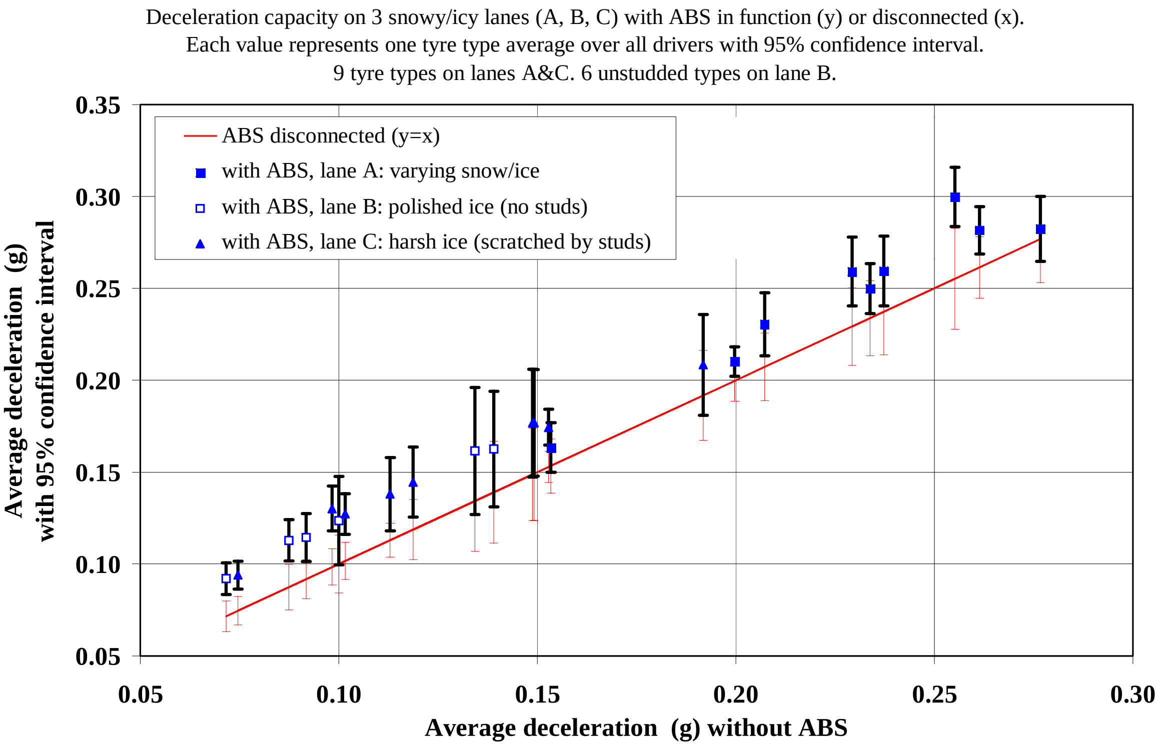
An extensive description of the methods is available in Swedish (Strandberg, 1995)[6].

3. Results

The deceleration statistics and plots presented below are based on test median values according to Eq.10. Like the first report on the experiments (in Swedish)[6], this paper contains population estimates given in average values and confidence intervals. Thereby, the statistical significance of any difference between two average values may be judged from the (lack of) overlap in their confidence intervals. Here, the mass-significance problem should be taken into account.

In addition to these estimates of population statistics, this paper presents plots with individual test data, standard deviations and number of observations. That may give an overview of the scatter due to individual deviations from the mean, and make it possible to approximate prediction intervals, etc, see for example Dowdy & Wearden (1991)[7]. It is likely that some readers will have such an interest, since this paper is to be presented at a Workshop on Traffic Accident Reconstruction; cf. Mogami (1998)[8].

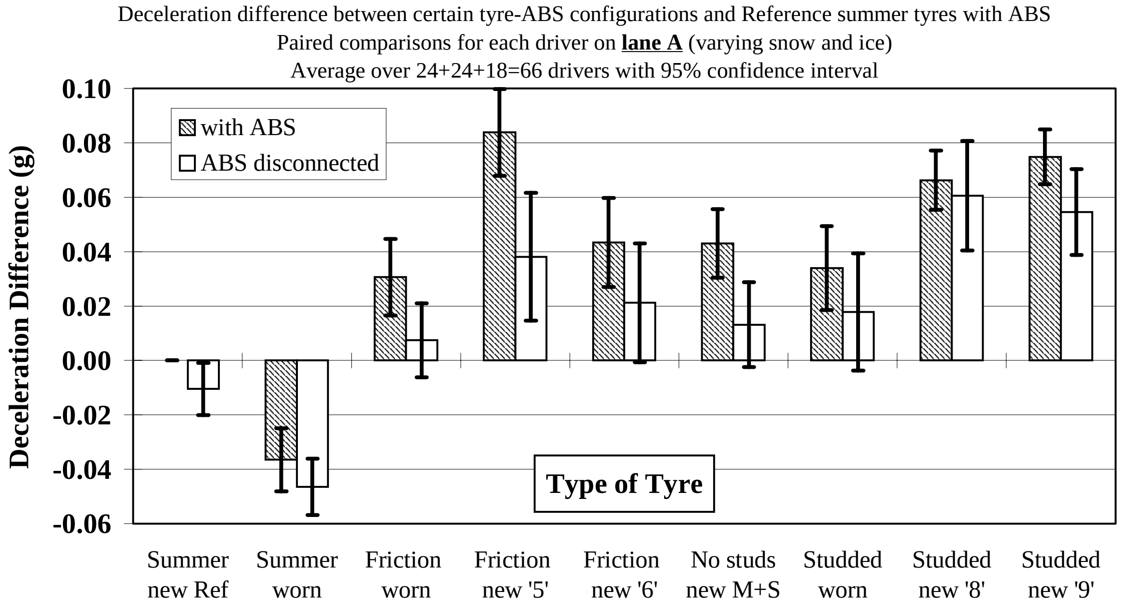
Deceleration averages: Deceleration mean values over all drivers and their confidence intervals have been computed to quantify the average deceleration performance of all tyre-ABS-road configurations. See Fig.4.



Deceleration capacity on 3 snowy/icy lanes (A, B, C) with ABS in function (y) or disconnected (x).
Each value represents one tyre type average over all drivers with 95% confidence interval.
9 tyre types on lanes A&C. 6 unstudded types on lane B.

Fig.4 Braking performance (determined by deceleration average over all drivers) on three surface types with nine tyre types and with ABS in function (y) or disconnected (x).

To distinguish the ABS influence on deceleration performance, paired comparisons were made for each lane with new summer tyres and ABS in function as reference. The average deceleration was greater with ABS than without for all 24 tyre-road surface combinations. See Fig.4 (all lanes), Fig.5 (lane A), Fig.6 (lane B) and Fig.7 (lane C).



Deceleration difference between certain tyre-ABS configurations and Reference summer tyres with ABS
Paired comparisons for each driver on **lane A** (varying snow and ice)
Average over 24+24+18=66 drivers with 95% confidence interval

Fig.5 Lane A average values over drivers of the differences in deceleration between the tests with each tyre type and the test with ABS and new summer tyres (Reference). Error lines represent 95% confidence intervals of the average values.

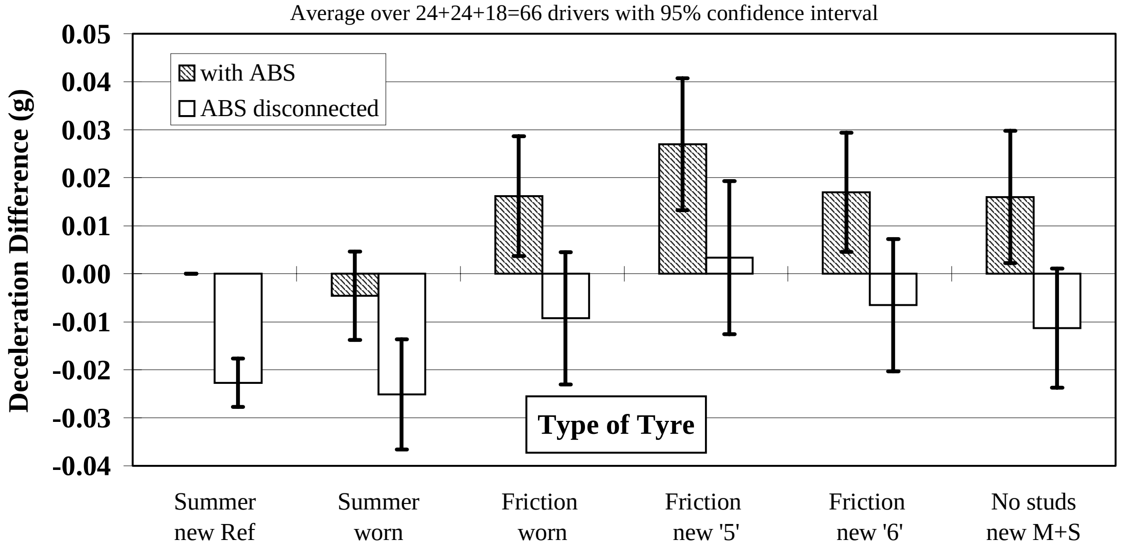

Deceleration difference between certain tyre-ABS configurations and Reference summer tyres with ABS
Paired comparisons for each driver on **lane B** (polished ice surface, no studs allowed)
Average over 24+24+18=66 drivers with 95% confidence interval

Fig.6 Lane B average values over drivers of the differences in deceleration between the tests with each tyre type and the test with ABS and new summer tyres (Reference). Error lines represent 95% confidence intervals of the average values.

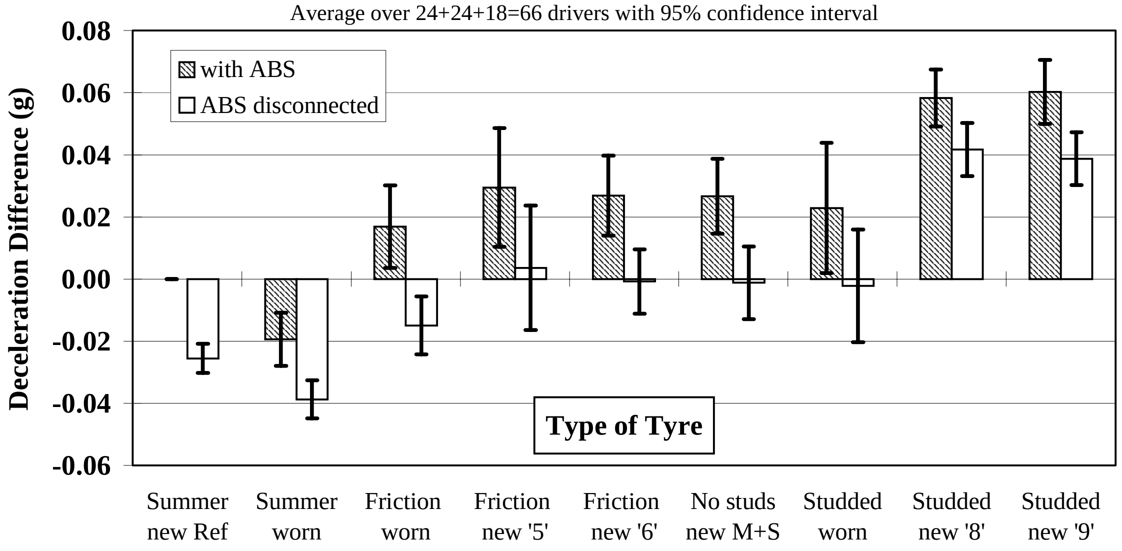

Deceleration difference between certain tyre-ABS configurations and Reference summer tyres with ABS
Paired comparisons for each driver on **lane C** (harsh ice surface, scratched by studs)
Average over 24+24+18=66 drivers with 95% confidence interval

Fig.7 Lane C average values over drivers of the differences in deceleration between the tests with each tyre type and the test with ABS and new summer tyres (Reference). Error lines represent 95% confidence intervals of the average values.

ABS gave greater *average* values for all conditions. However, many individual test pairs (ABS-switch on/off) had the opposite outcome, particularly on loose snow, which sometimes covered lane A (Fig.8). The snow layer thickness varied both in time and laterally due to the wheel tracks from braking tests and from returning cars. When the tracks were more slippery than the other parts of lane A, some drivers steered away from the tracks to improve adhesion.

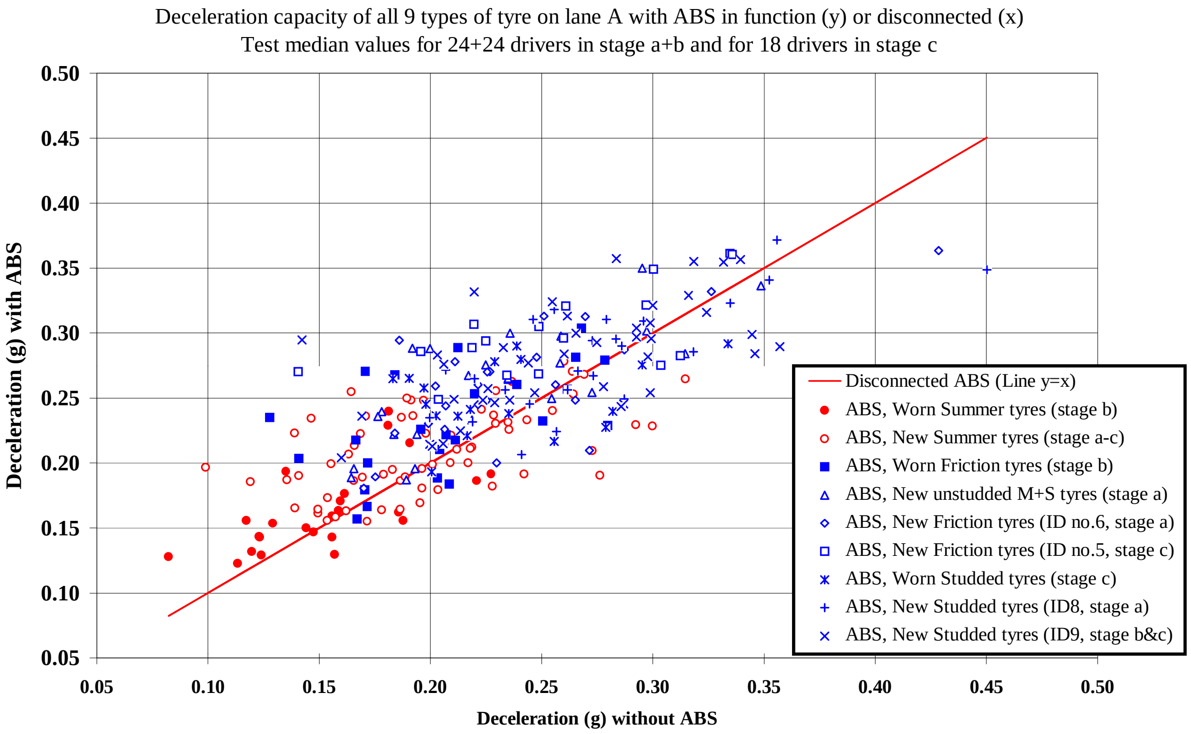


Fig.8 Braking performance (median deceleration in each test for all drivers). ABS in function (y) or disconnected (x). Nine types of tyre on lane A (varying snow/ice surface).

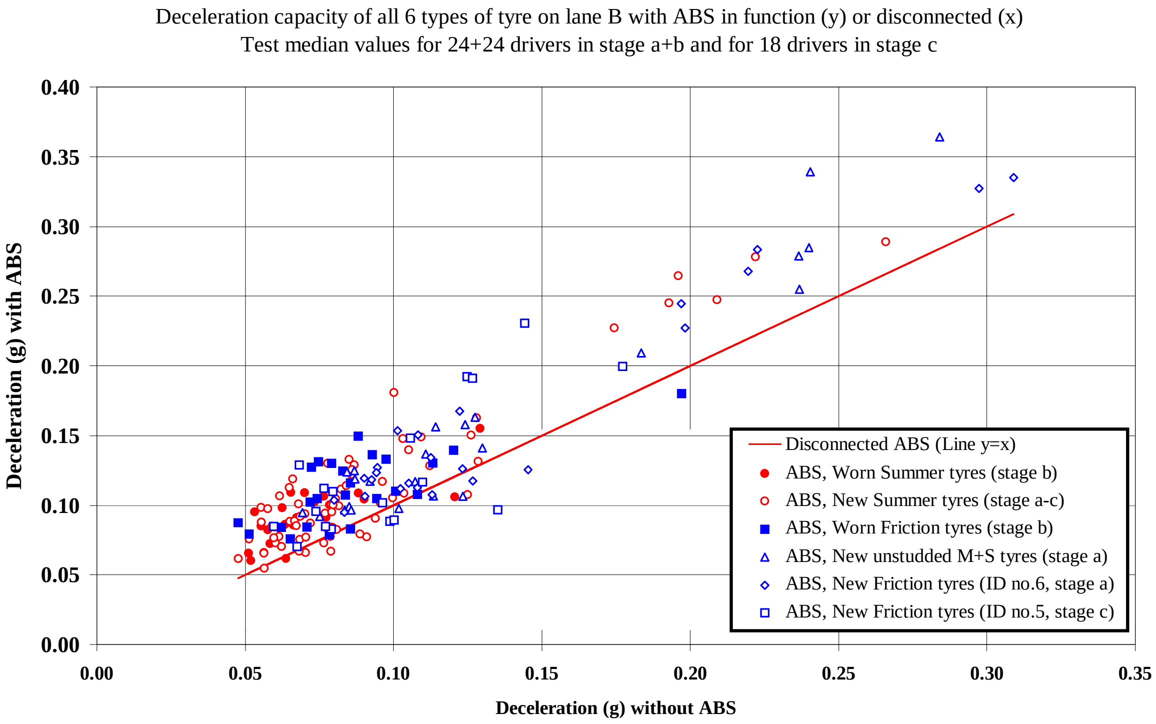


Fig.9 Braking performance (median deceleration in each test for all drivers). ABS in function (y) or disconnected (x). Six types of tyre on lane B (polished ice surface, no studs allowed).

On the polished ice surface (lane B, Fig.9) and on the harsh ice (lane C, Fig.10) ABS was superior in most tests and the scatter was less than on lane A.

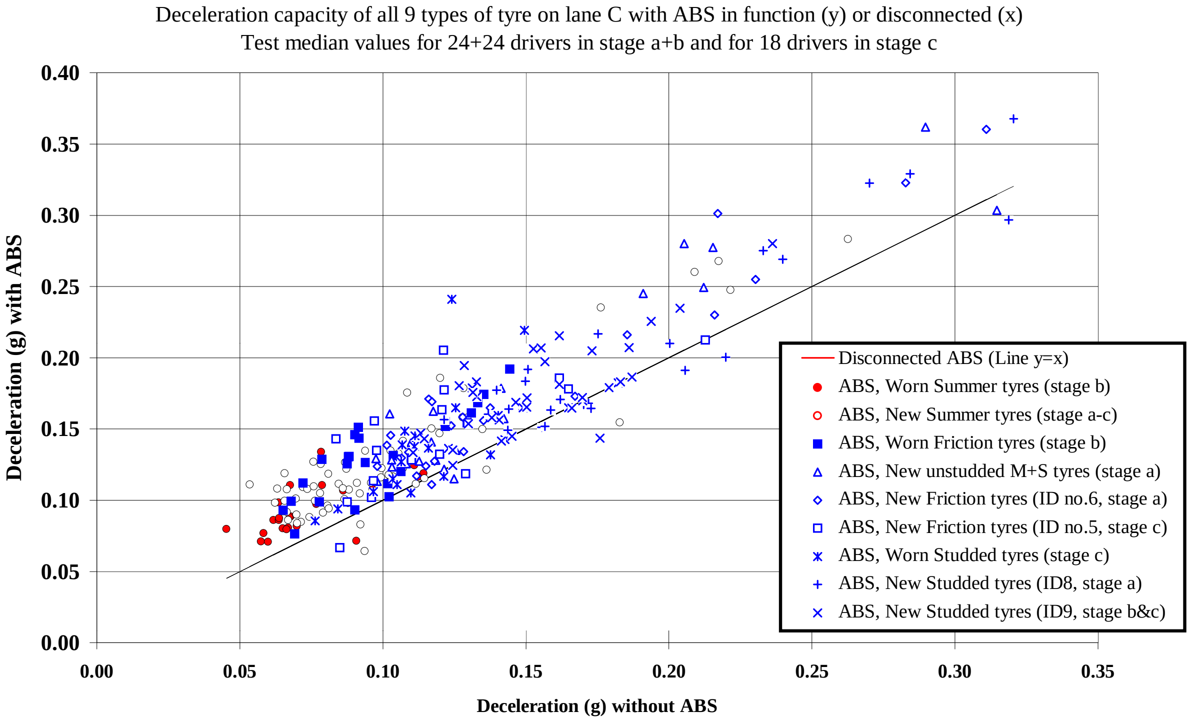


Fig.10 Braking performance (median deceleration in each test for all drivers). ABS in function (y) or disconnected (x). Nine types of tyre on lane C (harsh ice surface, scratched by studs).

Deceleration levels and variance: The scatter of deceleration data was illustrated in Fig.8-Fig.10. The following graphs (Fig.11-Fig.13) distinguish the same data between conditions. Central values are given by averaging the deceleration records over drivers and the variances are quantified by standard deviation error bars.

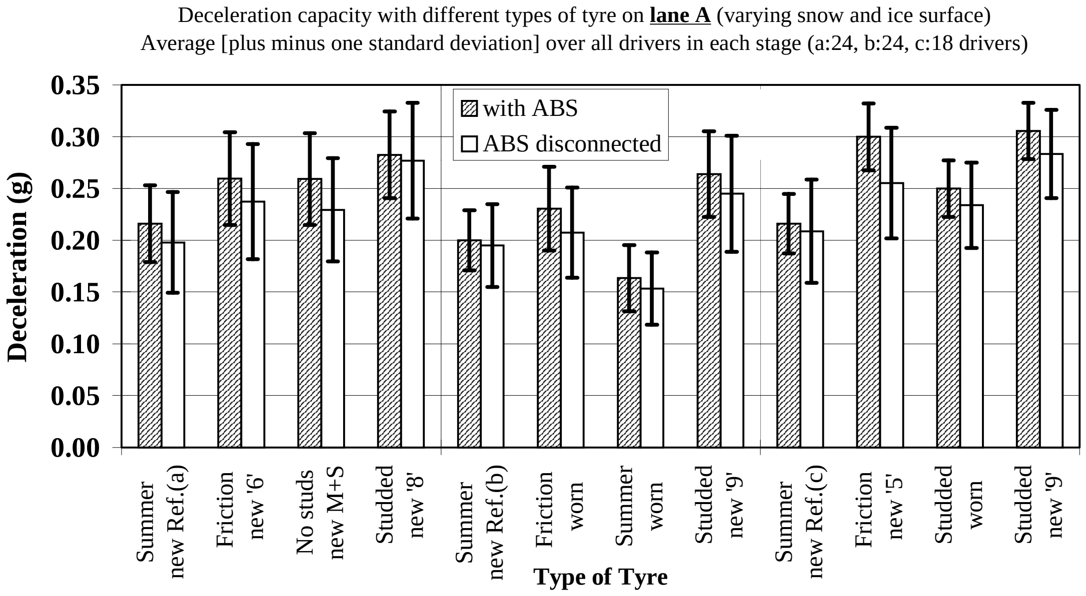


Fig.11 Lane A deceleration average values over drivers for the three weekly stages (a, b, c). Error lines represent plus minus one standard deviation.

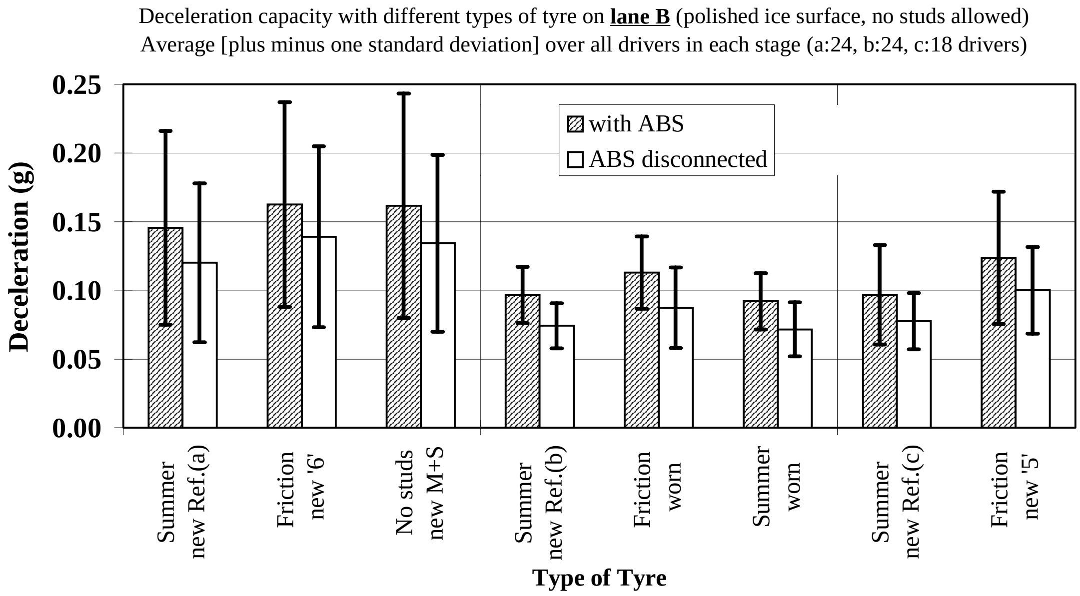


Fig.12 Lane B deceleration average values over drivers for the three weekly stages (a, b, c). Error lines represent plus minus one standard deviation.

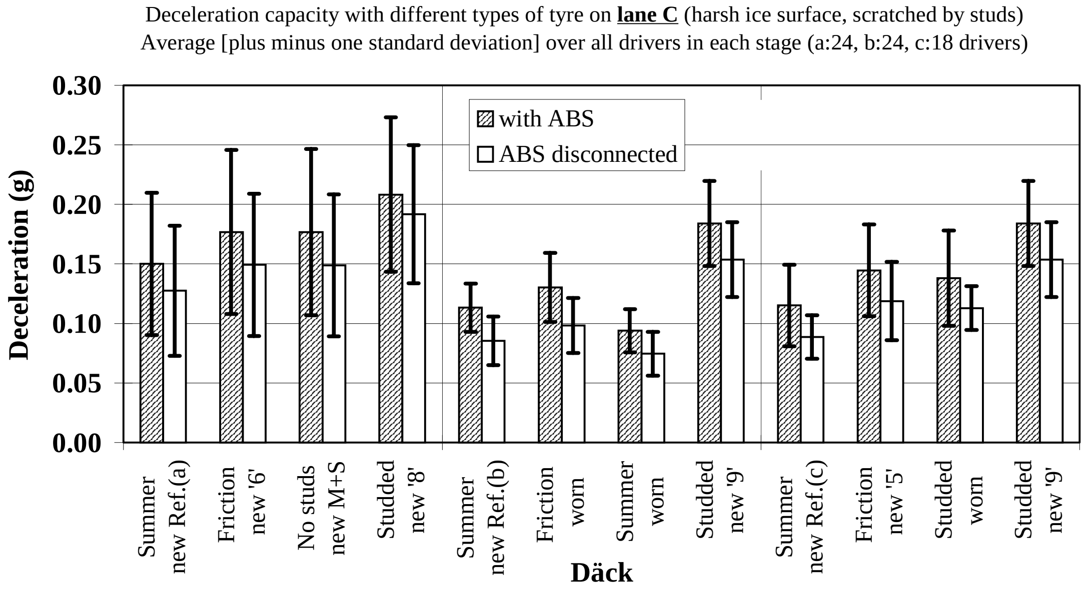


Fig.13 Lane C deceleration average values over drivers for the three weekly stages (a, b, c). Error lines represent plus minus one standard deviation.

Time lag requirements to avoid rear end collisions: The need of time lag in traffic queues increases both with road slipperiness and with variation in braking performance between drivers and vehicles. Referring to Fig.3, test data have been used for a simple evaluation of time lag minima for each lane and test session.

Cars and drivers exhibiting the smallest and the greatest deceleration records on each lane were selected from all 22 sessions. The inferior vehicle was assumed to be driven behind the superior one. The need of time lag was computed from Eq.5 and are presented in Fig.14.

Demand of time lag when the driver with the session's greatest deceleration is followed by the driver with the smallest.
Evaluated from recorded differences on each lane between the three drivers in each of 22 sessions.

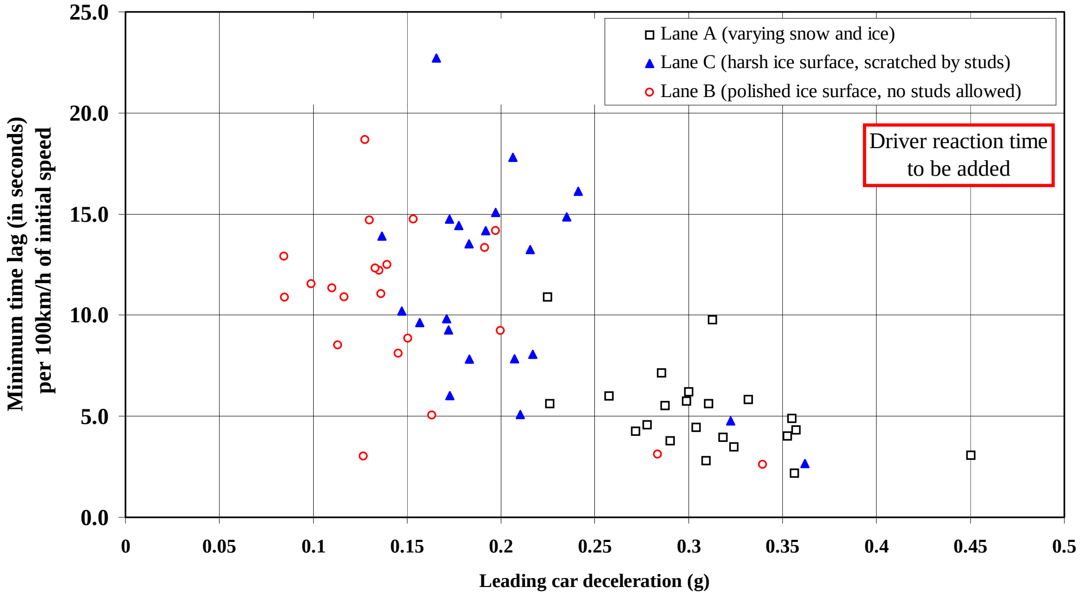


Fig.14 Minimum time lag if the car+driver with the session's greatest deceleration performance is driven in front of the most inferior vehicle on each lane. Same assumptions as in Fig.3.

ABS improved directional stability: In about 700 braking tests each with or without ABS, lane mark collisions have been recorded. The resulting sums are presented in Fig.15. Cars left the lane completely in 13% of the tests without ABS, but in only one (1) of the 700 ABS-tests.

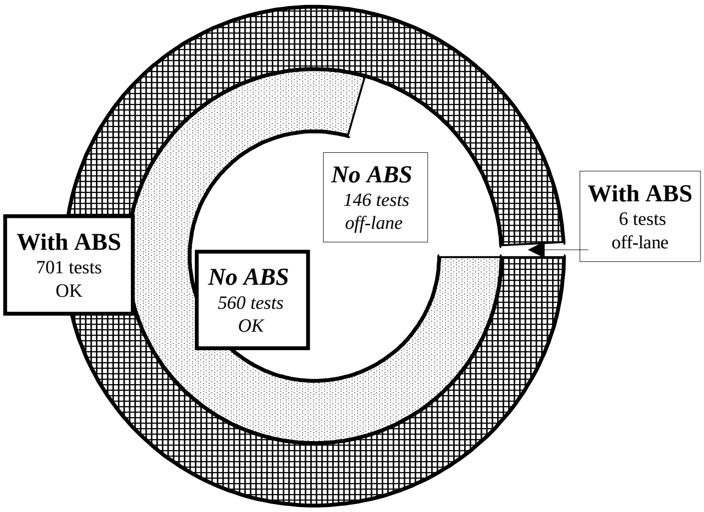


Fig.15 Successful braking tests (car remaining in lane and no marks hit) with or without ABS.

4. Discussion

Technical and educational measures: Tests with ordinary drivers have revealed substantial differences in braking performance on icy/snowy road surfaces among various types of tyre and cars with or without ABS. Results indicate that technical and educational measures offer a great potential of safety improvements.

The distinctive superiority of ABS brakes both in deceleration performance and in directional stability put serious doubts on the claims from believers of risk homeostasis (**RH**)[9,10]. They consider ABS and other technical improvements useless, and believe that drivers adapt their behaviour to keep risks constant. Negative results (no significant differences found) from various studies[11,12] are taken as proofs of RH, though many other scientists disagree on the principle; see e.g. Stottrup-Hansen et al. (1990)[13]. Though biased in annual mileage[14,17], insurance statistics from the U.S. (HLDI, 1994[15] & 1995[16]) have been considered proofs of RH. That seems to delay the transition from uncontrolled brakes to ABS in the car population.

Both driving and crash safety: Not only accident avoidance but also injury prevention may be effected, since crash speed is reduced with better braking performance. On the lane (B) with polished ice (no studs allowed), used summer tyres and disconnected ABS gave an average deceleration less than 50% of that with ABS and new winter tyres. In a situation where both cars start braking from the same point, the inferior car will go with 75% of the initial speed, where the superior car has stopped completely; see Strandberg (1995b[17], figure 2).

Whiplash injury prevention: Individual braking performance on each type of surface varied substantially between cars and drivers in many test sessions. A time lag of 3s between the vehicles would have been sufficient in less than 10% of the 66 cases, if the best car+driver was braking in front of the worst one from 70 km/h. Such time lag requirements are much greater than what is needed on dry or wet tarmac surfaces. The demand of greater gaps in car following situations is probably unexpected to most drivers of inferior vehicles. It may be responsible of many rear-end collisions and whiplash injuries.

Spread: The poor braking performance of certain vehicles on icy roads is a serious safety problem. The variations lead to dangerous mis-matches in the traffic flow. The great spread indicates that skid mark length only is insufficient for assessment of initial speed in accident investigations.

Unstudded tyres need studs to increase road adhesion: Irrespective of ABS, the average deceleration was greater on lane C than on lane B for all eight types of tyre without studs; see Fig.12 & Fig.13. Lanes B&C were covered with ice treated in the same way, except of that the surface of lane C was scratched and made harsh by the studded tyres. Since the lateral inclination of lane C was greater than of lane B, the advantage of harshness is probably underestimated in this study.

Road adhesion is increased by studs on ice-free road surfaces, too. This has been observed as a seasonal variation in Germany, which faded out after the winter of 1975/76, when studs were banned. Before that, the enhancement of road adhesion during spring and summer (due to traffic with studs in winter) may have reduced crash speeds and prevented some accidents, which would have occurred with more polished road surfaces. The advantage of stud scratching is well known among tyre development professionals and should be taken into account when prohibition of studs is considered.

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References in endnotes

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[1] Strandberg L (1989). Skidding Accidents and Their Avoidance with Different Cars. Proc. (pp.825-828) *TWELFTH INTERNATIONAL TECHNICAL CONFERENCE ON EXPERIMENTAL SAFETY VEHICLES, ESV*, Goteborg. Reprint 158, VTI, SE-58195 Linkoping, Sweden.

[2] SCB (1989) ... SIKA (1996). Traffic Injuries 1988 ... Traffic Injuries 1995 (annual publication). *Official Statistics of Sweden.* Statistiska Centralbyran, Swedish Institute for Transport and Communications Analysis, Statistics Sweden, SE-104 51 Stockholm.

[3] Strandberg L, Tengstrand G, Lanshammar H (1983). Accident hazards of rear wheel steered vehicles. In G.Johannsen, J.E.Rijnsdorp (eds.) IFAC (International Federation of Automatic Control) Symposium on *ANALYSIS, DESIGN AND EVALUATION OF MAN-MACHINE SYSTEMS*, 1982, Baden-Baden. *Pergamon Press*, Oxford & New York.

[4] Strandberg L (1991). Crash Avoidance Capability of 50 Drivers in Different Cars on Ice. Proceedings (pp.810-826) on the *THIRTEENTH INTERNATIONAL TECHNICAL CONFERENCE ON EXPERIMENTAL SAFETY VEHICLES, ESV*, Paris (paper S7O08). Reprint 179, VTI, Ibid.

[5] Strandberg L (1998). Less safe in spite of speed reduction? Concealed speed recordings of 66 drivers in cars with disconnectable ABS. (In Swedish with English summary: Farligare trots sänkt fart? Dold fartmätning på 66 förare i bilar med urkopplingsbar ABS.) Fakta 981004, *STOP*, Box 1, SE-59054 Sturefors. Free Internet download at *www.stop.se/test/*

[6] Strandberg L (1995). Braking performance of ordinary drivers on ice and snow surfaces. Driving experiments with 9 different types of tyre and disconnectable ABS. (In Swedish: Normalfoerares bromsfoermaaga paa vintervaeglag. Koerexperiment med 9 olika daeck-typer och urkopplingsbar ABS.) Dialog no.2, *VETA*, Box 1, SE-590 54 Sturefors. English summary on the Internet at *www.veta.se/abs66ice.htm*

[7] Dowdy S, Wearden S (1991). Statistics for Research, Second Edition. *John Wiley & Sons*. ISBN 0-471-85703-3.

[8] Mogami K (1998). Program of International Workshop on Traffic Accident Reconstruction. Tokyo, 12-13 Nov. 1998. *National Research Institute of Police Science*, Japan 102-0075 (Internet Home Page *www.nrips.go.jp*).

[9] Wilde G J S (1982). The Theory of Risk Homeostasis: Implications for safety and Health. *Risk Analysis*, Vol.2, No.4.

[10] OECD (1990). Behavioural adaptations to changes in the road transport system. Organisation for Economic Cooperation & Development, Road Transp. Res., Paris. IRRD 824028.

[11] Biehl B, Aschenbrenner M, Wurm G (1987). Einfluss der Risikokompensation auf die Wirkung von Verkehrssicherheitsmassnahmen am Beispiel ABS. Unfall und Sicherheitsforschung Strassenverkehr, Heft 63. Bundesanstalt für Strassenwesen, Germany.

[12] Aschenbrenner K M, Biehl B, Wurm G W (1992). Mehr Vehrkehrssicherheit durch bessere Technik? Feldtuntersuchungen zur Risikokompensation am Beispiel des Antiblockiersystem (ABS). Forschungsberichte No. 246. Bundesanstalt für Strassenwesen, 5060 Bergisch Gladbach 1, Brüderstr.53, Germany. ISSN 0173-7066.

[13] Stottrup-Hansen E, Ahlbom A, Axelson O, Hogstedt C, Juul Jensen U, Olsen J (1990). Negative Results - no effect or information? *Arbete och Hälsa* 1990:17, National Institute of Occupational Health, 171 84 Solna, Sweden.

[14] Strandberg L (1995c). Misleading anti-looks at Antilocks. Prologue 951115, *VETA*, Box 1, SE-590 54 Sturefors. To be available for download from the Internet web-site *www.stop.se*

[15] HLDI (1994). Collision and Property Damage Liability Losses of Passenger Cars With and Without Antilock Brakes. Insurance Special Report A-41. Highway Loss Data Institute, 1005 North Glebe Road, Arlington, Virginia 22201, U.S.A.

[16] HLDI (1995). Three Years' On-the-Road Experience with Antilock Brakes: An Update. Insurance Special Report A-47. Highway Loss Data Institute, Ibid.

[17] Strandberg L (1995b). Driving and crash safety with antilock brakes (ABS). Dialogue no.3, *VETA*, Box 1, SE-590 54 Sturefors. To be available for download on the Internet web-site *www.stop.se*