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Brake tests to evaluate the human behaviour at different brake pedal characteristics

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ABSTRACT-Brake-by-wire represents the replacement of traditional brake components such as pumps, hoses, fluids, brake boosters, and tandem master cylinders by electronic sensors and actuators. The different design of these brake concepts poses new challenges for the automotive industry with regard to availability and fallback levels in comparison to standard conventional brake systems. In order to evaluate this, the behaviour of 67 participants on different brake pedal characteristics was investigated during a static vehicle braking simulator test. Participants were assessed on their response to the braking modes: normal brake function, booster breakdown and brake circuit failure. The interpretation of these results and a new designed driver warning approach fed into another study using a dynamic vehicle test. First results suggest that a coordinated driver warning and information concept adapted to the brake failure is helpful in bringing the test vehicle to a safe stop.

Keywords: Brake failure, Fallback level, Brake pedal characteristics, Static vehicle test

1. Introduction

The conventional brake system of modern passenger cars has a hydraulic layout. The main components of this system are: a vacuum brake booster, a tandem master brake cylinder with fluid reservoir (TMC) and the front and rear wheel brakes. The brake pedal normally forms the interface between the driver and the brake system and has the task of transmitting the foot force on the pedal exerted by the driver to the brake booster via the push rod. The brake pedal characteristic is the functional relationship between pedal force, pedal travel, and deceleration. The brake pedal "feel" of automotive brake systems is commonly understood to be represented by the subjective evaluation of pedal travel, pedal force and vehicle deceleration in a brake manoeuvre(1). The vehicle reaction during braking is influenced by the complete brake system; however, the components of brake systems have different dynamics and are partly non-linear. Hence a scientific description of the brake pedal feel is very difficult. Consequently, there is no common definition of brake pedal "feel" corresponding to a particular braking manoeuvre and range of deceleration. The brake pedal provides feedback for the driver on his/her current braking manoeuvre and the state of the braking system. The fallback level for automotive brake systems is defined as the brake performance which a brake system achieves in the case of a partial system failure. Hydraulic-mechanical fallback levels are possible, both for brake-by-wire systems with hydraulic-mechanical transmission, and for standard conventional brake systems. If a failure occurs within the brake system, the driver is confronted with a different pedal characteristic, which may lead to an inappropriate braking response(2). There are different interpretations of the optimum fallback level. Legal regulations are well understood and constitute the minimum requirement of the brake system performance. However, these regulations do not address the question as to whether the fallback level of the brake system will subsequently be tolerable and controllable for the drivers. Current research in the area of the vehicle dynamics is not helpful as a reference for the acceptance of a specific brake pedal characteristic in a failure mode by a driver. Therefore, the aim of the current study is to achieve a better understanding of how the driver reacts, perceives and evaluates different brake pedal modes in a static brake simulator test. The results will be the starting point for a more precise investigation in the area of fallback level designs for future automotive brake systems. The overall task in this investigation is to determine what fallback level setup is acceptable and manageable for an every-day-driver, and which technical measures can be applied to increase the acceptability. In addition to the technical design, the investigation will determine whether the acceptance of a fallback level is also influenced by the characteristics of the driver, e.g. gender, driving experience or age.

2. Methods

A study was undertaken using a brake pedal simulator integrated in a BMW 3 series car. Participants of the study were requested to undertake a braking task in response to each of three scenarios representing driving situations requiring strong, average and slight braking manouevres; and displayed on a visual display unit located inside the car. The process was undertaken statically, without motion of the car. The task was to achieve a target deceleration force which was displayed on the screen. Participants were tested under three different brake pedal modes *(normal, booster failure and circuit failure)* for each scenario. Participants were not aware of the condition of the braking system in each of the modes tested. After each braking scenario, participants were given a questionnaire to complete with items relating to the distance, strength and comfort of the brake pedal; and items relating to mode preference and familiarity. Demographic data, technical understanding, and driving experience and behaviour were also assessed by means of questionnaire items.

2.1 Brake scenarios

The different brake scenarios may be described as follows:

2.1.1 Slight braking

Traffic Light Braking: At a normal urban driving the vehicle speed of approx. 50 km/h is reduced smoothly to a standstill in front of a traffic light. Duration: approx. 7 seconds. Deceleration: approx. 0.2 g.

2.1.2 Average braking

Country road: Driving on a country road with a vehicle speed of approx. 100 km/h; driver recognizes a local sign and reduces the speed to 50 km/h. Duration: approx. 5 seconds. Deceleration: approx. 0.4 g.

2.1.3 Strong braking

Motorway driving with sudden lane change of a car behind a lorry; speed reduction of the vehicle from approx. 130 km/h to approx. 80 km/h. Duration: approx. 3 seconds. Deceleration: approx. 0.6 g.

2.2 Brake pedal characteristics

The force/distance relationship for each of the three modes tested is illustrated in Figure 2 below.

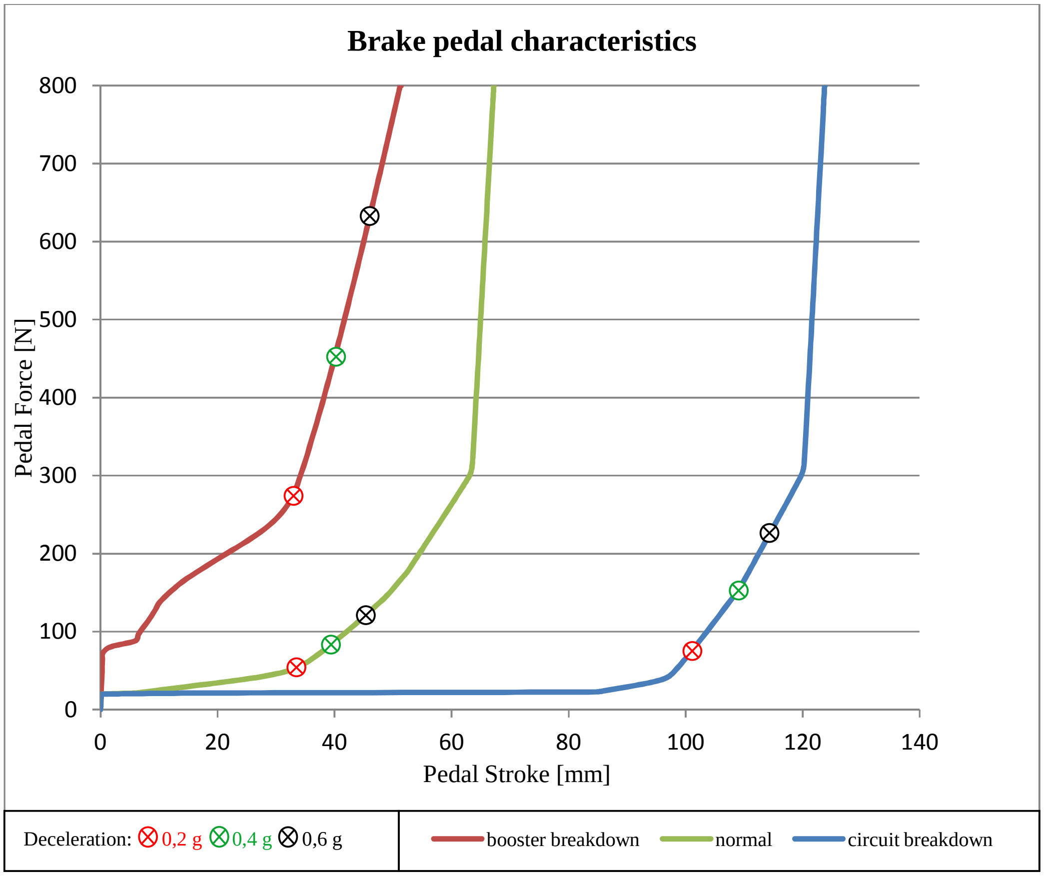

Figure 1: Brake pedal characteristics (*normal, booster breakdown and circuit breakdown modes*)

The Brake pedal characteristics is shown without the effect of the reaction disc inside the booster. It may be noted that to produce a force of a particular value requires more pedal travel under circuit failure mode and less pedal travel under booster failure mode compared to the normal operation; for example, to produce a force of 300 N requires a distance of approximately 35 mm under booster failure mode and approximately 120 mm under circuit failure, compared with approximately 65 mm under normal operation. Although forces in excess of 500 N may be theoretically generated with a pedal travel of approximately 40 mm under booster failure, Mendelson et al.(3) have observed that forces in excess of this value are achievable only by about 2.5 % of female drivers.

2.3 Questionnaire

The questionnaire given to participants for the test series was divided in five different sections:

2.3.1 Basic information

This section elicited physical attributes of the participants. Key demographic variables for statistical evaluation include, gender and age, which was categorised into the following groups: 20-29 years; 30-39 years; 40-49 years; 50 years and over.

2.3.2 Additional information

This section originally comprised two sub-sections; however, only one sub-section was subsequently incorporated into the analysis. This sub-section included a number of items used to categorise participants into the categories high, medium and low driving experience.

2.3.3 Technical understanding

One of the most important requirements of the static brake pedal simulation test was, that "normal car drivers" were to be tested and not participants with brake technology knowledge. Hence, the extent of the participant´s technical knowledge was assessed by the inclusion of a section in the questionnaire on technical understanding. From responses to items in this section, participants were given a score out of a possible maximum of 15 points. Technical knowledge was included in the statistical analysis to evaluate the relationship between participants.

2.3.4 The Manchester Driving Behaviour Questionnaire (MDBQ)

The Manchester Driver Behaviour Questionnaire (MDBQ) includes 50 questions designed to evaluate driver behaviour. Items on the MDBQ instrument are categorized as lapses, errors, ordinary violations and aggressive violations(4). Based on this test, many evaluations, with small changes of the questions, have been conducted all over the world. The purpose of the inclusion of the MBDQ instrument was twofold: primarily to verify that participants had normal driving habits by reference to validated norms; and secondarily to determine whether there is a significant correlation between driver behaviour and the validation of the brake pedal characteristics.

2.3.5 Participant evaluation of brake manoeuvres

This section comprised a number of items; all of which were answered for each of the three braking scenarios (slight, average and strong braking). The main items were 5-point Likert-style(5) items with responses ranging from 1 (very short / very weak / unacceptable) to 5 (very far / very strong / very comfortable); assessing distance, strength and comfort of the brake pedal:

- *How far did you have to actuate the brake pedal until the brake task was fulfilled? [Distance];*
- *How strongly did you have to actuate the brake until the brake task was fulfilled? [Strength];*
- *How comfortable was the brake pedal feel for you? [Comfort]*

3. Statistical analysis

The tests were completed by 67 participants: 39 men and 28 women; with ages in groups ranging from 20-29 years to 50 years or more. Full demographic characteristics of the sample are summarized in Table 1.

Table 1. Summary of participats

Categorical variable	**Frequency (%)**
Gender	
Male	39 (58.2%)
Female	28 (41.8%)

Age group	
20-29	20 (29.9%)
30-39	21 (31.3%)
40-49	15 (22.4%)
50+	11 (16.4%)
Annual driving range	
Under 5000 km p.a.	5 (7.5%)
5000-10000 km p.a.	15 (22.4%)
10000-20000 km p.a.	21 (31.3%)
Over 20000 km p.a.	26 (38.8%)
Numerical variable	**Mean (SD)**
Technical knowledge score (max 15)	10.2 (4.11)
MDBQ sub-scale scores [6]	
Lapses	1.93 (0.48)
Errors	1.63 (0.40)
Ordinary violations	2.46 (0.62)
Aggressive violations	1.77 (0.62)

The sample was summarized descriptively. Repeated measures analyses of variance (ANOVA) were conducted on the data, to assess the significance of variation in *comfort* scores across different braking modes, and different braking strengths[7]. The effect of the assumption of interval-level data on the questionnaire items relating to brake distance, force and comfort was assessed by sensitivity analyses in which corresponding non-parametric analyses using Friedman's test were conducted, and the results obtained from these tests compared against those obtained from corresponding parametric procedures[8]. The effect of factors and covariates on outcome measures was assessed using multiple regression analysis. For each of the *normal*, *booster failure* and *circuit failure* modes, in each of the braking modes, a main effects regression analysis was conducted, with the outcome measure considered to be the response to the questionnaire item *comfort*. Mean *comfort* scores (SD in brackets) for each of the 3 braking modes measured in each of the 3 braking strengths are summarized in Table 2 below.

Table 2. Mean (SD) comfort scores for *normal, booster failure* and *circuit failure* modes measured under *strong, average* and *slight* braking

Mode	Braking strength		
	Strong	Average	Slight
Normal	3.52 (0.766)	3.43 (0.679)	3.48 (0.725)
Booster failure	1.66 (0.789)	1.81 (0.941)	1.76 (0.922)
Circuit failure	1.97 (1.18)	2.28 (1.14)	2.37 (1.18)

It may be observed that in *normal* and *booster failure* braking modes, comfort scores were fairly static across different braking strengths; in *circuit failure* braking mode, *comfort* scores were substantially higher for slight and average braking than for strong braking. It may also be observed that *normal* mode *comfort* scores were consistently higher than *booster failure* and *circuit failure* braking mode scores. Sixty five out of the 67 participants (97.0%) reported that they would use the brake pedal in *normal* mode to drive on public roads during strong braking; 66 participants (98.5%) reported that they would use the brake pedal in *normal* mode to drive on public roads during average or slight braking. Sixteen out of the 67 participants (23.9%) reported that they would use the brake pedal in *booster failure* mode to drive on public roads during strong braking; 17 participants (25.4%) during average braking and 12 participants (17.9%) during slight braking. Twenty out of the 67 participants (29.9%) reported that they would use the brake pedal in *circuit failure* mode to drive on public roads during strong braking; 26 participants (38.8%) during average braking and 37 participants (55.2%) during slight braking. Fifty five out of the 67 participants (82.1%) reported that their preferred braking mode during strong braking was *normal*; 52 participants (77.6%) reported that their preferred braking mode during average or slight braking was *normal*. All participants in all braking tests who did not state *normal* as their preferred braking mode reported it to be the second choice mode. Three participants (4.5%) reported that they preferred the *booster failure* braking mode during strong, average or slight braking. Nine participants (13.4%) reported that they preferred the *circuit failure* braking mode during strong braking; 12 participants (17.9%) reported that they preferred the *circuit failure* braking mode during average or slight braking. Fifty eight of the 67 participants (86.6%) reported that the *normal* braking mode was most similar to that of the brake pedal in their own car (if they owned a car) during strong and slight braking. Fifty nine participants (88.1%) reported that the *normal* braking mode was most similar to that of the brake pedal in their own car (if they owned a car) during average braking.

3.1 Repeated measures ANOVAs - comparison across modes

Comfort scores did not differ significantly across *strong*, *average* and *slight* braking under the *normal* braking mode ($F_{2,132}$=0.547; p=0.580), or the *booster failure* braking mode ($F_{2,132}$=0.838; p=0.435). However, *comfort* levels were significantly different across *strong*, *average* and *slight* braking under the *circuit failure* braking mode ($F_{2,132}$=5.03; p=0.008). In this mode, pairwise comparisons, incorporating a Sidak correction [9] for multiple comparisons revealed *comfort* scores under *strong* braking to be significantly different to *comfort* scores under *average* braking (p=0.046) and *slight* braking (p=0.020), with scores being lower under *strong* braking (1.97) than under *average* braking (2.28) or *slight* braking (2.37) (Table 2). However, there was no evidence for a significant difference between *comfort* scores measured under *average* and *slight* braking. Friedman's tests conducted on the *normal*, *booster failure* and *circuit failure* modes across all levels of braking strength gave significance levels which were closely comparable with those obtained from the corresponding repeated measures ANOVAs. The corresponding *p*-values obtained were 0.501 for the *normal* braking mode, 0.541 for the *booster failure* braking mode and 0.001 for the *circuit failure* braking mode. Hence in all cases no changes to inferences would arise from the use of parametric analysis, suggesting that the assumption that the ordinal scores approximated well to interval-level data would be valid.

3.2 Repeated measures ANOVAs – comparison across braking strengths

Comfort scores were significantly different between *normal*, *booster failure* and *circuit failure* modes measured under *strong* braking ($F_{2,132}$=67.1; p<0.001), under *average* braking ($F_{2,132}$=45.4; p<0.001), and under *slight* braking ($F_{2,132}$=55.5; p<0.001). Pairwise comparisons, incorporating a Sidak correction for multiple comparisons, revealed that under all braking strengths, *normal* mode was scored significantly differently from either *booster failure* mode or *circuit failure* mode (p<0.001 in all cases); with *normal* mode having the consistently higher scores (Table 2). However, the difference between *comfort* scores in *booster failure* and *circuit failure* modes was not significant under any braking strength.

3.3 Regression analyses – normal braking mode

For strong braking, the sequential modelling strategy resulted in a final model including the *distance* variables, the *errors* subscale score of the MDBQ, and the *age range* variable; with the strongest association being indicated by the *distance* variable. For average braking, the sequential modelling strategy resulted in a final model including the *distance* variables, the *lapses* subscale score of the MDBQ, and the *age range* variable; with the strongest association being indicated by the *lapses* variable. For slight braking, the sequential modelling strategy resulted in a final model including the *distance* variables and the *technical knowledge* score; with the strongest association being indicated by the *distance* variable. The adjusted R_2 statistics of 0.13 to 0.21 indicated that all models were fairly good fits to the data.

3.4 Regression analyses – booster failure braking mode

For strong braking, the sequential modelling strategy resulted in a final model including the *Force* variable only. For average braking, the sequential modelling strategy resulted in a final model including the *force* and *annual driving* variables; with the strongest association being indicated by the *force* variable. For slight braking, the sequential modelling strategy resulted in a final model including the *force*, *age range* and *annual driving* variables; with the strongest association being indicated by *age range* and *annual driving* variables. The adjusted R_2 statistics indicated some disparity in goodness of fit: with the model being a very good fit to the data under *slight* braking (adjusted R_2=0.455); but a poor fit to the data under *strong* braking (adjusted R_2=0.083), and an adequate fit to the data under *average* braking (adjusted R_2=0.142).

3.5 Regression analyses – circuit failure braking mode

For strong braking, the sequential modelling strategy resulted in a final model including the *distance* and *force* variables, all four subscale scores of the MDBQ, *technical knowledge* scores, *gender*, *age range* and *annual driving* variables; however, none of these variables indicated statistical significance in a controlled model. For average braking, the sequential modelling strategy resulted in a final model including the *distance* and *force* variables, the *errors* subscale score of the MDBQ, and the *technical knowledge* scores variable; with the strongest association being indicated by the *technical knowledge scores* variable. For slight braking, the sequential modelling strategy resulted in a final model including the *distance*, *technical knowledge* scores and *age range* variables; with the strongest association being indicated by the *distance* and *technical knowledge* variables. The adjusted R_2 statistics of 0.14 to 0.27 indicated that all models were fairly good fits to the data.

4. Conclusions

The broad term of an optimal fallback level should be reduced by using a static braking test with probands. Therefore, the test was performed with two major fallback levels of a conventional braking system (brake booster breakdown and brake cirquit failure) aside from the normal brake pedal characteristic of the used test vehicle. The normal and failure brake modes where simulated in three different driving or rather braking scenarios. This simulation setup was tested with 67 participants. The achieved results were statistically processed and evaluated. Three conclusions can be recorded with regard to the static braking test:

1) The choosen approach for the evaluation on human behavior at different brake pedal characteristics is useful. The statistic results clearly show that the probands are able to distinguish the different brake pedal conditions.
2) Factors related to the brake pedal itself (distance, force) generally appear to be more significantly associated with comfort. This suggests that system-based measures to manage brake failure may be more effective than measures targeted at specific demographics, and is in line with findings of Jamson and Smith (2) who studied the responses of 48 drivers to booster and hydraulic brake failures; finding that servo failure was more challenging than circuit failure to most drivers.
3) For further dynamic braking tests with brake failures, a warning concept responding to the new distance and force behaviour of the fallback level could be constructive.

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