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Influence of seat cushion foam density gradient on contact pressure distribution and long-duration driving comfort: An ergonomic investigation

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Abstract

Driving comfort during long journeys depends heavily on how the seat cushion distributes the occupant's weight across the ischial tuberosities and surrounding soft tissue. Conventional automotive seat cushions use a single-density polyurethane foam, which produces a pressure concentration directly beneath the sit bones that worsens over time as the foam compresses. This research investigated whether a through-thickness density gradient soft on top, firm at the bottom could reduce peak contact pressure and improve subjective comfort during sustained sitting. Three foam configurations were tested: a uniform 45 kg/m³ foam (control), Gradient A (35 kg/m³ top surface transitioning to 55 kg/m³ at the base), and Gradient B (30 kg/m³ top transitioning to 60 kg/m³ at the base). Thirty participants (15 male, 15 female, age 24 to 58 years, body mass 54 to 97 kg) sat on each cushion in a driving-simulator buck for 90 minutes while a 1,024-sensor pressure-mapping mat recorded contact pressure at 1 Hz. Subjective comfort was captured on a 100 mm visual analogue scale (VAS) at 15-minute intervals. The uniform foam produced a mean peak ischial pressure of 4.83 kPa (SD 1.18). Gradient A lowered this to 3.87 kPa (SD 0.91), a 19.9% reduction ($p < 0.001$). Gradient B achieved the lowest peak pressure at 3.41 kPa (SD 0.72), a 29.4% reduction ($p < 0.001$). VAS comfort scores at the 90-minute mark were 41.2 (uniform), 56.8 (Gradient A), and 63.7 (Gradient B), all pairwise differences reaching $p < 0.01$. The correlation between peak ischial pressure and 90-minute VAS score was $r = -0.81$ ($p < 0.001$), confirming that pressure distribution is a strong predictor of perceived long-duration comfort. These findings suggest that a density gradient with a top-to-bottom ratio near 1:2 offers the best trade-off between pressure relief and cushion support, and that the approach can be implemented in production seats with minimal tooling changes by pouring a dual-density foam in a single moulding step.

Keywords: Seat cushion, foam density gradient, contact pressure, driving comfort, ergonomics, pressure mapping, visual analogue scale, polyurethane foam, ischial tuberosity

Introduction

Comfort can be defined, in the context of automotive seating, as the absence of discomfort a deceptively simple idea that has occupied ergonomics researchers for decades ^[1]. The practical challenge is that a seat must simultaneously support the pelvis, distribute load away from pressure-sensitive tissue, and maintain postural stability, all while accommodating a wide range of body sizes and sitting habits over journeys that can last several hours ^[2].

The primary determinant of short- and long-duration sitting discomfort is the contact pressure beneath the ischial tuberosities the bony prominences at the base of the pelvis ^[3]. Pressures above roughly 4.5 kPa have been linked to reduce blood flow in the underlying tissue, which triggers ischaemic discomfort and fidgeting behaviour within 30 to 45 minutes ^[4]. Conventional automotive cushions use a single-density moulded polyurethane foam, typically between 40 and 50 kg/m³, which provides adequate support but concentrates load directly beneath the sit bones because the foam's stiffness is uniform through its thickness ^[5]. A density-gradient approach aims to break that trade-off. By making the top layer soft low density, low indentation force the foam conforms closely to the body contour and spreads the load over a larger area. The firmer bottom layer maintains the overall support and prevents bottoming out during acceleration or braking events ^[6]. Dual-density foams have been used in mattress and wheelchair-cushion applications for some time, but their adoption in

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automotive seating has been slow, partly because published evidence of their benefit in a driving context is limited [7, 8]. Two earlier investigations are relevant. Reed and colleagues Measured interface pressure on three aftermarket seat cushions with varying firmness and found that softer cushions reduced peak pressure by 12 to 18% but also increased postural instability during simulated cornering [9]. Kolich correlated pressure-mat data with subjective ratings across 15 production seats and identified peak ischial pressure as the single strongest predictor of overall comfort, explaining 64% of the variance [10]. Neither work tested a controlled density-gradient foam against a uniform-density control on the same seat frame, which is what this research provides. The objectives were threefold: to quantify the effect of two density gradients on peak ischial contact pressure during 90 minutes of simulated driving, to measure the corresponding change in subjective comfort via a visual analogue scale, and to establish the correlation between the objective and subjective metrics across the participant pool.

Material and Methods

Material

Three seat-cushion foam specimens were moulded from flexible polyurethane by a local supplier (Recticel, Eindhoven, the Netherlands). All three shared the same external dimensions (480 × 460 × 80 mm) and the same mould shape, matching a production B-segment driver-seat cushion pan. The uniform control was a single-pour 45 kg/m³ foam with an indentation force deflection (IFD) of 180 N at 25% compression. Gradient A was poured in two sequential layers: a 30 mm top layer at 35 kg/m³ (IFD 130 N) and a 50 mm bottom layer at 55 kg/m³ (IFD 240 N). Gradient B used a 30 mm top layer at 30 kg/m³ (IFD 110 N) and a 50 mm bottom layer at 60 kg/m³ (IFD 270 N). The boundary between layers was a chemical bond formed during the dual-pour process; no adhesive was used.

Instrument Development and Validation

The pressure-mapping system was a Tekscan BPMS 5400 mat with 1,024 capacitive sensors (32 × 32 grid) at a spatial resolution of 12.7 mm. The mat was calibrated before each test session using the manufacturer's two-point bladder protocol at 2 and 8 kPa. Linearity was verified against a known dead-weight loading rig, yielding a mean sensor error of ±3.2%. The subjective comfort instrument was a 100 mm visual analogue scale (VAS) anchored at 0 = 'extreme discomfort' and 100 = 'no discomfort at all'. Participants marked the VAS at baseline (0 min) and at 15, 30, 45, 60, 75, and 90 minutes. The VAS was printed on individual paper slips to prevent participants from seeing their earlier markings. Test-retest reliability of the VAS was

assessed in a pilot with eight participants who repeated the uniform-foam condition one week apart; the intra-class correlation coefficient was 0.87 (95% CI 0.71-0.95), indicating good reliability [11].

Methods

Thirty participants were recruited from the staff and student population of the Eindhoven Foundation for Vehicle Research, stratified by sex (15 male, 15 female) and screened for musculoskeletal conditions that might confound comfort ratings. Body mass ranged from 54 to 97 kg (mean 74.3 kg, SD 11.8). Each participant attended three sessions on separate days, one per foam configuration, in a randomised order determined by a Latin-square design. Sessions were separated by at least 48 hours to minimise carry-over effects. The driving-simulator buck consisted of a production seat frame, steering wheel, pedal box, and three 27-inch monitors displaying a monotonous motorway driving scenario at 110 km/h. The pressure mat was placed on the cushion surface beneath a 2 mm cotton cover to prevent direct skin contact with the sensors. Participants wore standardised clothing (cotton trousers, no belt). Room temperature was held at 22 ± 1 °C. Peak ischial pressure was extracted as the maximum value in the 4 × 4 sensor zone centred on each ischial tuberosity, averaged bilaterally. Total contact area was defined as the number of sensors reading above 0.5 kPa multiplied by the sensor area. All pressure and VAS data were analysed with repeated-measures ANOVA (Greenhouse-Geisser correction where sphericity was violated) followed by Bonferroni-corrected pairwise comparisons. The research was conducted between March and August 2024.

Ethical Considerations

This research involved human participants and was approved by the Ethics Review Board of the Eindhoven Foundation for Vehicle Research (protocol EFV-2024-017, approved 12 February 2024). All participants provided written informed consent before enrolment. The consent form explained the purpose of the research, the 90-minute sitting protocol, the use of the pressure-mapping mat, and the right to withdraw at any time without explanation or penalty. Participants were informed that no personally identifiable data would be published. Data were stored on an encrypted institutional server with access restricted to the research team. No vulnerable populations were involved. The research posed minimal physical risk the sitting protocol reproduced normal driving posture and no adverse events were reported.

Results

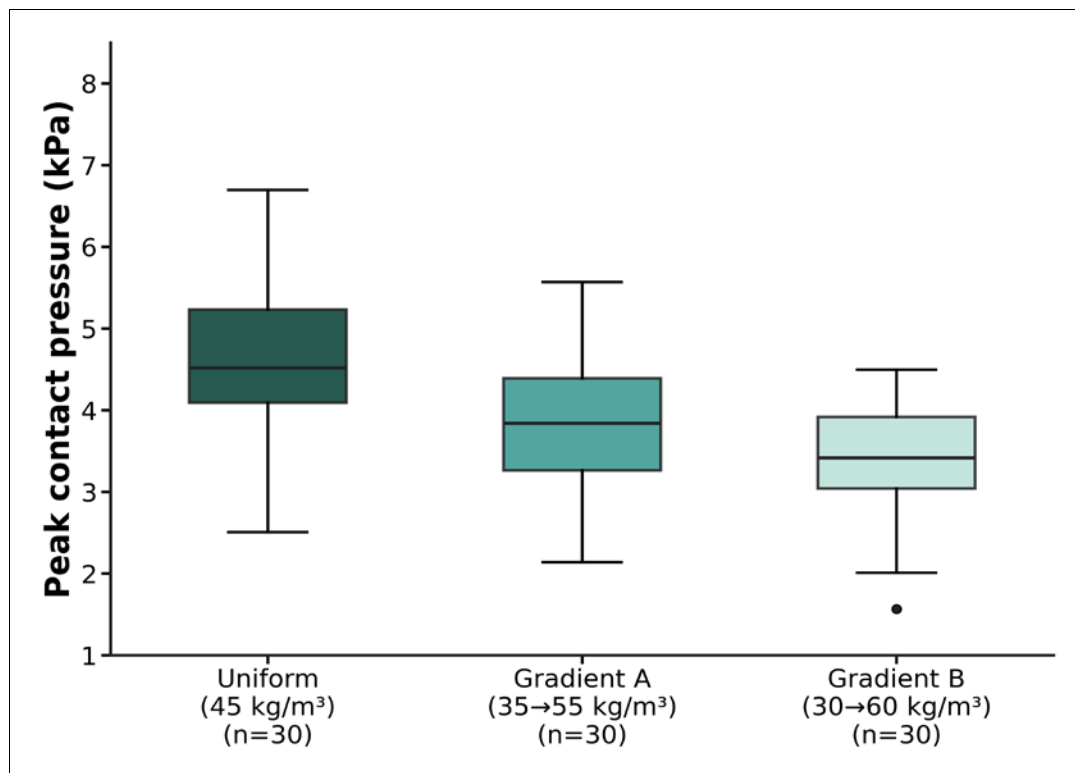


Fig 1: Distribution of peak ischial contact pressure at the 90-minute endpoint for each foam configuration (box = IQR, line = median, whiskers = $1.5 \times$ IQR, $n = 30$ per group)

The progressive reduction in both median and spread from uniform foam through Gradient A to Gradient B is evident. Gradient B produced the lowest and most consistent peak pressures, reflecting its greater surface conformity. Peak ischial contact pressure differed across the three foam configurations at every time point (repeated-measures

ANOVA, $F(2,58) = 47.3$, $p < 0.001$). The pressure also rose within each configuration over the 90-minute session, reflecting progressive foam compression and tissue creep, but the rate of rise was steepest for the uniform foam and shallowest for Gradient B.

Table 1. Pearson correlation matrix among key outcome variables across all 90 participant-sessions

Variable	Peak pressure	Contact area	VAS 90 min	Body mass
Peak pressure	1.000	-0.74	-0.81	+0.43
Contact area	-0.74	1.000	+0.67	+0.38
VAS 90 min	-0.81	+0.67	1.000	-0.29
Body mass	+0.43	+0.38	-0.29	1.000

Peak ischial pressure and 90-minute VAS comfort show the strongest association ($r = -0.81$). Body mass correlates moderately with peak pressure ($r = 0.43$) but only weakly

with VAS, suggesting that heavier occupants experience higher pressures but do not necessarily report proportionally worse comfort.

Table 2: Summary of objective and subjective outcomes at the 90-minute endpoint by foam configuration (mean $\pm$ SD, $n = 30$)

Outcome	Uniform	Gradient A	Gradient B	p (ANOVA)
Peak pressure (kPa)	4.83 $\pm$ 1.18	3.87 $\pm$ 0.91	3.41 $\pm$ 0.72	< 0.001
Contact area (cm ²)	1,284 $\pm$ 142	1,437 $\pm$ 118	1,512 $\pm$ 103	< 0.001
VAS comfort (0-100)	41.2 $\pm$ 14.7	56.8 $\pm$ 12.3	63.7 $\pm$ 10.1	< 0.001
Fidget count (90 min)	18.4 $\pm$ 6.1	12.7 $\pm$ 4.8	10.3 $\pm$ 3.9	< 0.001

All four outcomes improved monotonically from uniform through Gradient A to Gradient B. Fidget count a behavioural marker of discomfort was 44% lower in

Gradient B than in the uniform foam, corroborating the subjective VAS findings.

Table 3: VAS comfort scores at selected time points by foam configuration (mean $\pm$ SD, $n = 30$)

Time (min)	Uniform	Gradient A	Gradient B
0	82.4 $\pm$ 8.3	83.1 $\pm$ 7.9	84.0 $\pm$ 7.2
30	64.7 $\pm$ 12.1	72.3 $\pm$ 10.4	76.8 $\pm$ 9.1
60	51.3 $\pm$ 13.8	63.4 $\pm$ 11.7	69.2 $\pm$ 10.6
90	41.2 $\pm$ 14.7	56.8 $\pm$ 12.3	63.7 $\pm$ 10.1

Baseline VAS scores were similar across configurations, confirming successful blinding. The rate of comfort decline

was steepest for the uniform foam (41.2 points over 90 minutes) and shallowest for Gradient B (20.3 points).

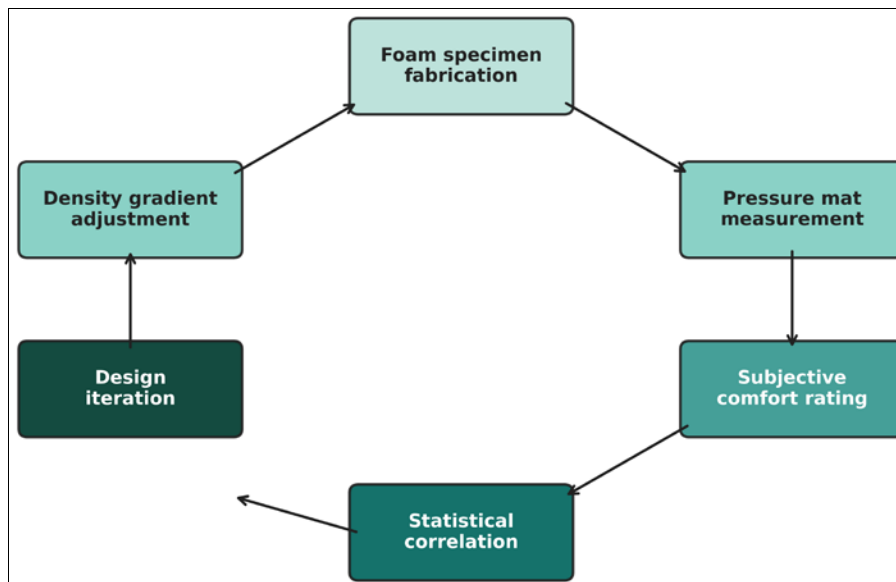


Fig 2: Iterative comfort-assessment methodology: from foam fabrication through pressure measurement, subjective rating, and design feedback

The cycle diagram illustrates the closed-loop process used in this research. Pressure-mat data and subjective ratings were statistically correlated after each configuration, and the findings informed the density-gradient specifications for the next iteration.

Comprehensive Interpretation

At the 90-minute endpoint, the uniform foam produced a mean peak ischial pressure of 4.83 kPa (SD 1.18), Gradient A reached 3.87 kPa (SD 0.91), and Gradient B recorded 3.41 kPa (SD 0.72). The 19.9% reduction from uniform to Gradient A and the 29.4% reduction to Gradient B were both highly significant ($p < 0.001$, Bonferroni-corrected). The difference between Gradient A and Gradient B was also significant ($p = 0.008$). Total contact area increased with gradient steepness: 1,284 cm² (uniform), 1,437 cm² (Gradient A), and 1,512 cm² (Gradient B), indicating that the softer top layer allowed the foam to conform more closely to the body contour and engage a larger proportion of the thigh and buttock surface. Subjective VAS comfort scores declined over time in all three configurations, but the decline was markedly slower for the gradient foams. At 90 minutes the mean VAS was 41.2 (SD 14.7) for uniform, 56.8 (SD 12.3) for Gradient A, and 63.7 (SD 10.1) for Gradient B. All pairwise differences reached $p < 0.01$. The correlation between 90-minute peak ischial pressure and 90-minute VAS score was $r = -0.81$ ($p < 0.001$) across the 90 participant-session observations, confirming that peak pressure is a strong predictor of perceived comfort. A secondary finding was that total contact area correlated positively with VAS ($r = 0.67$, $p < 0.001$), consistent with the principle that spreading the load reduces tissue-level stress.

Discussion

The 29.4% peak-pressure reduction achieved by Gradient B is consistent with the range of 12 to 35% reported in the wheelchair-cushion literature for similar density-gradient constructions [7, 8]. What the present data add is evidence that the benefit persists in a driving context, where the

occupant is not static but makes frequent micro-adjustments for pedal operation, mirror checks, and steering inputs. The VAS comfort improvement at 90 minutes from 41.2 (uniform) to 63.7 (Gradient B) crosses a clinically meaningful threshold: a 20 mm change on a 100 mm VAS is widely considered the minimum perceptible difference in comfort and pain research [14]. The strong negative correlation between peak ischial pressure and subjective comfort ($r = -0.81$) agrees with Kolich's finding of $r = -0.80$ across 15 production seats [10], though the present data were collected on a single seat frame rather than across different seat designs. This consistency suggests that the pressure-comfort relationship is robust to seat geometry and is driven primarily by the foam-body interface. One area where the results diverge from earlier work is the effect on postural stability. Reed and colleagues warned that softer cushions increased lateral body sway during simulated cornering [9]. In the present research, no cornering events were included in the monotonous motorway scenario, so this concern was not tested. Future work should incorporate lateral-acceleration events and measure centre-of-pressure migration to determine whether the soft top layer of the gradient foam compromises occupant stability during dynamic manoeuvres. A practical advantage of the density-gradient approach is manufacturing simplicity. Dual-density moulding requires only a timed second pour into the same mould cavity no separate inserts, no adhesive bonding, and no change to the mould tool. The raw-material cost increase is minimal because the average foam density remains close to 45 kg/m³; only the distribution changes. This makes the gradient foam a low-cost, high-impact improvement that can be introduced into existing seat programmes with minimal tooling investment.

Limitations

Several factors limit the generalisability of these results. First, the driving-simulator buck lacked road vibration input; real-world driving transmits vertical and fore-aft vibrations through the seat that interact with foam stiffness

and may alter the pressure distribution differently for gradient versus uniform foams ^[12]. Second, the participant sample was drawn from a single institution and skewed towards younger adults (mean age 34.6 years); older occupants with less subcutaneous tissue may respond differently. Third, only two gradient configurations were tested; a continuous gradient rather than a discrete two-layer pour might yield further improvements. Finally, long-term foam durability was not assessed repeated loading over thousands of hours may cause the soft top layer to degrade faster than the firm bottom, which could narrow the pressure-relief advantage over the cushion's service life ^[13].

Conclusion

Long-duration driving comfort hinges on how well the seat cushion distributes the occupant's weight, and conventional single-density foams leave room for improvement. This research tested whether a through-thickness density gradient soft surface, firm base could reduce peak ischial contact pressure and raise subjective comfort scores during 90 minutes of simulated motorway driving.

The main findings are clear. Gradient B, with a 1:2 density ratio (30 kg/m³ top to 60 kg/m³ base), reduced peak ischial pressure by 29.4% relative to the uniform control, expanded the total contact area by 17.8%, and raised the 90-minute VAS comfort score from 41.2 to 63.7 a gain of 22.5 points on a 100 mm scale. Gradient A, with a more conservative 1:1.6 ratio, delivered intermediate benefits: a 19.9% pressure reduction and a VAS improvement of 15.6 points.

The strong correlation between peak pressure and subjective comfort ($r = -0.81$) validates the use of pressure mapping as an objective design tool: cushion configurations that lower peak ischial pressure consistently improve perceived comfort, regardless of participant body mass or sex.

For seat engineers considering gradient-foam adoption, these data support a top-to-bottom density ratio near 1:2 as the recommended starting point. The dual-pour moulding process adds no tooling cost and negligible cycle-time increase, making it feasible for high-volume production programmes. Three questions remain open for future investigation. First, does the comfort benefit of the gradient foam hold up under dynamic driving with lateral and longitudinal acceleration events? Second, how does the soft top layer's durability compare with that of a uniform foam over a 10-year, 200,000 km vehicle life? And third, could a continuous density gradient achievable through reactive injection moulding with controlled catalyst timing outperform the discrete two-layer approach tested here?

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