INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED11
15 - 18 AUGUST 2011, TECHNICAL UNIVERSITY OF DENMARK

BENCHMARKING STUDY OF AUTOMOTIVE SEAT TRACK SENSITIVITY TO MANUFACTURING VARIATION

Maciej Mazur[1], Martin Leary[1], Sunan Huang[1], Tony Baxter[2] and Aleksandar SUBIC[1]
(1) RMIT University, School of Aerospace, Mechanical and Manufacturing Engineering, Australia (2) Futuris Automotive Interiors Pty Ltd, Australia

ABSTRACT

A benchmarking study is presented on the performance of automotive seat track profiles according to their sensitivity to manufacturing variation. Variation in rail geometry affects the elastic track preload and consequently the rolling effort of the track assembly. Rolling effort must be precisely controlled to achieve customer performance targets. Two benchmarking parameters are relevant to rolling effort: variation in bearing clearance and variation in bearing contact force. These were assessed using statistical tolerance analysis of CAD data, and numerical analysis, respectively.

Significant variation in performance was identified for the selected track profiles, which include commercially available designs and proposed concepts. The benchmarking approach demonstrated in this work provides a way of rapidly assessing the relative robustness of automotive seat track designs subject to manufacturing variation. The outcome assists automotive manufacturers to apply a systematic approach to automotive seat design based on a robust design evaluation of alternative embodiments.

Keywords: Robust design, automotive seat structures, tolerance analysis, benchmarking

Theme: Design Methods And Tools

1 INTRODUCTION

Automotive seating structures are subject to a rigorous set of comfort and safety demands requiring the accommodation of anthropometric variation of users while meeting safety standards under crash scenarios [1]. Seat position adjustment in multiple degrees-of-freedom (DoF) facilitates the location of the user within the vehicle cabin in a comfortable and functional seating position. An essential DoF required by all seating structure designs is the fore and aft movement of the seat. As automotive seating structures have evolved over an extended development period, there has been a convergence of practical embodiments. Accordingly, fore and aft movement is typically achieved using a sliding track assembly consisting of interlocking rail sections. Due to the stochastic nature of manufacturing processes, track assembly performance is affected by manufacturing variation. For low cost track assembly markets, latitude in manufacturing variation is desirable. For mature markets, predictable and repeatable functional efforts take priority. Accommodating the effects of manufacturing variation early in the development cycle through robust design is paramount to achieving competitive quality, cost and development time objectives for a range of target markets [2-4].

This work presents a benchmarking study of alternative automotive seat track profiles according to their sensitivity to manufacturing variation i.e. robustness. The analyzed track assemblies (e.g. Figures 1 and 2) include commercially available designs as well as proposed concepts (Table 1). All track assemblies consist of two interlocked rail sections (with symmetric or asymmetric profiles) separated by rolling elements (spherical and cylindrical). The upper and lower rail sections are elastically preloaded by an interference fit upon assembly. Variation in the geometric parameters of the rail section affects the magnitude of the elastic rail preload and consequently the rolling effort of the track assembly. Rolling effort is of significant importance to customer perceived product quality, and must be:

- sufficiently high to avoid chatter in the track assembly
- sufficiently low to allow the track to slide without excessive effort

Due to these conflicting requirements, rolling effort is highly sensitive to manufacturing variation which results in both large scale batch-to-batch variation between assembly production batches, as well as piece-to-piece variation within single assemblies. Large scale batch-to-batch variation can be accommodated using alternative bearing diameter increments between batches. Piece-to-piece variation however, is more difficult to accommodate as it requires alternative bearing diameters for each assembly. The aim of this work is to benchmark alternative track profiles according to their sensitivity to rolling effort variation in the presence of piece-to-piece manufacturing variation. Two benchmarking parameters are relevant to rolling effort: variation in bearing clearance and variation in bearing contact force.

Variation in bearing clearance may be assessed by CAD based tolerance analysis which accommodates expected manufacturing process capabilities. A statistical tolerance analysis approach was applied to quantify the expected variation [5]. It is highly desirable that the maximum variation between the upper specification limit (USL) and lower specification limit (LSL) be small, as it accommodates part-to-part variation within a track assembly with a small change in rolling effort.

Variation in bearing contact force can be quantified by the stiffness of the rail sections; i.e. the rate of change in bearing preload due to a change in rail section displacement. To benchmark the sensitivity of bearing preload to rail section geometries, a numerical simulation was conducted for various bearing increment sizes. The stiffness of each rail section was determined from the resultant displacement and contact force at the rail/bearing interface. The stiffness of the rail sections is an indicator of the performance robustness of the nominal track design. A rail profile which displays a low variation in contact force with displacement is desirable as it accommodated part-to-part variation with little change in rolling effort.

Track design	Style	Balls	Rollers	Comments
A	Symmetric	2 (upper) 2 (lower)	nil	Commercially available design. Figure 1
B	Asymmetric	1 (upper)	1 (lateral) 1 (lower)	Commercially available design. Figure 2
C	Symmetric	2 (upper) 2 (lower)	nil	Concept design 1
D	Symmetric	2 (upper) 2 (lower)	nil	Concept design 2
E	Symmetric	2 (upper)	2 (lower)	Concept design 3

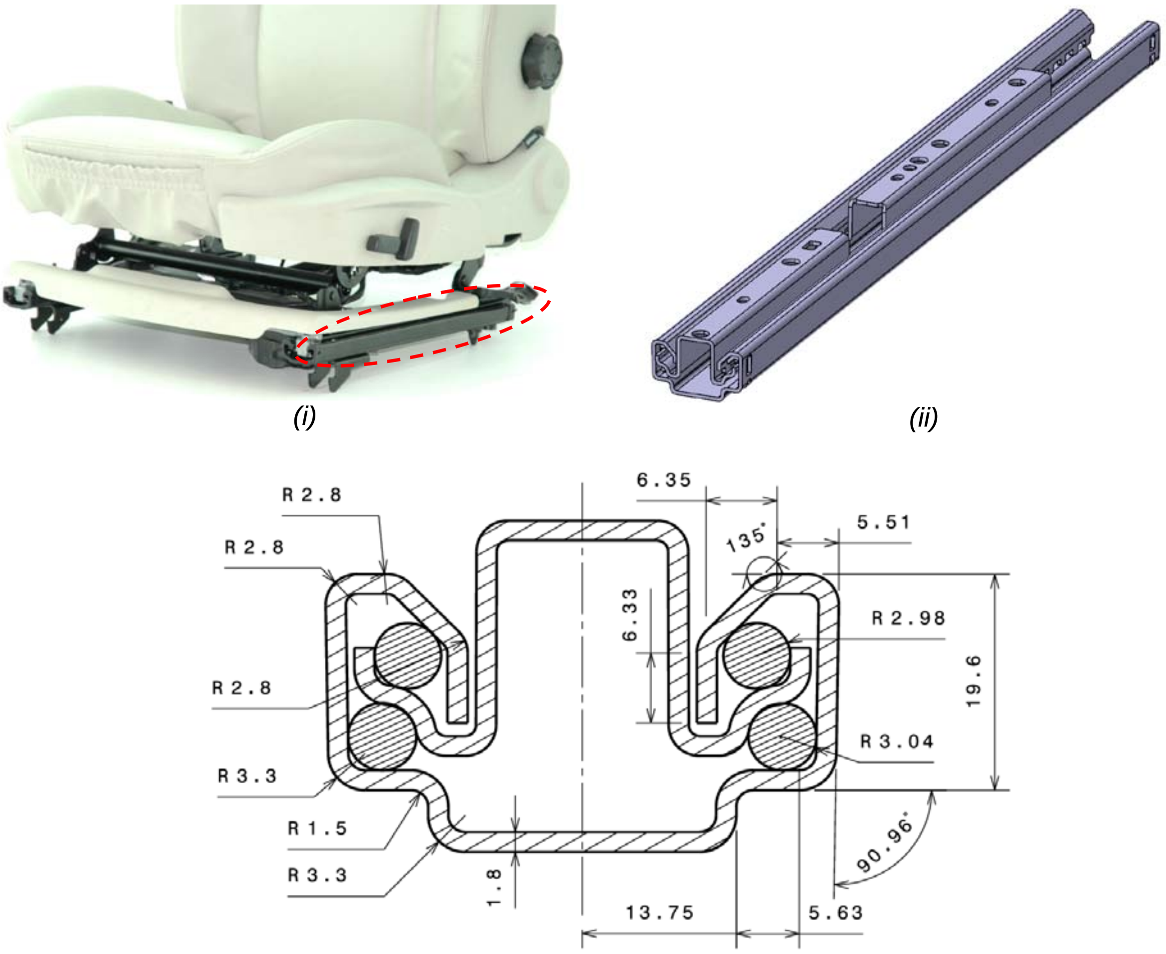
Table 1. Track designs considered in benchmarking analysis.

The benchmarking analysis applied in this work provides a way of rapidly assessing the relative robustness of automotive seat tracks when subject to expected manufacturing variation. This outcome assists automotive manufacturers to apply a systematic approach to automotive seat design based on a robust evaluation of alternative seat track embodiments.

2 METHOD

2.2 VARIATION IN BEARING CONTACT FORCE

A parametric Finite Element (FE) model of each track assembly was constructed to simulate the rail deflection due to an interference fit with the rolling element (Figure 3 and 4). The model was constructed to consider one-half of the symmetric rail profile. The ball size was progressively increased from the nominal clearance size in 0.1mm increments. The resultant contact force was integrated over the contact surfaces. The associated deflection of the upper and lower rail sections was recorded at marker locations corresponding to a common node in all simulations for the particular track under analysis (Figure 4(ii)). The average individual simulation time was approximately 400 seconds on a 3 GHz CPU.



(i)

(ii)

(iii)

Figure 1. Automotive seat (i) and seat track A (ii) including section view (iii). Symmetric track. All dimensions in mm.

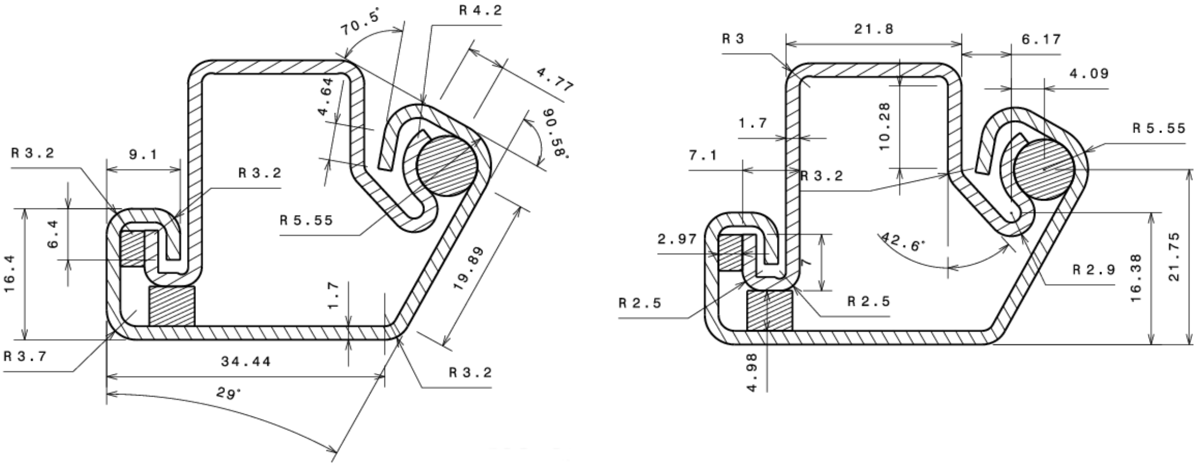
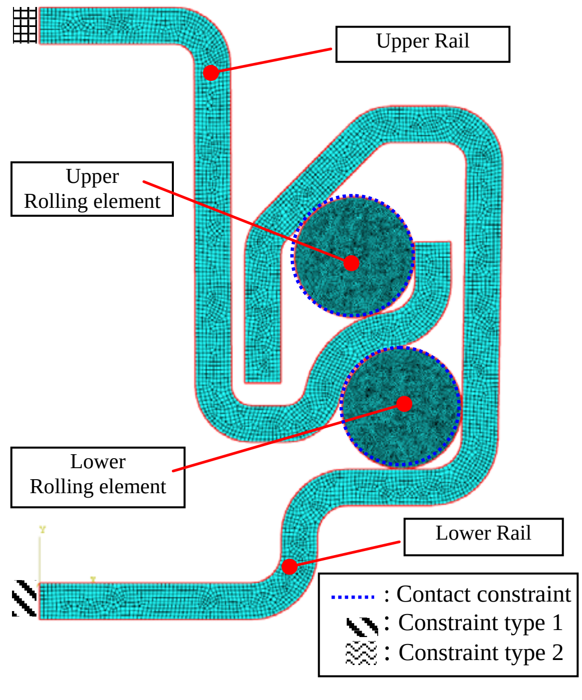


Figure 2. Seat track B section view. Asymmetric track. All dimensions in mm.



FE Model Details		
Upper Rail:	Number of nodes: 2216 Number of elements: 2441 Linear quadrilateral elements type CPS4I (plane stress element, $X_{rotation} = 0$, $Y_{rotation} = 0$, $Z_{disp} = 0$).	
Lower Rail:	Number of nodes: 3581 Number of elements: 3262 Linear quadrilateral elements of type CPS4I (plane stress element, $X_{rotation} = 0$, $Y_{rotation} = 0$, $Z_{disp} = 0$).	
Upper Ball:	Number of nodes: 3518 Number of elements: 3424 Linear quadrilateral elements of type CPS4I (plane stress element, $X_{rotation} = 0$, $Y_{rotation} = 0$, $Z_{disp} = 0$).	
Lower Ball:	Number of nodes: 3588 Number of elements: 3493 Linear quadrilateral elements of type CPS4I (plane stress element, $X_{rotation} = 0$, $Y_{rotation} = 0$, $Z_{disp} = 0$).	
Contact constraints:	Surface to surface contact with small sliding	
Boundary constraints:	Type 1:	Type 2:
	$X_{disp} = 0$ $Y_{disp} = 0$ $Z_{disp} = 0$ $X_{rotation} = 0$ $Y_{rotation} = 0$ $Z_{rotation} = 0$	$X_{disp} = 0$ $Z_{disp} = 0$ $X_{rotation} = 0$ $Y_{rotation} = 0$ $Z_{rotation} = 0$

Figure 3. Track A FE model details. All dimensions in mm.

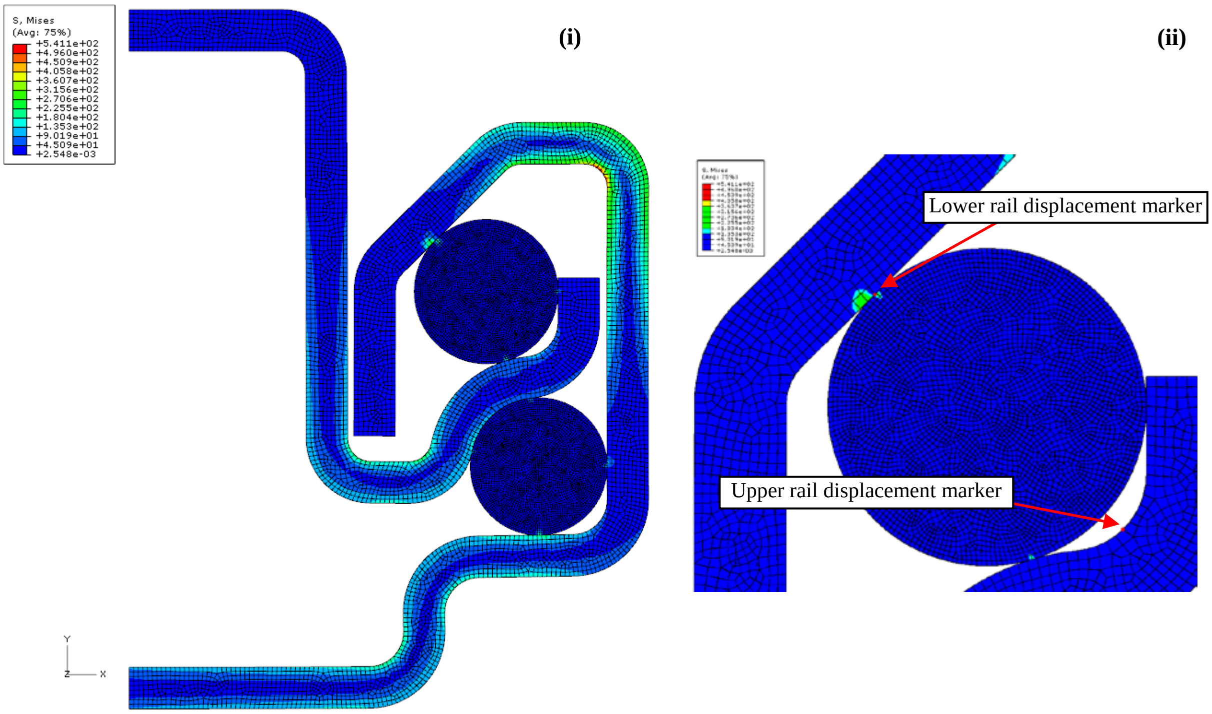


Figure 4. Track A: (i) rail displacement due to interference fit of bearing. (ii) Location of displacement markers.

2.2. VARIATION IN BEARING CLEARANCE

The ability of a manufacturing process to generate outputs consistently and accurately within the specification limits can be measured using Process Capability Indices (PCI) [6]. These indices compare the specification limits to the 6σ limits of the manufacturing process distribution, i.e. 99.73% of the predicted population, where a higher process index indicates a more accurate process. For example:

$$C_p = \frac{USL - LSL}{6\sigma} \quad (1)$$

$$C_{pk} = \min\left\{\frac{USL - \mu}{3\sigma}, \frac{\mu - LSL}{3\sigma}\right\} = \min\{C_{pl}, C_{pu}\} \quad (2)$$

$$C_{pm} = \frac{USL - LSL}{6\sqrt{\sigma^2 + (\mu - T)^2}} \quad \text{where } T \text{ is the target nominal} \quad (3)$$

Where:

C_p Compares process distribution with the specification limits assuming centred process mean.

C_{pk} Accommodates non-centred distributions, but does not provide explicit data on the location of the mean within the specification limits.

C_{pm} Measures the ability of a process to achieve any nominal value, *T*, and the specification limits (for example, Figure 5).

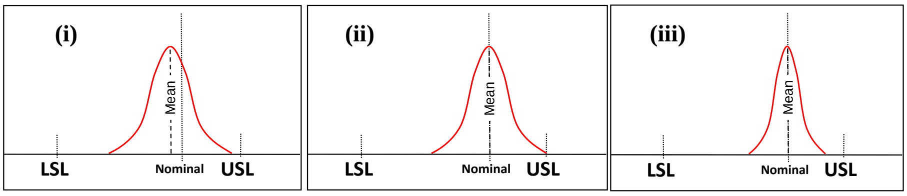


Figure 5. Example process output distributions. C_{pm} increasing from left to right image: (i) large standard deviation, mean not equal to nominal,(ii) large standard deviation, mean equal to nominal,(iii) small standard deviation, mean equal to nominal.

PCI data obtained from a collaborative partner was applied to quantify the expected manufacturing distribution for each parameter. Subsequently parametric models of track geometries were subjected to the following variation (no variation in linear dimensions or material thickness was applied):

Parameter	**Specification limits +/-**	**C_{pm}**	**σ**
Bend radii	0.1 mm	1	0.033
Bend angle	1°	1	0.333

Table 2 – Parameter variation used in statistical tolerance analysis

Each track was subjected to a statistical tolerance analysis based on a Monte Carlo simulation of 1000 samples. Studies suggest that 1000 samples provide sufficient accuracy in an assembly tolerance analysis problem [7]. Based on the applied variation, upper and lower specification limits for rolling element diameters were identified in order to achieve a $C_{pm} = 1$.

2.3. ASSUMPTIONS

The conducted analysis was subject to a number of assumptions in order to allow for reasonable scope of analysis within limited analysis time:

- Estimates of the process capabilities were applied to establish upper and lower specification limits for the rail sections (no variation in linear dimensions or material thickness was applied)
- Variation in symmetric rail sections was assumed to be equal on either side of the axis of symmetry.
- CAE was based on a planar model; therefore the magnitude of rolling element preload is based on deformation of the full rail length, rather than point contact.

- Rail stiffness was assessed at three points. Stiffness shows a linear trend for moderate rail displacement. Further increases in ball rolling element diameter result in a non-linear trend.
- Rail stiffness was assessed for spherical (ball) elements only, not cylindrical elements.

3 RESULTS

3.1 TRACK A

Track A is a commercially available symmetric rail design with cylindrical rolling elements (Figure 1 (iii)). Contact force was calculated for the scenarios of Table 3 and summarized (Section 3.4).

Scenario	Ball interference (mm)	Upper Ball diameter (mm)	Lower Ball diameter (mm)
Nom. size	0	5.944	5.944
Simulation 1	0.1	6.044	6.044
Simulation 2	0.2	6.144	6.144
Simulation 3	0.3	6.244	6.244

Table 3 - Track A ball dimensions used for contact force simulation.

A statistical tolerance analysis was conducted for track A rail sections in order to identify the expected clearances at the rolling element locations. A parametric CAD model of the rail profiles was used for the analysis. The separation distance between the vertical extremities of the upper and lower rail was held constant while the rail section parameters were subjected to a Monte Carlo simulation based statistical tolerance analysis of 1000 samples. The resultant distributions of rail clearances are shown in figure 6 and the identified specification limits in Table 4. The results are summarized in Section 3.4.

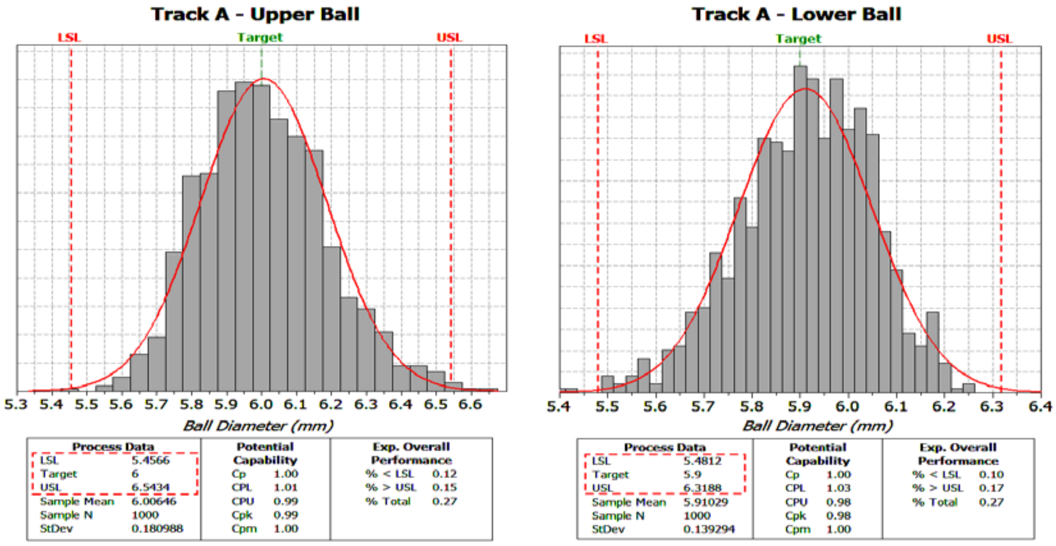


Figure 6 – Track A rolling element clearance distributions.

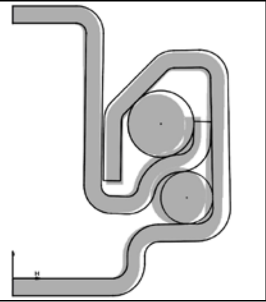
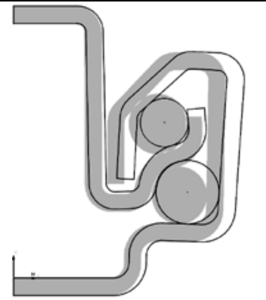
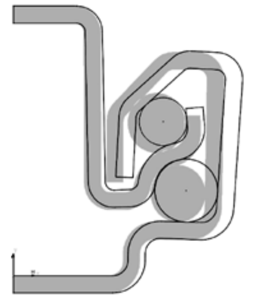
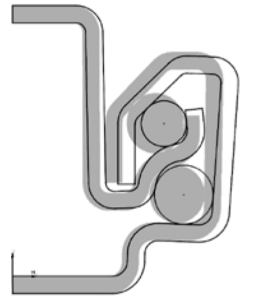
	UB USL	UB LSL	LB USL	LB LSL
Profiles				
Spec. Limits	*6.543 mm*	*5.457 mm*	*6.319 mm*	*5.481 mm*

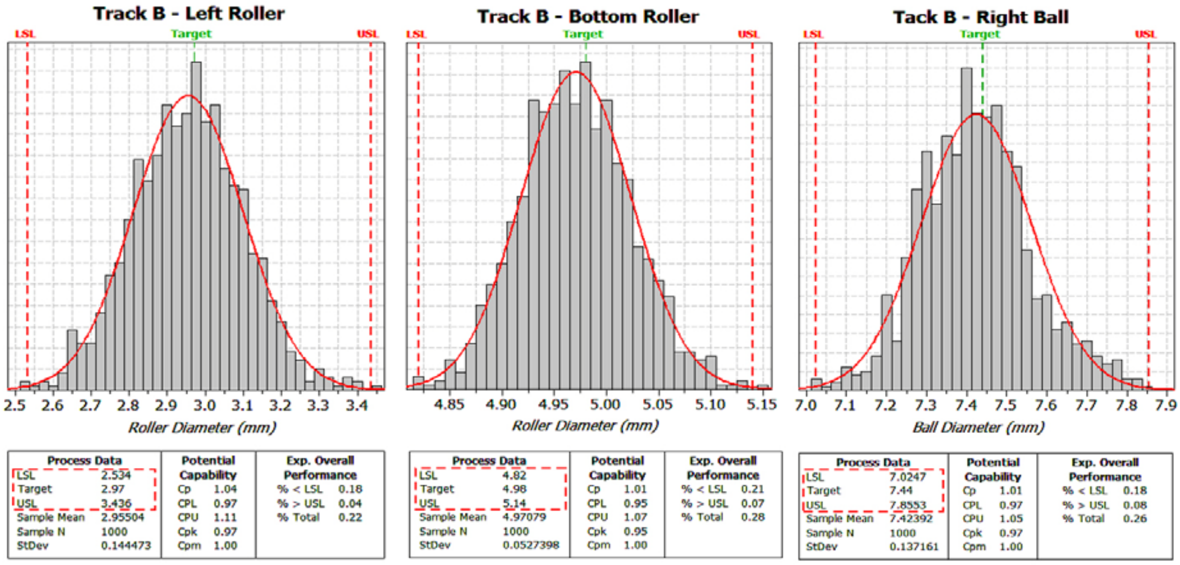
Table 4 - Track A rolling element specification limits. Shaded profile corresponds to nominal rail dimensions. Upper Ball (UB), Lower Ball (LB).

3.2 TRACK B

Track B is a commercially available rail concept design incorporating spherical and cylindrical rolling elements (Figure 1 (iii)). As the rail has no axis of symmetry, the entire track profile was considered in the contact force and statistical tolerance analyses. Contact force was calculated for the scenarios of Table 5 and summarized in Section 3.4. Distributions of rail clearances are shown in figure 7 and the identified specification limits in Table 6. The results are summarized in Section 3.4.

Scenario	Ball interference (mm)	Upper Ball diameter (mm)	Bottom roller diameter (mm)	Left roller diameter (mm)
Nom. size	0	7.44	4.98	2.97
Simulation 1	0.1	7.54	4.98	2.97
Simulation 2	0.2	7.64	4.98	2.97
Simulation 3	0.3	7.74	4.98	2.97

Table 5 - Track B Ball dimensions used for contact force simulation.



```
Process Data              Potential      Exp. Overall
                          Capability     Performance
LSL          2.534        Cp     1.04    % < LSL  0.18
Target       2.97         CPL    0.97    % > USL  0.04
USL          3.436        CPU    1.11    % Total  0.22
Sample Mean  2.95504      Cpk    0.97
Sample N     1000         Cpm    1.00
StDev        0.144473
```

```
Process Data              Potential      Exp. Overall
                          Capability     Performance
LSL          4.82         Cp     1.01    % < LSL  0.21
Target       4.98         CPL    0.95    % > USL  0.07
USL          5.14         CPU    1.07    % Total  0.28
Sample Mean  4.97079      Cpk    0.95
Sample N     1000         Cpm    1.00
StDev        0.0527398
```

```
Process Data              Potential      Exp. Overall
                          Capability     Performance
LSL          7.0247       Cp     1.01    % < LSL  0.18
Target       7.44         CPL    0.97    % > USL  0.08
USL          7.8553       CPU    1.05    % Total  0.26
Sample Mean  7.42392      Cpk    0.97
Sample N     1000         Cpm    1.00
StDev        0.137161
```

Figure 7 – Track B rolling element clearance distributions.

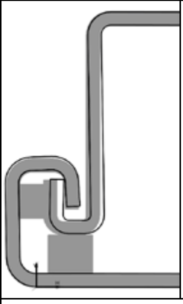
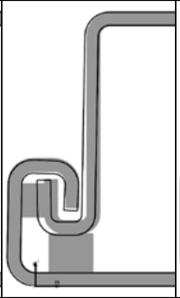
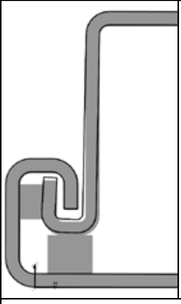
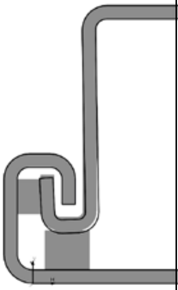
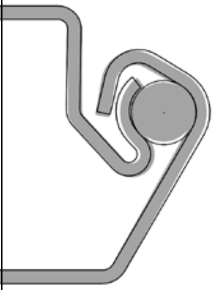
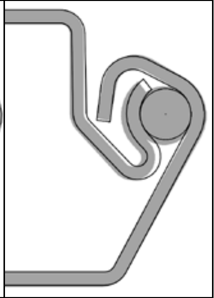
	LR USL	LR LSL	BR USL	BR LSL	RB USL	RB LSL
Profiles						
Spec. limits	*3.436mm*	*2.534mm*	*5.140mm*	*4.820mm*	*7.855mm*	*7.025mm*

Table 6 - Track B rolling element specification limits. Shaded profile corresponds to nominal rail dimensions. Left Roller (LR), Bottom Roller (BR), Right Ball (RB).

3.3 TRACKS C-E

Tracks C, D and E are alternative conceptual track designs incorporating spherical and cylindrical rolling elements. Contact force and statistical tolerance analyses were carried out for the rail section as per the procedure demonstrated in sections 3.1 and 3.2. The results are summarized in Section 3.4.

3.4 SUMMARY OF RESULTS

The results of the contact analysis conducted for the analyzed track profiles are shown in Figure 8 and 9. Variation in bearing contact force is quantified by the stiffness of the rail sections; i.e. the rate of change in bearing load due to a change in rail section displacement at the rail/bearing interface. The stiffness of the rail sections is an indicator of the performance robustness of the nominal track design. A rail profile showing low variation in contact force with displacement (small gradient) is desirable as it accommodates part-to-part variation with a small change in rolling effort.

Although some tracks show a significantly high and undesirable stiffness (such as Track D) they offer other performance advantages warranting their inclusion within the concept design set, for instance:

- material use efficiency
- ease of pressing
- ease of metrological assessment facilitating simple process control measures

For such designs, although they show poor performance robustness in rolling effort (as is the focus of this benchmarking study) their use may be appropriate for low cost applications where consumer quality expectations are lower.

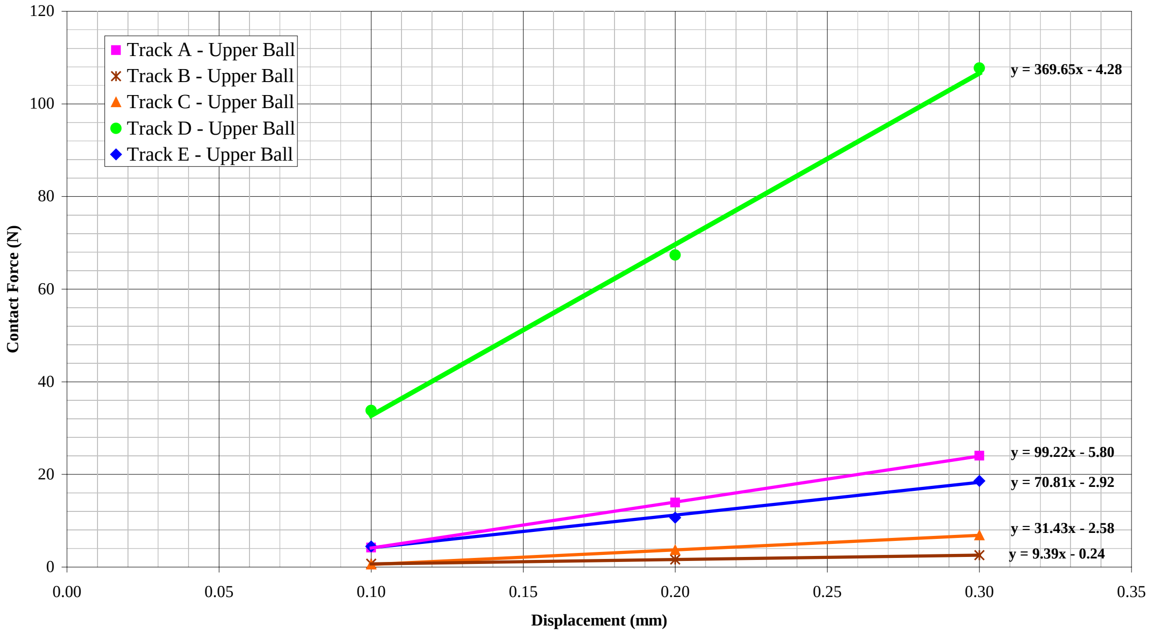


Figure 8 – Rail stiffness at upper ball location (contact force versus resultant marker displacement magnitude)

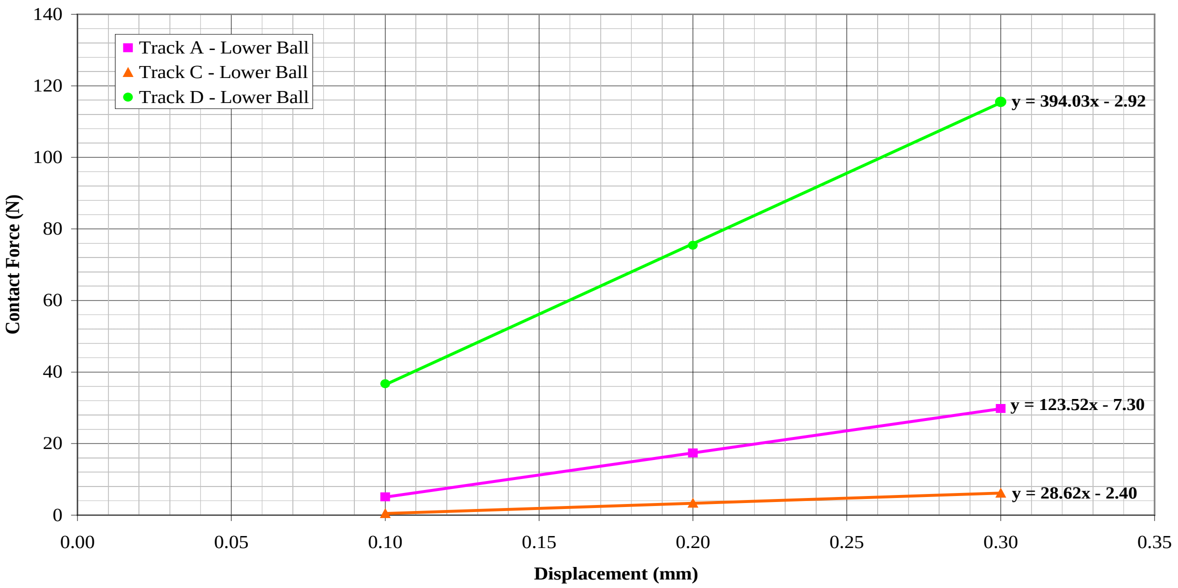


Figure 9 – Rail stiffness at lower ball location (contact force versus resultant marker displacement magnitude)

A summary of statistical tolerance analysis results for the analyzed track profiles is shown in Figure 10. A track profile with minimum variation between the upper and lower specification limits is preferable as this reduces piece to piece variation within the track assembly thereby reducing fluctuation in rolling effort of the track assembly.

The analyzed profiles can be benchmarked according to performance robustness of contact force and bearing clearance. Table 7 shows the performance of the analyzed tracks and ranks the design globally using a square weighted sum of performance in both analyzed categories.

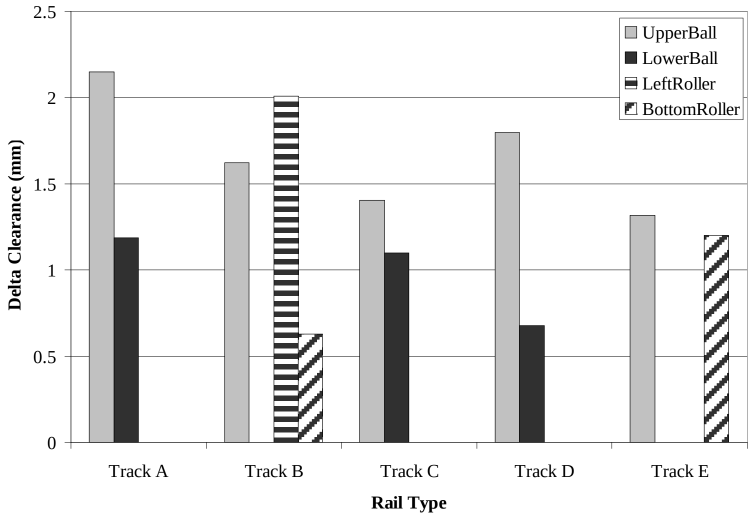


Figure 10 - Magnitude of variation in nominal bearing clearance versus track type.

Track design	**Robustness of contact force**	**Robustness of bearing clearance**	**Overall Performance rank**
A	3	1	2
B	4	5	5
C	2	2	**1**
D	5	3	4
E	1	4	3

Table 7 – Performance ranking of track profiles.

4. CONCLUDING REMARKS

Automotive seating design is subject to numerous competing objectives aimed at satisfying comfort and safety requirements. Manufacturing inducted variation in seat track rolling effort is particularly relevant to customer comfort and perceived product quality. Historically, track assemblies have been designed solely with strength and material use in mind. Consideration of customer perceived quality (such as functional effort) was not prioritized at the concept stage, as it was typically considered as too difficult, and time consuming to consider at the stage of the development cycle where many physical properties remained undefined.

However, assessing customer perceived quality later in the design cycle following the commissioning of manufacturing when tooling has been laid down, can incur significant cost penalties if the selected concept is sensitive to manufacturing variation. The quality of the customer experience has then to be managed with at the manufacturing stage for the life of the product with costly counter measures. Estimating sensitivity to manufacturing variation at the conceptual design stage will reduce the cost of poor quality to a minimum (within the given design solution set), and highlight control factors in the selected concept which need to be prioritized from an ongoing quality perspective. This in turn allows the construction of metrology and process control strategies designed to mitigate the residual risk.

In this work a rapidly implemented manufacturing sensitivity benchmarking study was carried out for alternative automotive seat track designs. The benchmarking study focused on seat track rolling effort by considering variation in bearing clearance and variation in bearing contact force. Significant variation in sensitivity to manufacturing variation was identified between alternative automotive seat track designs. The benchmarking study identified conceptual designs which offer superior performance robustness compared to existing designs.

The benchmarking approach applied in this work demonstrated a method of rapidly assessing the relative robustness of automotive seat tracks when subject to expected manufacturing variation. This outcome assists automotive manufacturers to apply a systematic approach to automotive seat design based on a robust evaluation of alternative conceptual seat track embodiments.

REFERENCES

[1] Leary, M., Mazur, M. Gruijters, J., Subic. A., *Benchmarking and Optimisation of Automotive Seat Structures. In Wellnitz, Subic, Leary (Ed.), Sustainable Automotive Tech-nologies* (Springer, Berlin 2010).

[2] Park, S.H., *Robust design and analysis for quality engineering*. (Chapman & Hall, London, 1996).

[3] Phadke, M.S., *Quality engineering using robust design*. (Prentice-Hall, New Jersey, 1989).

[4] Wu, Y., *Taguchi methods for robust design*. (The American Society of Mechanical Engineers, NewYork, 2000).

[5] Shah JJ, A.G., Shen Z, Davidson JK., Navigating the Tolerance Analysis Maze. *Computer Aided Design and Applications*, 2007, 4(5), pp705-718.

[6] Pearn WL, K.S., *Encyclopedia And Handbook of Process Capability Indices: A Comprehensive Exposition of Quality Control Measures (Series on Quality, Reliability and Engineering Statistics)*. (World Scientific Publishing, New Jersey, 2006).

[7] Gao J, C.K., Magleby SP. Comparison of assembly tolerance analysis by direct linearization and modified Monte Carlo simulation methods. *Proceedings of the ASME Design Engineering Technical Conference Boston*, pp353–3601995).