HEALTH & SAFETY LABORATORY

HSL & CHSD-4B ERGONOMICS TEAM SUMMARY REPORT

HSE Health & Safety Executive

Report title:

Predicted force application and suitability of the containment systems of the Orbiter fairground ride, manufactured by Tivoli owned by Darren Matthews

Occupier:

N/A

Client No:

Location No:
N/A (mobile)

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Visit date:
03/11/06

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Marches Office, Stoke-on-Trent

Report Date:
21/05/07

HSL Authorising Officer:
David Riley

HSL Report Number:
ERG07/12

SUMMARY:
Measures of accelerations taken on the Tivoli Orbiter ride show that riders are subjected to significant g-forces acting in X (positive 0.41 – negative 0.88g), Y (negative 1.66 – negative 0.18 g) and Z axis, and that lap-bar containment is required for passenger safety.

The maximum forces (reactive or active) applied to the lap-bar by occupants are calculated to give inspectors an indication of the kinds of force that may be applied to these bars. Peak forces around 22000N pushing force may be applied, and around 234Nm of torque although these would require two adults applying intentional force on the bar, which is foreseeable but not likely.

The most suitable height restriction for the Tivoli Orbiter ride is 4 foot 6 inches or 1372 mm.

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1.0 Introduction

The ergonomics assessment of the Orbiter ride has two main aims:

1. To establish the forces which are likely to be exerted on the handrail. This includes reactive forces due to passengers hanging on and active forces due to passengers pushing against the handrail with their backs braced against the seat back.

2. To establish the effectiveness of the containment system (i.e. handrail) as a means of preventing passengers being ejected from the ride (given the ride forces which will be experienced).

The cars on the Orbiter ride are similar in design to cars on a number of rides. This similarity includes the handrail / lap bar containment device. Figure 1 shows a car on the Orbiter ride (a) and the entire ride (b) and the ride in motion about mid-cycle (c).

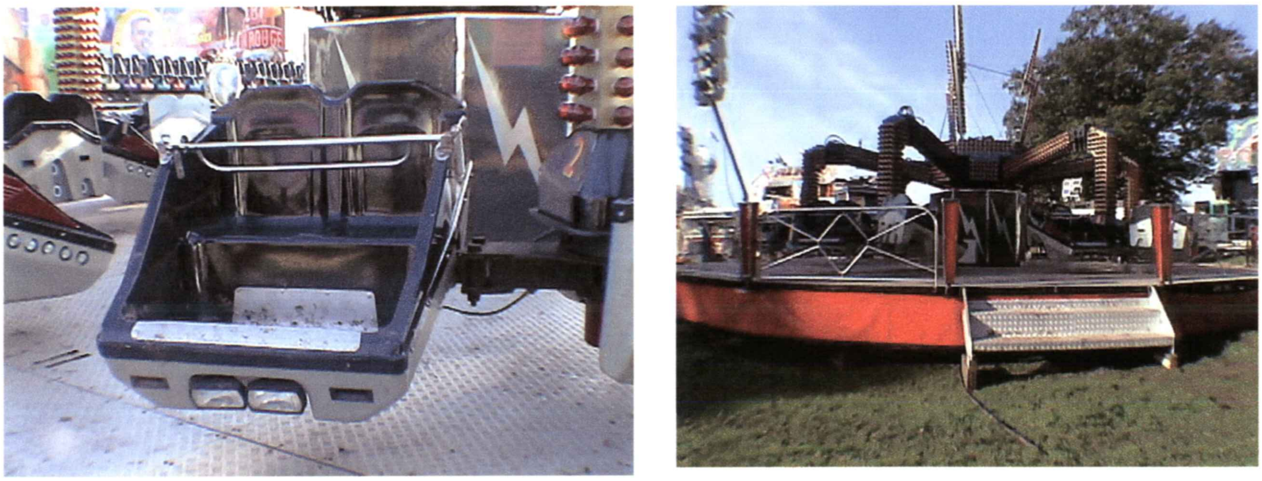


Figure 1: a) Orbiter car **b) Orbiter ride start of ride-cycle**

c) Orbiter ride mid ride-cycle

2.0 Ride Forces

2.1 Forces on passengers and passive forces on handrail

Forces on passengers
As the ride moves, passengers experience forces, which can cause them to move in certain directions. This assessment of the forces on passengers and potential directions of passenger movement, assumes that passengers are not actively trying to move, i.e. they are sitting passively in the car.

Forces on hand rail (passive)
If a passive passenger was experiencing ride forces acting forwards out of the seat or vertically upwards whilst holding onto the handrail, the passenger may have to exert a force on the handrail to counteract the ride forces (e.g. to stop themselves sliding forwards in the seat)

To assess the scope for passive passenger ejection, the ride forces were considered during the ride cycle. These are shown on the following graph, in each of the three directions of acceleration. These g-forces were measured for the purpose of this report using tri-axial pre-amplified accelerometer (Entran EGCS3-A-25) fastened to the seat pan of the ride, at the outside occupant position.

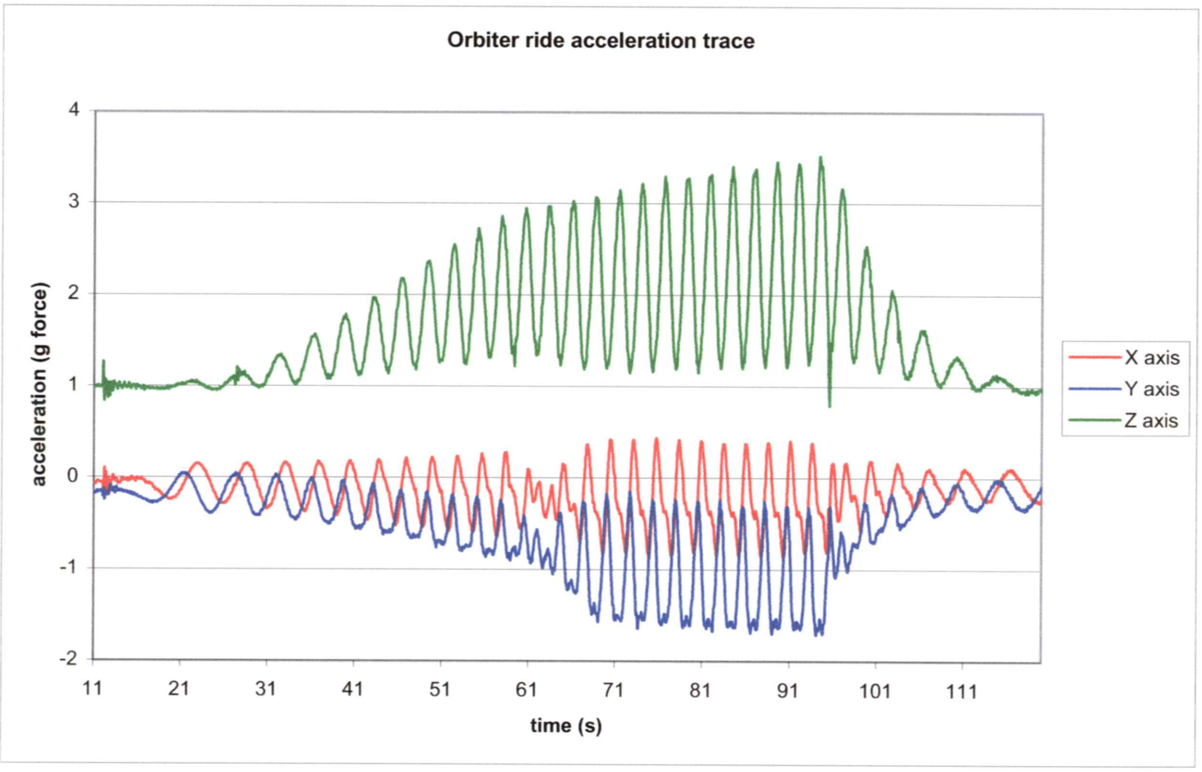


Figure 2. Measured Orbiter ride accelerations during entire ride cycle

IMPORTANT NOTE:

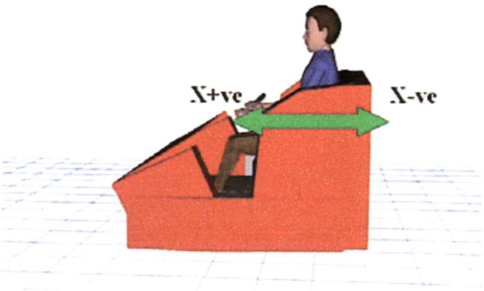
All g-forces are described relative to the seat position (i.e. relative to the position of a seated person). For example a negative g-force in the x-axis would be a g-force that would push someone back against their seat back, regardless of the orientation of the ride relative to the ground at that point in time.

The convention for naming g-forces directions are provided below in Figure 3:

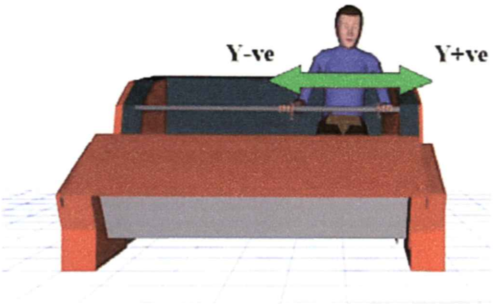
Figure3 **Illustrating the naming conventions of the effects of tri-axis g-forces on occupants of a fair ground ride.**

NOTE: green arrow indicates resulting 'movement' of occupant.

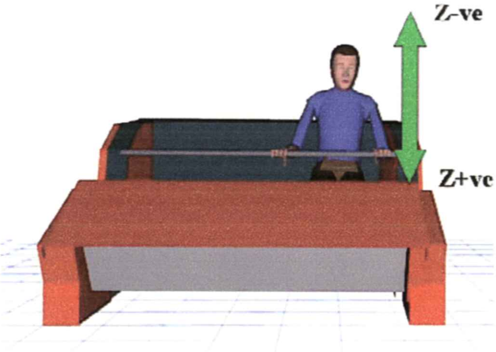
- X-axis g-forces are fore/aft forces
  - Positive = pushing a person away from their seat back, sliding them forwards.
  - Negative = pushing a person into the seat back.



- Y-axis g-forces are side to side forces
  - Positive = pushing a person to their left hand side (e.g. the centrifugal force generated by the clockwise car rotation).
  - Negative = pushing a person to their right hand side (e.g. the centrifugal force generated by any (assumed) anti-clockwise car rotation).

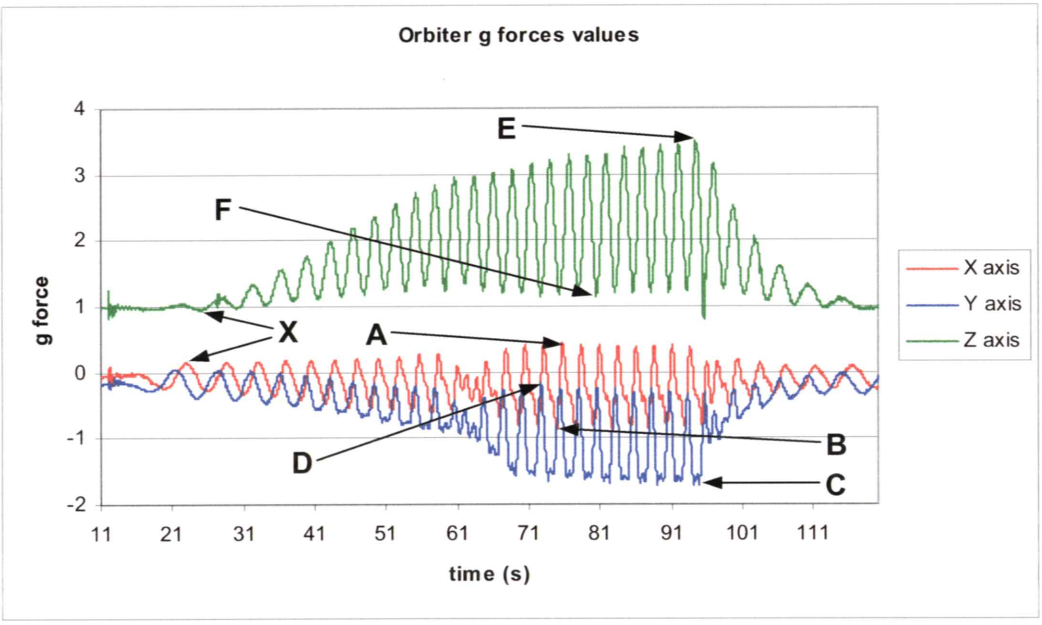


- Z-axis g-forces are up/down forces
  - Positive = pushing a person downwards into their seat (e.g. the force felt due to gravity when seated stationary and on a surface which is horizontal relative to the ground).
  - Negative = pushing a person upwards out of their seat.



In Figure 4 the letters and arrows denote the following stages of a cars rotation during mid-ride movements (i.e. when the ride is running at normal operating speed):

Figure 4. **Key points of g-force activity during entire ride cycle**



A Peak positive fore-aft (x-axis) g-force (0.41g)– occurs as the car rotates downwards and the movement / gravity contributes to a net resultant force acting pushes a person away from their seat back, sliding them forwards.

B Peak negative fore-aft (x-axis) g-force (-0.88g)– occurs as the car rotates upwards and the movement / gravity contributes to a net force which pushes a person into the seat back.

C Peak negative side-side (y-axis) g-force (-1.66g) – occurs as the car reaches the bottom of its movement (closest to ground) and gravity contributes to a force, which moves passengers significantly to the right.

D Least negative side-side (y-axis) g-force (-0.18g) – occurs as the car reaches the top of its movement (furthest to ground) and gravity contributes to a force, which moves passengers gently to the right.

E Peak perpendicular (z-axis) g-force (3.5g) – occurs as the car moves beyond the bottom of its rotation movement and journeys upwards (the increased net forwards rotation speed around the central column increases the centripetal force which acts perpendicular to the seat). This force pushes the occupant down into their seat pan.

F Low perpendicular (z-axis) g-force (1.16g) – occurs as the car moves through the top of its axis of motion and travel downwards (as well as rotating around the central column).

3. Forces on the handrail

3.1 Reactive bracing-forces on the handrail

The peak positive fore-aft (x-axis) g-force (0.41g) means that passengers may need to impart a force up to the equivalent of 41% of their weight (approximately) onto the handrail during downwards rotation of a car to prevent themselves from falling forwards (assuming they are not also bracing with their feet / legs or abdominal muscles). Figure 4 shows the levels of these maximum passive forces that passengers may impart on the handrail during mid cycle of the ride.

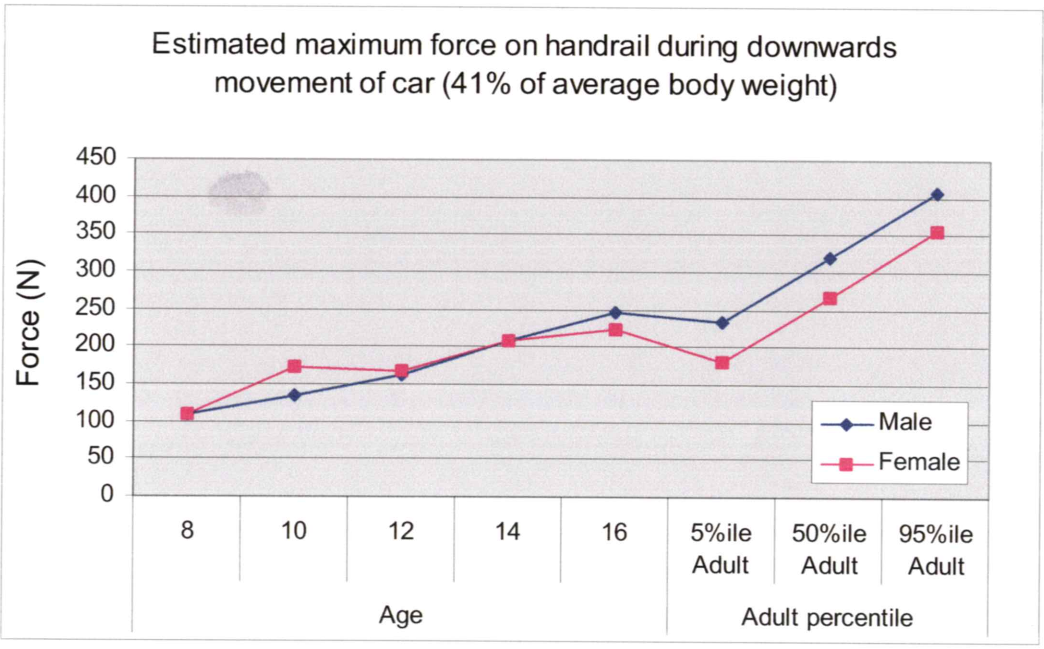


Figure 5. **Estimated maximum passive bracing-forces on handrail during downward rotation in the start-up period (Source; AdultData and ChildData).**

These figures will be affected by the positive forces in the z-axis pushing the occupant into the seat during the mid cycle of the ride, and also may be affected by the frictional properties of the seat surface. These factors would act to reduce the forces on the handrail slightly.

3.2 Passenger pushing-forces (active forces) on the handrail

The position of the handrail / lap-bar means that passengers are most likely to exert a combination of upwards and horizontal push forces. The height of the main bar above the seat pan is above the range of possible seated elbow heights of the occupants, and the height of the supplemental bar is at approximately elbow height of a 50th percentile ("average") 16 year old, or a 95th percentile ("large") 10 year old. The maximal force application possible on both bars will be very similar with a slight alteration of the seated occupant's posture and so these shall be considered the same for the time being. However, as the supplemental bar is anchored to the main bar pushing on the supplemental bar will create a moment which may be understood through the simple equation of:

$$\underset{\text{(on main bar)}}{\text{Moment (Nm)}} \quad = \quad \underset{\text{(force on supplemental bar)}}{\text{Force (N)}} \quad \text{X} \quad \underset{\text{(length of supplemental bar)}}{\text{Distance (M)}}$$

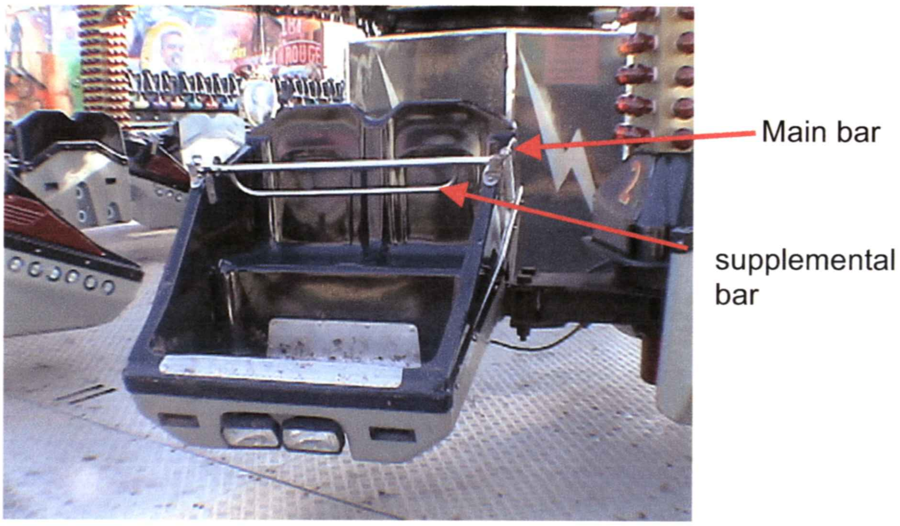


Figure 6. **Photograph illustrating the main and supplemental bar.**

Tables 1 and 2 contain details of the maximum forces that could potentially be exerted on the main handrail (main bar) by passengers. A maximum force on the handrail is also estimated for a range of possible passenger loadings (eg. for two 12 year olds).

Table 1. Horizontal pushing-forces which seated passengers could exert on the main bar

	Average maximum horizontal pushing-force (seated / back braced) (N)	Example passenger combinations			
Strong Adult Male	1000 +	• •	•		
Average Adult Male / Strong Adult Female	650 to 750				•
Weak Adult Male / Average Adult Female	500 to 650				•
Avg. 12 Yr. Old	674(m) , 498(f)		•	• •	
Avg. 10 Yr. Old	532(m) , 603(f)				
Avg. 8 Yr. Old	378(m) , 416(f)				
Estimated maximum forces for passenger combinations (N)		2000	1674	1348	1400

References: ChildData(1995) & based on Kroemer, K (1974)

Table 2. Vertical (upwards) lifting-forces which seated passengers could exert on main bar

	Average maximum vertical lifting-force (seated) with arms bent between 60 and 120 degrees at elbow (N)	Example passenger combinations		
Strong Adult Male	365 to 551 N	• •		
Average Adult Male	218 to 267		• •	
Weak Adult Male	89 to 107			
Avg. 9.5 to 10.5 Yr. Old	66N			• •
Estimated maximum forces for passenger combinations (N)		1102	534	132

Child forces based on torque figures and an average 10 year old elbow-to-grip length of 286mm (In ChildData, arm bent 90 degrees at elbow). Adult values taken from AdultData (1998) & cross checked for validity with Force Limits in Manual Work (1980).

The presence of the supplemental bar below the main bar means that force applied to this results in a torque at the anchor points of the main bar. Given that the measured supplemental bar was 134m long and at an angle of approximately 70° to horizontal and assuming that the force application on this bar is once again directly horizontal, the following table, Table 3, presents the possible push forces provided in Table 1 to a push on this supplemental bar. The resultant torques are those that might be expected on the main bar due to the leverage effect of the supplemental bar.

Table 3. Estimated resultant torque on the main bar when maximum horizontal pushing-forces are applied to supplemental bar

	Estimated torque on main bar when max horizontal forces applied to supplemental bar (Nm)	**Example passenger combinations**			
Strong Adult Male	117	● ●	●		
Average Adult Male / Strong Adult Female	76 to 87.6				●
Weak Adult Male / Average Adult Female	58.5 to 76.5				●
Avg. 12 Yr. Old	58.3(m) to 78.9(f)		●	● ●	
Avg. 10 Yr. Old	70.6(m) to 62.2(f)				
Avg. 8 Yr. Old	48.7(m) to 44.2(f)				
Estimated maximum torques for passenger combinations (Nm)		234	195.9	157.8	164.1

References: ChildData(1995) & based on Kroemer, K (1974)

Based on the available data, it is possible that up to 2000N pushing-force (2 strong adult males) could be exerted on the handrail. Although under normal conditions (i.e. the majority of passenger combinations) it is unlikely that pushing-forces would be that high. There is also potential for maximum vertical lift forces in excess of 1100N (approximately 110 Kgf), however under normal conditions, and assuming passengers actually try to lift open the handrail, the forces are unlikely to exceed 500 to 600 N (approximately 50 to 60Kgf).

The torque applied by pushing the lower supplemental handrail may place the main bar under greater stress and should be considered in the assessment of the strength of the bar and its attachment. There is a potential for a maximum torque of 234Nm to be applied to the bar, but given the 'normal' combinations of passengers (an adult and child) the forces are unlikely to exceed 200Nm, assuming that both passengers apply maximum pushing-force on this bar simultaneously.

4. Effectiveness of passenger containment of Orbiter

The Orbiter ride has a minimum height restriction of 1219mm (4 foot stature) (see Figure 7 – note that this has been reduced at some point previously). This is approximately equivalent to the average height of a 6½ year old boy, a small (27th%ile) 7 year old, or a tall (75th %ile) 6 year old (male – female height discrepancies are still minor at these ages).

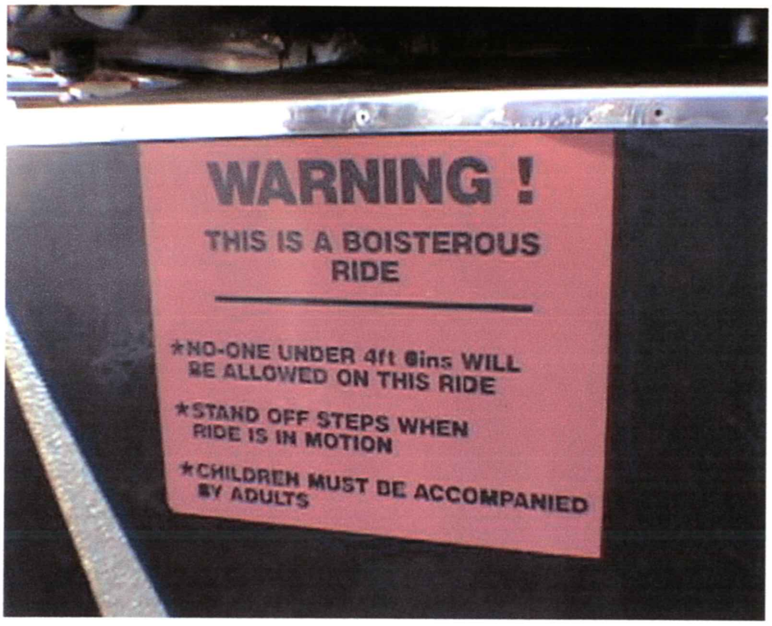


Figure 7. **Photograph illustrating height restriction poster.**

4.1 At Ride Start-up

The forces that the passengers experience during the start-up period appear to be slightly different from those experienced during the main ride-cycle. The g-force measures show that instead of being exposed to forces pushing the passengers into the back and bottom of their seats, as with during the mid cycle of the ride, there is a slight amount of activity raising the occupant upwards and also forwards, effectively pushing them out of the seat. This is denoted with the letter X in Figure 4. These forces though are at relatively low levels, and are for a short duration (approximately 3 seconds). The majority of the passengers, who can touch the vehicle floor, should be able to actively brace against this start-up force even with the restraint lap bar open. However, smaller passengers, who's feet do not reach the floor would be at risk of tipping forwards and so possible ejection from these start up forces in the event of a complete failure of the restraint lap bar (for example if this were left open or was broken).

The footwell offers potential containment and all but the shortest riders could brace with their legs against the positive fore-aft (x) g-force. Anthropometric regression calculations[1] show that at the given height restrictions for the ride (4 foot or 1219mm) the shortest popliteal height (between the knee and floor) will be around 26cm, which would leave the feet hanging (and not contacting the ride floor) by 8cm and mean they would probably not be able to actively brace at the ride start-up. It is most unlikely that even the taller riders could effectively brace themselves against falling using only their legs if the handrail failed and opened.

4.2 During Ride Mid-Cycle

Using the height restriction data and measurements of the ride taken on the day of the observations a 3D computer model of the Orbiter ride was built using the software JACK. This software allows for the inclusion of anthropometrically accurate human models to be placed in simulated environments to perform checks on fit and reach. The following paragraphs discuss the efficacy of the restraint systems of the Orbiter, while considering the possible ejection routes of the smallest riders.

Figure 8 illustrates a combination of riders including a 50th percentile adult female and a 50th percentile 6-year-old boy.

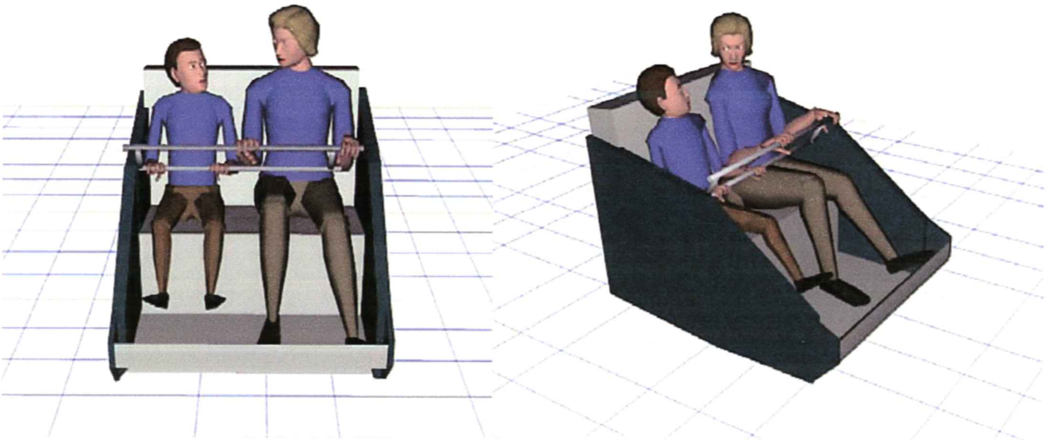


Figure 8. **JACK illustration of mother and 6-year-old boy on ride.**

Figure 9 shows a model of a 1250mm stature child (50th percentile 7 year old boy) sitting with his back against the backrest. The seating is modelled on dimensions recorded by HSL on the 3rd November 2006.

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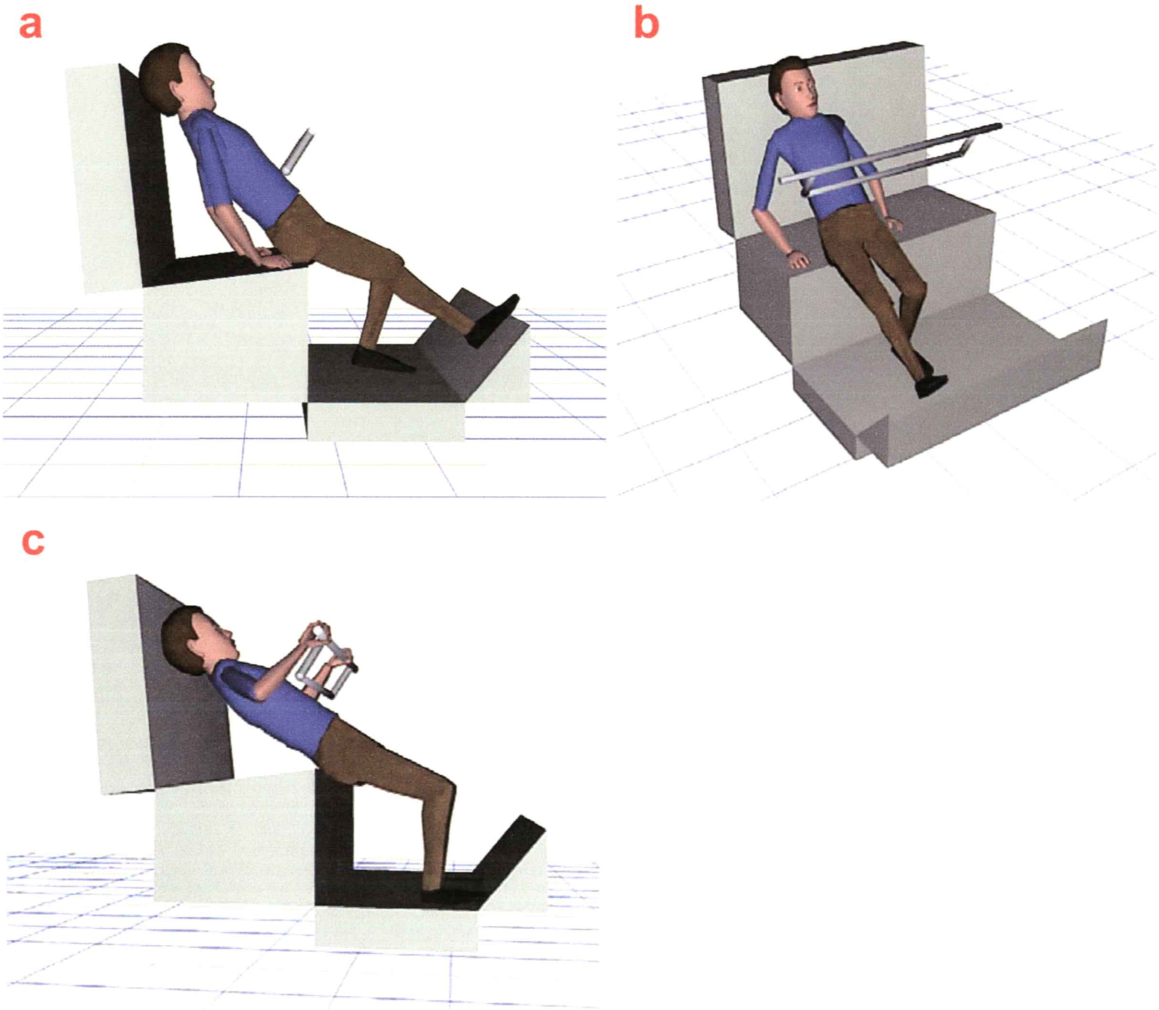
[1] Anthropometrics; BSI; 1990

Figure 9. Model of 1250mm stature child sitting in car

Figure 9 illustrates that smaller passengers sitting with their backs against the seat back would not be able to brace themselves against positive x-axis g-force with their legs / feet, they would be reliant on the handrail for bracing.

In terms of the suitability of the containment system under normal circumstances, JACK models were used to investigate the most likely route to ejection, when the handrail is closed. The following figures illustrate the likely postures that would be assumed during an ejection underneath the handrail. Ejection over the top of the ride containment would conceivably only arise when the occupant is kneeling or standing on their seat. While this behaviour could occur it is unlikely. While it is arguable that the physical containment system should stop occupants from getting into such dangerous situations this is primarily controlled through proper management of the occupants by the ride operators.

Figure 10 **Potential postures during an ejection underneath the containment systems in the Orbiter of a 1250mm stature child, representing the smallest occupant on the ride**



Figures 10 a & b illustrate the small occupant sliding forwards and downwards underneath the lap bar restraint, at a crucial moment of the slide, where the buttocks would leave the seat pan and the occupant would be reliant on supporting their body weight (rendered heavier due to the g-force vector from the combination of positive accelerations in the z and x axes) on their own limbs. Figure 10c illustrates a similar moment during a forwards slip while the occupant is holding onto the main lap bar with two hands and not gripping on the seat pan.

During a movement of this nature and then *forwards* slip of the buttocks, a small occupant (such as a 50th percentile 6 year old boy) would normally make foot contact with the floor approximately at the point at which their buttock would slip from the seat pan (as the length of the outstretched leg is similar to the seat-floor distance). The occupant should then be able to halt the movement at this point through foot contact with the floor/footwell of the ride, making the chance of an ejection from this ride in this manner generally low. However, the sideways g-forces of the ride are significant, (negative 1.66g, in the y-axis), and exposure to this may induce a sideways sliding/leaning of an occupant, especially when riding alone. In such circumstances the smaller occupant, who then slips forwards as well as sideways may not be in a suitable position to make positive contact of their feet against the floor and footwell, and would conceivably struggle to actively brace against the g-force exposures from the ride. The peaks of sideways (y-axis) g-forces occur almost simultaneously with a moderate negative (rearwards) acceleration of the occupant and peak positive z-axis g-forces (pushing the occupant downwards), which could complicate active bracing if the occupant is already slumped or sliding forwards, by pushing them slightly backwards and downwards.

A demonstration of the type of posture described above is illustrated in Figure 11.

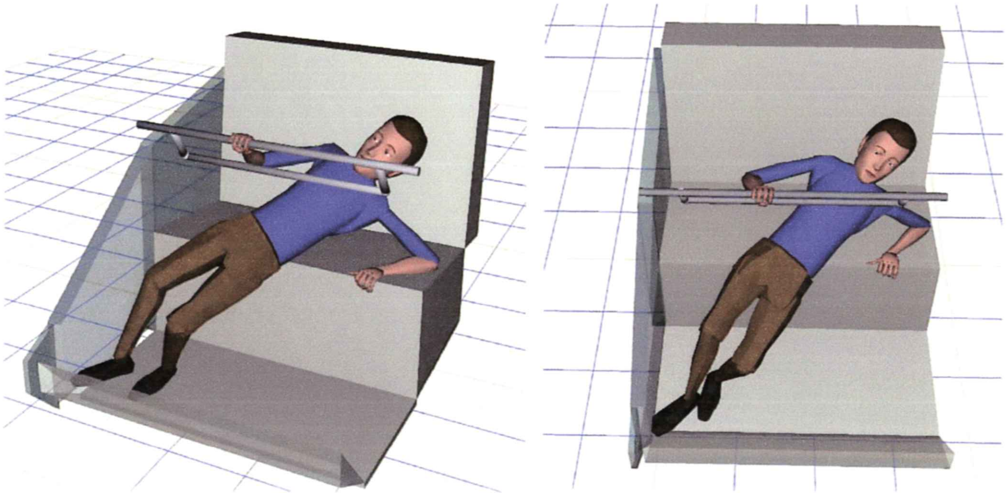


Figure 11. 50th percentile 6 year old child (smallest possible occupant) slumping forwards and sideways from seat

The gap between the handrail and the seat pan was measured at 235mm. The chest depth of an average UK 7 year old is 145mm, 90mm less than the gap (both males and females). These figures suggest that passengers who comply with the minimum height restriction will be able to fit through the gap between the handrail and seat pan if slumping/falling in the manner described above. Chest depth is used as the critical anthropometric dimension because although abdominal depth is generally higher, there is greater scope for compression of the abdomen. Although there may be some scope for tissue compression in the chest amongst smaller passengers that would technically enable them to fit through the gap, the awkwardness of the posture and the active effort, which would be required to fit through the gap, mean it is not considered to be a likely scenario. This discrepancy in chest depths and the height of the lap bar restraint means that it is essential the passengers do not arrive at such a compromised position. This means that passengers should be allowed to use their feet to actively restrain themselves, especially if they are slumping or sliding forwards on the seat.

In order to ensure all passengers are able to actively use their feet to brace against the floor while remaining seated (forwards on the seat), the ride height restriction should be considered for change. This is related to the popliteal height of the passengers, and the minimum distance (with a correction for footwear) required is 34.5cm (the height of the seat pan from the floor). This corresponds to the popliteal height of a mean (50th percentile) 9 year old. The stature of such a person is 133cm or approximately 4 foot 5 inches, which would fall below the previous height restriction for this ride, which was 4 foot 6 inches (1372 mm). Reverting the height restriction to this former figure would reduce the likelihood of small occupants slipping forwards and downwards, leading to ejection from the ride.

5. Conclusions

- It is considered likely that if the containment system (i.e. the handrail) fails, passengers would have less facility to brace against negative fore-aft (x) g-force and would begin to come out of the ride during the downwards rotation of the car (possibly leading to ejection).

- The maximum reactive bracing-force, which a single passenger may impart against the handrail, is approximately 600N for a large adult male.

- The maximum active bracing-force, which a single passenger may exert on the handrail, is approximately 1000N (a strong adult male).

- The maximum active vertical lifting-force, which a single passenger may exert on the handrail, is approximately 550N.

- The maximum torque, which a single passenger may exert on the handrail, is approximately 117Nm.

- In the majority of cases the typical total active forces (pushing and lifting) on the handrail are unlikely to exceed 1600N and 550N respectively (combined figures for 2 passengers in a car) or 200Nm of torque.

- The critical dimension of the containment system is the maximum gap between the handrail and the seat pan (235mm). Passengers who comply with the height restriction of 1219mm would still fit underneath this handrail and may, in exceptional circumstance be subject to ejection from their seat. However, this is unlikely.

- Although passengers towards the lower end of the present permissible height range will not be able to brace themselves with their feet, this bracing facility is not considered necessary providing the handrail operates effectively and the passengers can support up to 41% of their own body weight on their arms for brief, regular periods.

- Revert the height restriction to 4 foot 6 inches (1372 mm) to significantly reduce the likelihood of small occupants slipping forwards and slumping underneath the handrail.