Whistler Sliding Centre
Sled Trajectory and Track
Construction Study
An Independent Safety Audit As Recommended by the BC Coroner

Final Report

Commissioned by
Whistler 2010 Sport Legacies Society
Whistler Sport Legacies is a not-for-profit society that now operates three 2010 Olympic and Paralympic Winter Games venues – the Whistler Olympic Park, the Whistler Sliding Centre, and the Whistler Athletes’ Centre. The organization’s mission is to operate its Olympic legacy venues to advance high performance sport development and recreational sport participation, in a manner that ensures economic, environmental, and social sustainability.
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Report Technology

This document is the complete report and has been compiled in an interactive electronic format with the capability to print off individual sections as needed. An electronic format was chosen because of the significant amount of data that was analyzed, the form of the data itself and the advanced technologies used to support the analysis and findings.

The form of the data that was gathered was either in standard text, video, 2D and 3D CAD drawings or digital images. Using an electronic format allows the reader to review the findings in the report by accessing all of the technologies that were used in this study including:

- Zoom capability for high resolution images,
- Full video play and replay capability,
- CAD overlays.
Disclaimer Notice

Any statement contained in the report ("Report") prepared by the Board of Governors of the Southern Alberta Institute of Technology ("SAIT") for Whistler Sport Legacies ("WSL") in relation to the architecture, design and construction of the bobsleigh, luge and skeleton track (the "Track") located at the Whistler Sliding Centre ("WSC") are by way of general observations based on SAIT’s analyses and findings in the Report. SAIT is not responsible or liable in any manner for reliance by any party, including without limitation WSL, for any changes or modifications implemented on the basis of the report to the architecture, design and construction of the Track and related infrastructure.

The observations and findings made by SAIT in the Report do not signify and are not intended by SAIT to signify any finding of fault or liability on the part of any individual or entity.
About SAIT Polytechnic

The Southern Alberta Institute of Technology (SAIT Polytechnic, Calgary, Alberta), offers more than 100 career programs in technology, trades and business. SAIT delivers relevant, skill-oriented education to 77,000 registrants each year, offering four applied degrees, 65 diploma and certificate programs, 33 apprenticeship trades and 1,600 continuing education and corporate training courses. SAIT students further their passions through eight academic schools: Business, Construction, Energy, Health and Public Safety, Hospitality and Tourism, Information and Communications Technologies, Manufacturing and Automation, and Transportation. SAIT is a leader in applied research and innovation, providing expertise and resources to industry and real-world learning experiences to students. SAIT is a member of Polytechnics Canada and one of Alberta's Top 50 Employers.

About the Sled Trajectory Study Consortium

The complex, highly-technical analysis required specialized resources and advanced technologies from across North America and abroad. The Project Consortium involved six lead organizations and six additional supporting organizations with over fifty people working on the study. The Construction Study was carried out by Dialog (Edmonton, Alberta), a company specializing in architectural and engineering design. The Survey was led by Terra Pacific (Vancouver, BC), an organization that specializes in monitoring and quantity surveys of slope movement, bridge stability, and ice rink shifting. The Trajectory Study was done by Bromley Technologies (Rotherham, UK) a company dedicated to the research, development and manufacture of high performance Skeleton and Bobsleigh technologies in parallel with research programs focusing on sled and bobsleigh track dynamics. The Orthopaedic and Injury Biomechanics Group at the University of British Columbia (Vancouver, BC), which specializes in the analysis of accidents and resultant injuries led the Trauma Study. The Safety Audit was conducted by MacKenzie Safety and Training Consulting Ltd. (Calgary, Alberta) which specializes in assessing safety systems and training in workplace safety. Supporting the lead organizations were Performance Engineered Solutions (Rotherham, UK), University of Leeds (Leeds, UK), Synaptic Analysis Consulting Group (Vancouver, BC), Epic Scan, (Medford, OR) and the Centre for Advance Product Evaluation (Westfield, IN).
## Abstract

In response to the Coroner’s report into the death of Nodar Kumaritashvili at the 2010 Olympics, a technical study of the Whistler Sliding Centre Track was undertaken. The scope of this study was to carry out a comprehensive technical analysis of the combined bobsleigh, luge and skeleton Track. The primary objective of the study is to provide observations, identify deficiencies and make recommendations for improvements in four areas including: track construction; trajectory envelope; traumatic injury and safety protection measures. The objectives were met by: conducting an “as-designed” versus “as-constructed” audit; doing a track survey; developing a trajectory model and running various scenarios; carrying out a retrospective incident and trauma study and conducting a track safety audit.

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**Distribution Statement**

Confidential Internal Document

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**No. of Pages**

352
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</tbody>
</table>
# TABLE OF CONTENTS

ACKNOWLEDGEMENTS .......................................................................................................................... 1  
EXECUTIVE SUMMARY ....................................................................................................................... 2  
CHAPTER 1 - INTRODUCTION ........................................................................................................... 14  
CHAPTER 2 - REVIEW .......................................................................................................................... 33  
CHAPTER 3 - TRACK SURVEY AND SCAN ....................................................................................... 67  
CHAPTER 4 - CONSTRUCTION AUDIT ............................................................................................ 79  
CHAPTER 5 - RETROSPECTIVE TRAUMA STUDY ............................................................................ 141  
CHAPTER 6 TRAJECTORY STUDY ................................................................................................... 185  
CHAPTER 7 - SAFETY AUDIT ............................................................................................................. 299  
APPENDIX ............................................................................................................................................ 335
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ACKNOWLEDGEMENTS

The SAIT Polytechnic team would like to acknowledge the efforts and long hours invested by the individual study teams specifically – Dialog, Terra Pacific Land Surveying Ltd. Bromley Technologies, The University of British Columbia and MacKenzie Safety Training and Consulting Ltd. This type of comprehensive study on a sliding track has never been attempted before and the learning curve, within a very aggressive timeline, was steep. The leadership and knowledge of the lead investigators within these organizations was exemplary. They also brought in technical expertise from Epic Scan, Synaptic Analysis Consulting Group Ltd., CAPE, University of Leeds, Performance Engineered Solutions and we thank them for their contribution with their leading edge technologies in unique global expertise. We would also like to acknowledge the entire Whistler Sports Legacies – Whistler Sliding Centre staff and consultants for their professionalism and sincere desire to improve the Track. Their openness and transparency allowed all of our teams to carry out their studies in a timely manner.
EXECUTIVE SUMMARY

On March 4, 2011, the Whistler Sports Legacies (WSL) awarded SAIT Polytechnic (Southern Alberta Institute of Technology) a contract to carry out a comprehensive study of the Whistler Sliding Centre (WSC) track (“Track”). The study was divided into five component reports, including:

1. A report on the “as-is” constructed Track versus the design.
2. A survey of the Track to verify gradient changes and position, the structural components, the shape of the concrete and an estimate of the ice profile.
3. A report on the potential trajectories, including the velocities and pressures a sled could experience as it travels the length of the Track.
4. A retrospective report on the trauma athletes experienced as a result of incidents on the Track.
5. A report on the safety measures in place to protect athletes, spectators and employees from injury if an athlete loses control of a sled.

While the results of the study may lead to design changes, it is not intended to provide specific detailed recommendations or modifications to the design of the Track. It is the sole responsibility of the WSL to engage a third party to carry out design changes to address any deficiencies identified in the study.

This comprehensive technical study of a sliding track is the first of its kind in the world and required a unique combination of expertise and technologies. A global team of experts with experience in land surveying, 3 Dimensional scanning, safety audits, large scale civil engineering and structural design, trauma analysis, sensor technology and trajectory modeling were assembled.

A multi-level strategy was used to gather, compile and analyze the significant amount of data. A number of standard, industry-accepted approaches, using state-of-the-art technologies, were used to carry out the analysis for each component area.

The study was conducted over a six-month period with site visits at the end of the sliding season and in the late spring. The analysis of the Track included:

- A survey of the Track
- Laser scans of the ice surface and concrete surface
- Dynamic data for 28 runs of sleds sliding down the Track
- Over 2,500 VANOC and WSC documents related to Track design, construction and safety
- Over 43,200 runs from over 1600 run sheets
- Medical records pertaining to 46 incidents were analyzed
- Over 327 Control Tower Logs, over 111 Accident Reports and 11 videos as well as numerous sliding logs, injury registrations documents, patient care forms and medical encounter forms.
- 300 photographs
- A computer simulation of the Track with over 300,000 data points
• Over 270 trajectory simulations
• Over 700 cross-sections of the Track

The fully-integrated methodology used 3 Dimensional scans and surveys of the Track to link the five primary components with each other. The “ice-in” and “as-constructed” scans and surveys were tied to the original “as-designed” survey, linking them to the historical design and construction documents.

A 3 Dimensional computer model of the “as-designed” Track surface was created from the design documents. The “as-designed” surface was compared to the “as-constructed” concrete surface model, generated from the concrete laser scan of the Track, at a moment in time, by overlaying the two surfaces. The same approach was used to create the ice profile along the entire length of the Track by overlaying the ice scan model on to the concrete scan. The comparison of the surfaces was studied using two methods. One method examined vertical cross-sections of the overlay taken every 2.5 m along the length of the Track. The second method used 3 Dimensional contour maps of the surfaces.

Documentation provided by the Track designer to the contractor – including the drawings and specifications for construction of the Track and selected photographs taken during construction – were reviewed.

The scan of the ice was used to create the model of the Track for the trajectory simulation software. Free body particle models of sleds for the five sliding sports were used with the trajectory software to study the trajectory envelope. The free body particle models were validated against the dynamic data gathered at the start of the study.

The retrospective incident analysis was carried out using two highly-detailed databases created from the tower logs, accident reports, run sheets and medical files.

Frequency plots of incidents and incident severity created along sections of the Track were used to identify any critical areas and trends. To the extent allowed by available data, the risk of injury was analysed in relation to the various start positions and protective barriers or walls, as well as the athletes’ gender, experience and discipline.

In order to measure severity of injuries occurring in track incidents, medical documentation was obtained from the Whistler Health Care Centre (WHCC) and the VANOC Whistler Polyclinic (VANOC WPc). The Abbreviated Injury Score (AIS) and Injury Severity Score (ISS) were used to classify the injuries. The Maximum Abbreviated Injury Score (MAIS) was used as a representation of crash severity.

The Safety Audit was limited to the Track and facilities during winter on-track operations, and reviewed existing policies and procedures included in the WSC’s current safety management system. During the review additional hazards were identified, but analysis was confined to items directly related to sliding track operations.

The safety audit included a review of policies, emergency response plans and management practices related to Track activity. It included the identification of existing protective measures, and their location and application along the length of the Track.

An assessment of the current state of the safety program at the WSC Track was carried out using a Certificate of Recognition (COR™) Benchmark Audit. The COR™ program
is an occupational health and safety accreditation program that verifies a fully implemented safety & health program which meets national standards.

Facility observations were conducted during site visits in the late winter and late spring of 2011, and included: athletes sliding; worker activity in clearing and preparing the Track; Track structure and design; operational activities; and, hazard control methods. Photographs were taken of the Track and safety barriers. Measurements of barriers that were constructed on the Track were made and compared with track documents.

The regulations from the International Federations for the three sliding sports – the Federation Internationale Bobsleigh et Toboggan (FIBT) and Federation Internationale Luge (FIL) – were referenced extensively in the analysis, specifically sections related to the design, sliding equipment, safety and operation of the Track.

Findings

The following are the key findings of the study.

1. The organization and order of the design and construction information, drawings, etc., was very difficult to follow.

2. Given the tolerances that can be achieved for this type of mountain-side construction, the “as-constructed” geometry of the Whistler Sliding Centre Track meets the design expectations.

3. The controls for entry into the Track – including starting stations, buildings, shelters, bridges and tunnels – showed little or no deviation from the planned construction. The location of handrails and other external barriers also appeared to be consistent with drawings when they were indicated.

4. A track is constructed based on “speculative design” which is based on field knowledge and ongoing continuous learning as opposed to modeling alone.

5. The design documentation indicates that the group responsible for the design of the Track was competent in designing this type of facility.

6. The FIBT and FIL provided little detail on the homologation procedure in their regulations.

7. Placement of the barriers appeared to be consistent with the homologation recommendations, but there were no barriers identified on any construction drawings.

8. The ice shape or ‘fillet' between the track wall and the base of the track needs special attention in all areas where impacts are experienced reducing the chance that “small ramps” are inadvertently created on which sled runners can ride up onto.

9. Only the crash barrier constructed after the fatality on February 12, 2010, was documented; however, there were no design notes or calculations.
10. There were no specifications to guide the engineering and construction of the safety barriers.

11. The Coroner’s report recommended a number of safety measures be implemented. From the team’s observations, it can be concluded that all items identified in the report were acted on.

12. The trajectory study for the four man bobsleigh found 23 scenarios where the maximum predicted G-forces exceeded the FIBT guidelines.

13. The trajectory study for the men’s singles luge found 4 scenarios where the maximum predicted G-forces exceed 5 G’s.

14. The trajectory study for the two man bobsleigh found 8 scenarios where the maximum predicted G-forces exceed 5 G’s.

15. The trajectory study for the men’s skeleton found 15 scenarios where the maximum predicted G-forces exceed 5 G’s.

16. The trajectory study for the doubles luge found 1 scenario where the maximum predicted G-forces exceed 5 G’s.

17. A review of the literature and available data shows there is significant variance in the numeric value of variables, such as co-efficient of friction (CoF) and drag co-efficient, used in trajectory modeling.

18. The numeric values of the trajectory modeling variables are highly guarded and are constantly changing with ice conditions and improvements in equipment.

19. It was found there is a geometrical “hump” designed into the concrete and ice surface between the corners 12 and 13, which can push a sled towards a later exit from corner 12 and later entry in corner 13 and which could result in a less optimal run trajectory.

20. In the 43,266 runs on record at the WSC, there were 710 incidents (1.64% of total runs).

21. Runs for all disciplines combined that were taken from Lady Start 2, Lady Start 1 and Men’s Luge Start, had the highest percentage of incidents (crashes and/or bodily injury) at 3.0 percent, 2.8 percent, and 2.7 percent respectively and these differences were not statistically significant.

22. A comparison of the incident rate from the upper three starts on the track combined (Men’s Luge, Lady Start 1, and Lady Start 2) pre- and post-Feb. 12, 2010 revealed a decrease in the rate of incidents from 3.0 % to 1.0 %. Although this drop was statistically significant, an analysis which was limited to Lady Start 1 and Lady Start 2 showed an even more dramatic drop from 3.3 % to 1.0 % indicating that factors (such as ice conditions, track profile, experience or
weather) other than start position likely played a significant role in the decreased incident rate.

23. When the overall data for Men’s Luge was examined and not stratified by date, a comparison of the incident rate from Men’s Start to the incident rate from Lady Start 1 and Lady Start 2 combined only resulted in a small decrease in the number of incidents from 2.8 % to 2.5 %, and this difference was not statistically significant.

24. Less than 0.5% of the runs from the Tourist start resulted in an incident.

25. More than 75% of all sliders slid on the track between 1 and 9 times with less than 5% of the sliders having slid on the track more than 70 times and less than 20 sliders ever using the track more than 300 times.

26. An interplay exists between the risks associated with increasing track exposure and the expected benefit of increasing experience. In general, the crash rate first increased with exposure and then decreased likely reflecting a benefit of experience.

27. The highest incident rate for a gender-discipline combination occurred with the 2-man bobsled. The male incident rate was 3.4% and the female incident rate was 2.9%. The male vs. female results for singles luge and skeleton were less than 1% for all cases.

28. In general, it was found that the majority of Track incidents occurred on the lower portion of the Track – 79% of total incidents occurred in corner 13 to 16 and the outrun.

29. Less than 0.5% of the total runs taken resulted in injury. A total of 0.2% of sliders received medical care at the clinic after an incident.

30. Of the medically documented incidents, 52.2% were found to be classified as MAIS 1 injuries (minor), 43.5% to be MAIS 2 (moderate) and the remaining 4.3% to be unclassified because of a lack of detailed information or diagnoses in the medical records.

31. The risk of obtaining an abbreviated injury scale (AIS) injury of 2 (moderate injury) or greater on the Whistler Sliding Centre track was found to be less than 0.1%.

32. Of the clinically documented injuries, the most common were abrasions/lacerations/contusions, representing 52%.

33. The analysis of the possibility of a slider being ejected or partially ejected from the Track identified two incidents.
34. The team could not find any indication that the WSC has staff trained in incident investigation.

35. The Safety Certificate of Recognition (COR™) tool used to complete the audit resulted in a combined score of 68% for the completed audit. A score of 80% is required to obtain a Safety Certificate of Recognition.

36. The International Federation regulations on safety, medical response and equipment safety are limited to general statements and procedures for competition. There is no requirement for the tracks to document incidents, and no evidence that follow-up has been completed on any documentation that may exist.

37. The International Federation regulations provide detailed descriptions of sled materials and assembly but are void of any reference to the definition of crash worthiness.

38. The International Federation regulations do not specify requirements for the progression of an athlete to advance through the different start locations to the top of a track, or the number of runs that must be taken as a measure of competency.

39. The International Federation regulations do not define a maximum safe velocity to guide track designers.

40. The International Federation regulations do not define an engineering standard for safety barriers that are based on crash testing.

Limitations

There were a number of limitations that impacted the findings:

1. During the testing in March 2011 where the dynamic data was gathered, 4 man sleds were only allowed to be launched from the Damen (Ladies Luge) Start. The data to validate the 4 man bobsleds reflects the lower speeds and lower G Forces that would occur at a lower start.

2. Differences in the incident information recorded in the tower logs and run sheets resulted in a discrepancy of 263 incidents.

3. Only 11 crash videos were available for analysis. Analysis was further limited by video quality and poor camera angles.

4. Analysis of the medical documentation also involved several challenges including discrepancies between the radiological report and the physician analysis; handwritten documents that were difficult to interpret.

5. Without being able to identify specific impact points, the dynamics of the impact, the frequency at a specific location, and pilot correction or other contributions to
an impact from videos, the recommendations in this study are restricted to identifying areas for more detailed analysis or design improvements.

6. The WSC was unable to obtain similar data from other tracks homologated by the FIBT and FIL. Therefore, this study is limited to the data recorded for the WSC Track. It cannot be determined whether the incident rates of the WSC Track are higher or lower than any other track.

7. Without access to near-miss or loss reports, the team has to assume the control measures in place are adequate.

8. In the absence of documents reporting on-track worker injuries or close calls, it was assumed the procedures in place were adequate.

9. There were no completed documents to prove workers were tested for competence. As there were no incidents reported to identify deficiencies, it was assumed training was adequate.

10. The review of the hazard assessment process, including controls, was limited to the available documentation and observations of activities in late March 2011.

11. During the safety audit, the team was unable to verify details about changes to the safety procedures or Track modifications and the reasons for such changes.

Recommendations

For improved “Athlete Safety” it is recommended that:

1. The Whistler Sliding Centre investigate sensors and other technologies as part of an Injury Surveillance System to carry out ongoing measurements of athlete exposure to forces and vibrations acting on the body.

2. The Whistler Sliding Centre implement the use of “visual indicators” on the track to eliminate the “white tube” effect athletes experience as they travel down a track.

3. The FIBT and FIL define a safety procedure, including measures for non-compliance, based on recording incidents, analyzing incident records and retaining incident records to assess the safety continuous improvement plan for all tracks.

4. The FIBT and FIL provide guidance on the use of “visual indicators” on the track to eliminate the “white tube” effect athletes experience as they travel down a track.

5. The FIBT and FIL conduct equipment crash worthiness and protection tests on all equipment, and consider equipment design criteria that would dissipate energy.
6. The FIBT and FIL define and implement a helmet embargo procedure for all athletes involved in incidents where the efficacy of helmet may be compromised.

7. The FIBT and FIL develop formal criteria defining an athlete's competence to compete on a specific track.

8. The FIBT and FIL should create an Incident Surveillance System, based on the Federation Internationale de Ski (FIS) and incorporate knowledge gained from this report, as well as other studies of track accidents, when setting specifications for sleds and protective safety measures such as walls, barriers and crash equipment.

For improved “Track Design and Modeling” it is recommended that:

1. The Whistler Sliding Centre investigate use of Global Positioning Systems (GPS) and other technologies to continuously refine the trajectory model that was developed as part of this study.

2. The Whistler Sliding Centre should retain the original designer of the Track or an organization with equal knowledge and competence to engineer and document any modifications to the Track.

3. The original designer of the Track should take responsibility for reviewing the design and construction findings of this report and engineer improvements to address any deficiencies identified.

4. The FIBT and FIL should develop a more detailed procedure for track homologation, similar to the Federation Internationale de Motorcyclisme (FIM) procedure (section 029.11).

5. If the Track must be ground to make the surface smoother, it is recommended that no more than 5 mm of shotcrete be removed. If more than this amount is removed, the concrete cover over the reinforcing steel and refrigeration pipes will be too thin and the long-term durability of the Track will be compromised.

6. It is recommended that a more stable line be created from the exit of corner 12 into the entry of corner 13 and that this can be achieved by:
   a. the ice profile in C12 be shaped, where possible to create a longer exit radius and thus more progressive and less extreme exit trajectory out of Curve 12 into Curve 13.
   b. the significance of the impact on sled trajectory of the designed bump at the exit from C12 to the entry of C13 should be reduced.

7. It is recommended that the profiles between C15 to C16 be fine tuned to enable more natural variability in the line of choice towards C16 so that they allow
athletes to choose their entry line into C16 with the potential of reducing the centripetal accelerations (g forces) experienced through the initial part of C16.

8. Modelling of potential crash events be undertaken to examine “what-if” scenarios and provide insight into the potential for injury and the effect of potential safety measures.

9. The Whistler Sliding Centre continually evaluate the Track configuration and crash outcomes as they occur.

10. The FIBT and FIL provide more detailed track design criteria – beyond top speeds and g-force exposure – to guide track designers.

11. In order to provide transparency in the design of sliding tracks, the FIBT and FIL should validate the output from the trajectory simulation models: publish and annually review the range of values for the co-efficient of friction (CoF) and drag co-efficient used in the design and analysis of tracks; and annually review the output of the simulations in terms of “g-forces” and velocities using the revised, published CoF and drag values.

12. The FIBT and FIL should provide more specific guidance to track designers by clearly defining the basis of a maximum safe velocity.

13. The FIBT and FIL provide more detailed specifications for protective safety measures such as walls, barriers and crash equipment similar to that taken when specifying safety barriers for highways in Canada [CSA (2006)] and FIM (Standards for Road Racing Circuits 2012, p36 ff). The standard safety barrier designs should be developed from consideration of such things as:

- Incidents that have occurred.
- Marks from sleds travelling across the existing safety barriers on tracks.
- Crash testing.
- Trajectory modeling.
- Structural analysis and design.

14. The operators of the Whistler track, under the direction of the Federations, should install the standard safety barrier system at all corners and locations along the length of the track where there is no control on the free flowing path of a sled.
For improved “Track Operations” it is recommended that:

1. The Whistler Sliding Centre work with the track designer to develop a filet ice measurement and cutting tool, similar to the standard groove cutting tool used at the bobsleigh and skeleton start, to continuously monitor the optimum ice filet radius along the length of the track.

2. The Whistler Sliding Centre develop a protocol to ensure the collection of important parameters within incident reports.

3. The Whistler Sliding Centre implement automated record-keeping of all incidents.

4. There should be communication between the control tower and the first responders after each incident to eliminate inconsistencies and reporting errors.

5. The Whistler Sliding Centre should collect data from workers around the track associated with near misses and incorporate that information into incident analysis.

6. Reporting be encouraged from Track users and those involved in Track activities, such as coaches and visitors.

7. The Whistler Sliding Centre implement and monitor a track etiquette protocol for all coaches, athletes and visitors, such as media and spectators, to ensure site rules, governing the viewing and recording of athletes sliding, the use of flash photography and reaching into or entering the sliding track or field of play, are enforced.

8. The Whistler Sliding Centre tests all workers for competence in the tasks they are required to perform as part of their job duties.

9. Ongoing reviews of the emergency response system should be conducted throughout all operating phases and seasons of the year, internally and involving community emergency services. All emergency response drills should be documented and the plans reviewed to ensure the absence of gaps and an active, effective communication system.

10. The Whistler Sliding Centre train all staff involved in incident investigation, and assign trained staff to investigate all near misses and incidents at the facility.

11. The FIBT and FIL define a continuous improvement plan for all tracks that includes plans for Management reviews, audits, regular track maintenance and takes into account a continuous analysis of incident data as part of an Incident Surveillance System.
For improved “Document Control and Analysis” it is recommended that:

1. Representatives of the Whistler Sliding Centre should assemble the most current IBG Consulting Engineering documentation for the Track, and archive the remaining reports and drawings.

2. Representatives of the Whistler Sliding Centre should assemble the most current Stantec Architecture Ltd. drawings and specifications for the Track and related facilities, and archive the remaining documentation.

3. The Whistler Sliding Centre implement a continuous improvement plan that includes documentation around regular management reviews, audits, a regular track maintenance plan and takes into account a continuous analysis of incident data as part of an Incident Surveillance System.

4. The Whistler Sliding Centre create and implement a “Track is Clear” checklist including checks that ensure movable barriers are locked in place.

5. The Whistler Sliding Centre develop a waiver or sign-off sheet to document that all athletes, coaches and visitors are provided with information about site hazards and property rules.

6. All applicable VANOC forms and policies be reviewed and converted to WSL forms and policies.

7. The Whistler Sliding Centre’s Change Management procedures include provisions for regular Management reviews, audits and more detailed documentation, describing the changes and confirming implementation.
Conclusions

In summary, it can be concluded that:

The group responsible for the design of the Track was competent in track design.

There was evidence in the design, construction and operation of the track to minimize unreasonable risk based on the guidance in the Federations’ regulations and the inherent level of risk in the sport.

The WSC Track was generally constructed within the design tolerances in terms of the intended shape of the track.

The Track was constructed in the intended design location.

Construction documentation needs to be better organized with only the latest document versions used for reference purposes.

The potential exists for high velocities and G forces that may exceed those specified in International Federations’ regulations.

The incident rate is less than 2% for over 43,000 runs.

There is less than a 0.5% risk of an incident leading to an injury and 0.2% requiring medical attention.

The incident performance can not be compared to the incident rate of other tracks.

The FIBT and FIL regulations describe the right to participate and admission into the International Federation (IF). The FIBT regulations describe the requirements for test competitions and training on new tracks. However, neither Federation provides details on competency (in terms of both skill and experience), as it relates to safety, and defer to the National Sporting Organization (NSO) to assess competency and put forward names to compete in IF-sanctioned events.

There is no regulation in either IF’s documents describing the progression of an athlete through the different start locations to the top of a track, or the number of runs taken as a measure of competency to travel down a track safely.

The FIBT and FIL should develop formal criteria defining an athlete’s competence to compete safely on a specific track.

Safety practices at the Track follow generally accepted standards with some opportunities for improvement in documentation.

The International Federations’ regulations should provide more detailed guidance on track design, a maximum safe velocity, rollover barrier design standards, safety measures, incident analysis, equipment safety and driver/slider competence and equipment.
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CHAPTER 1 - INTRODUCTION

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TABLE OF CONTENTS

CHAPTER 1 - INTRODUCTION ............................................................................................................. 14
  1.1 History of the Track ..................................................................................................................... 20
  1.2 Objective of the Study ................................................................................................................. 21
  1.3 Presentation of the Report .......................................................................................................... 22
  1.4 Contributing Organizations ........................................................................................................... 22
  1.5 Timeline ...................................................................................................................................... 24
  1.6 Study Methodology ..................................................................................................................... 25

LIST OF FIGURES

Figure 1.4.1: Organizational Chart .................................................................................................. 23
Figure 1.6.1: Document Reference Map (complete track) ................................................................. 26
Figure 1.6.2: Document Reference Map (top) .................................................................................... 27
Figure 1.6.3: Document Reference Map (upper) ............................................................................... 28
Figure 1.6.4: Document Reference Map (middle) ............................................................................. 29
Figure 1.6.5: Document Reference Map (lower) ............................................................................... 30
Figure 1.6.6: Document Reference Map (finish) ............................................................................. 31

LIST OF TABLES

Table 1.4.1: Contributing Organizations ........................................................................................... 23
Table 1.5.1: Summary of Key Project Milestones ............................................................................. 24
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While descending the Track, on February 12, 2010 at 10:50, Georgian luge athlete Nodar Kumaritashvili collided with a section of the ice wall on the final corner and was ejected to the outside of the Track, where he struck a metal post. Mr. Kumaritashvili sustained injuries that proved immediately fatal.

In the accident report, the British Columbia Coroners Service made the following recommendation:

“It is recommended that the Whistler 2010 Legacies Society undertake a comprehensive safety audit of the Whistler track, including, but not limited to, an independent review of the track design and track speeds, placement and configuration of crash barriers and other protective measures, to address the possibility of violent crashes inside the track and the possibility of athletes or sleds leaving the track and potentially causing injuries to the athlete, track workers or spectators.”

The BC Coroner also made the following comments:

“While VANOC was formed for the purpose of planning, organizing, funding and hosting the 2010 Games, including the construction and operation of the Whistler Sliding Centre, the Whistler Legacies Society, later renamed Whistler 2010 Sport Legacies Society, was established as a not-for-profit corporation for the purpose of operating the Whistler area Olympic venues, including the Whistler Sliding Centre, following the culmination of the Games. The Whistler 2010 Sport Legacies Society took over the operation of the Whistler Sliding Centre, from VANOC, on the asset transfer date of May 31, 2010. This investigation recognized that some of the most acknowledged experts in the area of sliding sports and track development were involved in the creation of the Whistler track. It would also appear that the best practices known at the time were followed. However, Mr. Kumaritashvili’s death has proven the Whistler track is capable of producing a serious incident, despite all of the safety measures that have been previously considered adequate. Further and greater scrutiny of safety issues at the track is advisable. Consideration may be given to involving an independent and previously unaffiliated entity to carry out the audit, in order to provide either a new perspective or a corroborative perspective capable of restoring confidence in the Whistler track. It is anticipated that such an audit would not only reflect on the safety of top-level competitive athletes, but also consider the safety of the tourist, the recreational track user, and the public in general.”

The full report can be viewed on the BC Coroner’s website:


The safety of all Track users, workers and spectators is of utmost importance to Whistler Sport Legacies (WSL). In December 2010, to comply with the BC Coroner’s recommendations, Expressions of Interest (EOIs) were invited from persons or
organizations prepared to conduct an independent evaluation of the sled trajectories at the Whistler Sliding Centre Track (the “Safety Audit”). EOIs were required to demonstrate an understanding of the desired outcomes and address the key objectives of the Safety Audit. All EOIs were evaluated and the highest rated were invited to submit detailed proposals in response to a comprehensive Request for Proposals issued by WSL.

In February 2011, SAIT (Southern Alberta Institute of Technology) Polytechnic’s Sports and Wellness Engineering Technology applied research group was selected to lead the Safety Audit. Along with SAIT, the lead investigating organizations consisted of a consortium of global experts including: Bromley Technologies Ltd; Terra Pacific Surveying; DIALOG; the University of British Columbia; Synaptic Analysis Consulting Group; CAPE; and MacKenzie Consulting.

As a condition of the agreement between SAIT and WSL, all members of the study team completed non-restriction and confidentiality agreements.

Upon signing the agreement and throughout the term of the study, WSL released design, construction, safety and homologation documents to the study team.

1.1 History of the Track

Built for the Vancouver 2010 Olympic Winter Games (Games), the Whistler Sliding Centre features a combined bobsleigh, luge and skeleton track (Track). The Track is located on the lower slope of Blackcomb Mountain in Whistler, British Columbia, which is 125 km (78 miles) north of Vancouver.

On April 1, 2004, the Vancouver Organizing Committee for the 2010 Olympic and Paralympic Winter Games (VANOC) contracted Ingenieurburo Gurgel (IBG) as a consultant to design the Track. (Appendix C.1 - 70583 - C 1133 - IBG 01-Apr-04.pdf)

Design work culminated with the release of the final design parameters on August 15, 2004. (Appendix C.1 - 5158 - Final Design 15-Aug-04.doc) In the final design document, IBG clearly describes the design parameters for the Track including projected speeds and centrifugal forces.

Stantec Architecture was subcontracted to produce the architectural and construction drawings. Construction took place from June 2005 to December 2007.

The first runs from the junior start were taken on December 19, 2007.

Homologation of the Track took place from March 5–8, 2008. The Track was subsequently approved for use by both the International Bobsleigh and Tobogganing Federation (FIBT) and the International Luge Federation (FIL), conditional upon VANOC acting on specific recommendations to maximize track safety and optimize ice conditions.
The Canadian National bobsleigh, skeleton and luge teams began training on the Track soon after the first runs were made. They continue to regularly use the Track, along with the Canada Olympic Park track in Calgary, for training and selection races. International teams began using the Track for training sessions in November 2008 (FIL), with FIBT following in January 2009. (http://www.fil-luge.org/index.php?id=424&L=0&tx_ttnews[tt_news]=3471&cHash=68dc1e48e7274badfe424e810324db4a, http://www.fibt.com/fileadmin/Circulars/Circ7830-E%20Vancouver.pdf)

The first World Cup skeleton and bobsleigh races were held at the Track from February 5–7, 2009, and the first World Cup luge events were held February 19–21, 2009. The Games were held February 12–27, 2010. In the following 2010-11 season, the World Cup bobsleigh and skeleton races took place November 25–27, 2010. There were no World Cup luge events held at the Track in the 2010-11 season.

1.2 Objective of the Study

The scope of this study – to carry out a comprehensive technical analysis of the combined bobsleigh, luge and skeleton Track at the Whistler Sliding Centre (WSC), operated by the Whistler Sports Legacies (WSL) – was defined in the original Request for Proposals.

In general terms, the primary objective of the study is to provide observations, identify deficiencies and make recommendations for improvements in four areas:

- Track construction
- The trajectory envelope
- Traumatic injury
- Safety protection measures

These objectives have been met and the following key deliverables provided:

- An “as-designed” versus “as-constructed” audit
- A track survey
- A trajectory model
- A retrospective incident and trauma study
- A track safety audit
1.3 Presentation of the Report

This report has three parts.

1. Chapter 2 is an overview of the entire audit, presented in terms of each individual component: design & construction, incident reporting and use & operations. This chapter ties the component studies together.

2. The second section is comprised of Chapters 3–7. Each chapter provides a detailed report on an individual component, including a description of the methodology, findings and observations written by the team responsible for that area.

3. The final section, in the Appendix, is the supporting data and information in terms of interactive 2 Dimensional cross sections, 3 Dimensional contour plots, detailed data summaries, videos and photographs.

To capture the extensive range of data – including more than 40,000 runs and 3,000 Track cross sections, 300 photographs, two laser scans with cloud data and a trajectory model – this report uses an electronic format. Where possible, the digital objects, photos, videos and interactive 3D contour map may be accessed from the main report.

1.4 Contributing Organizations

In order to meet the objectives of the study, it was necessary to assemble a team of experienced professionals with unique technical expertise, able to work across technologies to provide an integrated analysis of the Track. The team could not have any prior association with the design, construction or homologation of the track. The complex, highly-technical analysis required specialized resources and advanced technologies from across North America and abroad.

A list of the organizations and their leads is shown in Table 1.4.1. The project organization structure is presented in Figure 1.4.1.
<table>
<thead>
<tr>
<th>Lead</th>
<th>Organization</th>
<th>Role in Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dr. Alex Zahavich</td>
<td>SAIT Polytechnic</td>
<td>Project Manager</td>
</tr>
<tr>
<td>Jim Montgomery</td>
<td>DIALOG</td>
<td>Design &amp; Construction Analysis</td>
</tr>
<tr>
<td>Richard Bromley</td>
<td>Bromley Technologies Ltd.</td>
<td>Sled Trajectory Study</td>
</tr>
<tr>
<td>Mike Bernemann</td>
<td>Terra Pacific Land Surveying Ltd.</td>
<td>Survey and Scan</td>
</tr>
<tr>
<td>Shelly MacKenzie</td>
<td>MacKenzie Safety Training and</td>
<td>Safety Audit</td>
</tr>
<tr>
<td>Dr. Peter Cripton</td>
<td>University of British Columbia</td>
<td>Trauma Study</td>
</tr>
<tr>
<td>Dan Fleetcroft</td>
<td>Performance Engineered Solutions</td>
<td>Sled Trajectory Study</td>
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<tr>
<td>Darrin Richards</td>
<td>Synaptic Analysis Consulting</td>
<td>Trauma Study</td>
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<tr>
<td>Ryan Woodward</td>
<td>Epic Scan</td>
<td>3D Scan</td>
</tr>
<tr>
<td>Brad Hart</td>
<td>Northwest Surveying</td>
<td>Site Survey</td>
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<td></td>
<td>Leeds University</td>
<td>Trajectory Model</td>
</tr>
<tr>
<td>Ryan Hoover</td>
<td>CAPE</td>
<td>Dynamic Data Collection</td>
</tr>
</tbody>
</table>

Table 1.4.1: Contributing Organizations

Figure 1.4.1: Organizational Chart
1.5 Timeline

The timeline for the completion of the project was driven by the Whistler Sliding Centre. At the front end, the real-time data – including the first 3D scan and sled dynamics – had to be collected with the Track in full “ice-in” configuration. With the contract awarded on March 8, 2011, this provided one week to assemble the project team and launch testing.

The WSC also requested that a draft of preliminary observations and recommendations be available by the end of August, providing staff with the opportunity to modify the Track prior to adding ice for the 2011-12 season. A draft report was submitted in October 2011 and the final report was submitted October 2012.

A summary of the key milestones for the project is presented in Table 1.5.1. Given that a comprehensive study with this magnitude of data, technical breadth and use of advanced technology had never been attempted on a sliding track, the timeline was quite aggressive. It left no margin for error to accommodate modifications to conventional analysis methods or changes in scope resulting from additional data or findings.

<table>
<thead>
<tr>
<th>Date</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>March 8, 2011</td>
<td>Contract signed</td>
</tr>
<tr>
<td>March 13–17</td>
<td>Dynamic data collection</td>
</tr>
<tr>
<td>March 21–25</td>
<td>“Ice-in” track scan</td>
</tr>
<tr>
<td>May 13</td>
<td>Project update conference call with WSC</td>
</tr>
<tr>
<td>May 25</td>
<td>“As-constructed ice-out” Track scan</td>
</tr>
<tr>
<td>June 5</td>
<td>Comprehensive on-site safety audit of Track</td>
</tr>
<tr>
<td>June 5</td>
<td>RCMP fatality report released to team</td>
</tr>
<tr>
<td>June 20</td>
<td>AUTOCAD files received from IBG</td>
</tr>
<tr>
<td>July 7</td>
<td>Mid-term hold report presentation</td>
</tr>
<tr>
<td>August 31</td>
<td>Draft observations and recommendations</td>
</tr>
<tr>
<td>October 31 2011</td>
<td>Submission of Draft Report</td>
</tr>
<tr>
<td>October 2012</td>
<td>Submission of Final Report</td>
</tr>
</tbody>
</table>

Table 1.5.1: Summary of Key Project Milestones
1.6 Study Methodology

This comprehensive technical study required a multi-level strategy to gather, compile and analyze the significant amount of data. For the overall project, a fully-integrated methodology was used to link all components with each other. At the individual component level, the methodologies used were generally-accepted, standard approaches specific to each technical area. These approaches are described in detail in the individual reports presented in subsequent chapters.

The integrated method used a core element – 3D scans and surveys of the Track – to link all aspects of the study. The “ice-in” and “as-constructed” scans and surveys were tied to the original “as-designed” survey, linking them to the historical design and construction documents.

The “as-designed” versus “as-constructed” analysis was accomplished with an overlay of the scans on the design models. The trajectory study used the model developed from the “ice-in” scan, while the retrospective trauma analysis and safety audit were tied to the scans and design survey reference system.

The reference map created from the original design drawings is a key tool for navigating through the report. Linking all components to the scans and design survey provides a common reference system for integrating the individual components. As well, with all observations and recommendations tied to the reference system, this report can be used as a practical working document for WSC staff to identify areas of the Track that may require modification.

The following figures, 1.6.1 to 1.6.6, have been compiled in this chapter and will be referred to throughout the report. In the figures, the Track has been divided into five sections, based on discussions with WSC staff, and are defined by the location of clearly identified expansion joints in the Track.
Figure 1.6.1: Document Reference Map (complete track)
Figure 1.6.2: Document Reference Map (top)
Figure 1.6.3: Document Reference Map (upper)
Figure 1.6.4: Document Reference Map (middle)
Figure 1.6.5: Document Reference Map (lower)
Figure 1.6.6: Document Reference Map (finish)
CHAPTER 2 - REVIEW

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TABLE OF CONTENTS

CHAPTER 2 - REVIEW .................................................................................................. 33

2.1 Track Design and Modelling ............................................................................... 37
   2.1.1 Methodology .................................................................................................. 40
   2.1.2 Assumptions and Limitations ...................................................................... 45
   2.1.3 Findings and Observations ......................................................................... 46
   2.1.4 Recommendations ...................................................................................... 49

2.2 Athlete Safety ..................................................................................................... 51
   2.2.1 Methodology .................................................................................................. 51
   2.2.2 Assumptions .................................................................................................. 53
   2.2.3 Results and Findings ................................................................................. 54
   2.2.4 Limitations and Implications of the Analysis ............................................. 57
   2.2.5 Recommendations ...................................................................................... 58

2.3 Track Operations ................................................................................................ 59
   2.3.1 Findings ....................................................................................................... 59
   2.3.2 Limitations and Implications of the Analysis ............................................. 63
   2.3.3 Recommendations ...................................................................................... 63

2.4 Conclusions ........................................................................................................ 65
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This study is divided into four component areas, with each area addressed as an individual study. Each of the four investigations share common elements. The objective of this chapter is to consolidate the work of the individual investigations, linking the results to common themes related to the day-to-day operation of the Track.

This chapter has four sections:
- Design and construction of the Track (Section 2.1)
- Incidents (Section 2.2)
- Track use and operation (Section 2.3)
- Summary (Section 2.4)

Section one provides the design background, the construction method and an analysis of the final constructed Track compared to the intended design. Section two describes the findings and presents recommendations relative to past incidents that occurred on the Track, up to and including activity in March 2011. Section three provides perspective on how the Track is used in terms of training, competition and recreational activities. Section four provides a summary.

This chapter draws from the reports of the individual studies presented in the subsequent chapters but for ease of readability does not have embedded figures. For more detail on specific documentation which supports the information presented in this chapter, the reader is directed to the component reports in the chapters that follow.

2.1 Track Design and Modelling

The design of a sliding track capable of hosting internationally-sanctioned luge, bobsleigh and skeleton competitions is a complex process, with a limited number of engineering consulting firms having the required capability and experience. VANOC selected Ingenieurburo Gurgel (IBG) soon after Vancouver was awarded the 2010 Olympic Games. IBG submitted the final design document (Final Design – var03a) to VANOC on August 15, 2004. A design document typically describes the purpose, design philosophy, assumptions, constraints and projected performance of the project. From this document, final construction design drawings and quality metrics are created. IBG’s 31-page document provides a thorough guide, which Stantec architects used to produce final construction plans. The following is a general description of the site and design philosophy as written in the IBG document:
“The track is aligned in North-West – orientation.

The site is approximately 825m in length with the ground sloping in a westerly direction by 125m width measure in a north south direction.

This configuration determines the layout of the track which can be characterized as tight curves with limited straightaways.

The competition length is 1450 m for bobsled and 1395 m for luge (sleds). The whole track has a length of 1700 m.

The basic elements of the curves are a clotoide – typical of other international tracks – at the entrance – in the intermediate member a circular arc – clotoide at the exit.

The curves had to show small clotoides at the entrance in order to be raked to the limited available space.”

A clotoide (or clothoid) is a curve with a changing radius, as typical in a spiral.

Further along in the document, IBG describes the anticipated performance parameters of the Track based on its trajectory design model.

“The track is considered a very fast track – max. v = 139,0 k.p.h (4-bobsled).

This is primarily determined relatively high grade differential between the highest start area, that being the Men’s Luge and the low point of the track.

At a distance of 250 m from the start a speed of v = 93 k.p.h. is attained (in accordance with the rules that require 80 k.p.h.)

Beyond 350 m from the start the speed is permanently greater than 100 k.p.h.

The loading from the centrifugal force (g – forces) are relatively high with max. N = 4,9 for the 4-bobsled and with max. N = 5,0 for luge.

These forces do not exceed in 3 seconds in any curve as required in the international rules.

In some instances a vertical radius has been formed so that the vertical centrifugal force shows is less than 1.0 to offer greater level of difficulty.

A g-force of N = 0,41 is attained at the end of the “bent straight line” (C8) with N (Sx = 714,5 m) and in the straight line in from of curve C12 with N = 0,67.”

The international rules referenced by IBG are distributed annually by the International Federations (IF):

- “International Rules Bobsleigh,” Fédération Internationale de Bobsleigh et de Toboganning (FIBT)
- “International Rules Skeleton,” Fédération Internationale de Bobsleigh et de Toboganning (FIBT)
- “IRO International Luge Regulations – Artificial Track,” International Luge Federation (FIL)

In these documents, the International Federations provide broad design parameters for sliding tracks.
The following excerpts are from the 2010 FIBT rules, where bobsleigh and skeleton share many of the same rules. “Section 16 APPENDIX: THE TRACK,” is from both the bobsleigh and skeleton 2010 editions:

“16. APPENDIX 4: THE TRACK

Combined Bobsleigh, Skeleton and Luge Tracks

16.7 Length of the Track

New Artificial combined bob, luge and skeleton tracks shall be 1200 - 1650 meters long, 1200 meters of which shall be sloping downhill. The last approx. 100 – 150 meters may consist, depending on speed, of an uphill stretch that shall have bends.

The maximum gradient of this stretch must not exceed 12%.

Speed at the finish shall be higher than 80 Km/hr.

16.8 Track Characteristics

The track shall include elements of varying technical difficulty.

Particularly demanding elements in terms of driving technique shall be located in the first stretch which accounts for two thirds of the track.

At design level, it is to be foreseen to be able to reach a speed of between 80 and 100 Km/hr after the first 250 meters.

Bends, combinations of bends and straight stretches of a suitable length shall be inserted into the track.

16.11 Bends

The bends must be constructed in such a way as to allow sleds to move not only along a single trajectory, but to provide a band of possible trajectories from which to choose.

In the central part of the bend, the trajectory should extend along the upper half of the bend.

Entries and exits from bends must be rounded so that the sleds can take them smoothly with no risk of capsizing, if no mistake is made in driving.

16.12 Guardrails in Bends

Guardrails in bends (bumpers) must be constructed in such a way that they return the sleds on to the track.

They must be sufficiently long and wide.

16.13 Centrifugal Force

The maximum time for which centrifugal force of ‘4G’ may occur is 3 seconds.

The maximum centrifugal force allowed is ‘5G’; this centrifugal force must not last for more than 2 seconds.

No centrifugal force in excess of ‘5G’ is allowed.

16.17 Solar and Weather Protection Devices

The stretches of the track exposed to the sun and / or to adverse weather conditions must be protected by means of proper devices.

On bends, protection may be provided by fixed roofs combined with the coverings of the bends.
On straight stretches, a removable type of covering, open on one side of the track, must be adopted. It is forbidden to install roofs with fixed coverings on straight stretches. Any pillars and fixture systems shall be at a distance of 50 cm from the inside of the track wall.

Coverings shall not interfere significantly with television filming or the view of spectators. They should possibly be of the removable type.

Local climate conditions must be duly considered.”

As bobsleigh, skeleton and luge share artificial tracks, the FIBT and FIL mirror each other in terms of guidelines for track design – with the exception of certain parameters, such as start areas, that are specific to the individual sports.

The following excerpt is from the 2010 FIL Supplement 1 – Regulations for Artificial Luge Track section 3.1.1 where velocities are specified:

The gradient of the track should be designed in a way that a speed of approx. 80 km/h is reached approx. 250 m after the start. The average gradient of a track from the men’s start to the low point should not exceed 10%. The average gradient of the second half of the track should not exceed 8%. The calculated maximum speed must not exceed 135 km/h. The technically difficult track elements (labyrinth, left-left or right-right combinations) should be incorporated in the first two thirds of the track.

For a track to host international competitions, it must be homologated by the International Federations. In sliding sports, homologation is defined as the sanctioning or official approval of a track for international training and competition. The homologation process is described in the regulations of the International Federations (sec.16.24 in FIBT regulations and Sup. 1, sec. 3.6 in the FIL regulations).

According to the homologation documents reviewed in this study, on September 8, 2006, VANOC met with FIBT and FIL to review construction progress and plan the homologation process. The first runs on the Track were taken from the junior start on December 19, 2007.

Homologation of the Track took place March 5-8, 2008. The Track was subsequently approved for use by both the FIBT and the FIL, conditional upon VANOC acting on specific recommendations to maximize Track safety and optimize ice conditions. These recommendations were reviewed and implemented by the Whistler Sliding Centre. On October 30, 2008, the International Federations gave final approval to the Track, which opened for its first international training sessions in November 2008.

With this background, the study team carried out its analysis of the design and construction of the Track.

2.1.1 Methodology

Due to the complexity of the Track’s shape and the mountainous terrain of the site, the team selected a combination of strategies to assess its design and construction. In the construction audit, a comparative analysis was used to assess the fit of the constructed (“as-built”) Track to the original design, and to determine if it was built within reasonable
tOLERANCES. A similar analysis was used to develop the ice profile along the length of the Track.

A significant aspect of sliding track design is the “envelope” sleds use to travel down the track. The envelope is the range or breadth of trajectory paths. Typically, there is an optimum trajectory “line” down a track that is considered the fastest. The models used to develop a line and envelope – and predict the velocities and g-forces experienced while travelling within the envelope – rely on three parameters: sled weight, drag co-efficient (in air), and co-efficient of friction (metal to ice). An analysis of the trajectory envelope was necessary to assess the design of the Track.

A number of standard, industry-accepted methodologies, using state-of-the-art technologies, were used in the design and construction analysis of the Track. Detailed descriptions of the specific methods are reported in the individual component chapters.

Dialog, Terra Pacific and Epic Scan worked together to carry out this part of the study. In general terms, a detailed topographic survey of the ice surface – and associated structures integral to the Track, including the roofs, walls and the concrete surface beneath the ice – was produced. A system of 3 Dimensional laser scanners, 3-dimensional robotic total stations, and precise digital levels were used to scan the Track with ice in, as well as the concrete surface after the ice melted.

Terra Pacific completed an independent control survey prior to the 3 Dimensional scanning done by Epic Scan. The control survey set field points that would be required to orient the 3 Dimensional scans to a local-coordinate system over a closed loop of the 1.5 km track. Multiple sets of angles and distances were measured and the results were averaged, giving a horizontal misclosure of 8 mm. The misclosure was distributed over the course of the traverse giving a plus or minus 3 mm misclosure for the horizontal coordinates of the control traverse. A precise level was used, closing all loops to 5 mm or better giving a plus or minus 2 mm vertical misclosure for the control points. A GPS was then used with three systems simultaneously to obtain coordinates that checked to within 5 mm or better of the conventional survey. These control points were used by Epic Scan to calculate the position of the scanner.

Once all the control points were set and adjusted, a 3 Dimensional scanning system was used to scan the surface of the ice and, later, the concrete. The scan of the Track was obtained by using two different ground based LiDAR systems deployed by Epic Scan. The scanners produced a point cloud of geometric samples on the surface of the subject – in this case, the ice and concrete. These points were used to extrapolate the shape of the ice and concrete.

The scan of the ice was completed in late March immediately after the Track was closed for the season. At the time, there was a significant amount of snow in and around the Track, as much as 2 to 3 metres in some places, with a temperature range of -4.5 to 9° C. The scan of the concrete was completed at the end of May on dry ground, with a temperature range of 7 to 17° C.

The “scan” coordinate system was used to align the ice scan data. At the time of the “concrete” scan, registration information was provided in the “as-designed” coordinate system. An attempt was made to work within the “as-designed” coordinate system but
the large coordinate values created issues with the software. This is a well-known issue when working within the 3 Dimensional manipulation and CAD softwares. It was decided to continue working in the “scan” coordinate system, and to have the as-designed 3 Dimensional information provided in this coordinate system.

The individual scans were assembled or “knitted” using a system of common targets and geometries, and they were registered to the survey file. Critical to this process is the amount of error between the survey points and the geometry of the points used throughout the site. The same process was used for both the concrete and ice scans.

In order to test the comparison of the “as-built” surface to the “as-designed” surface produced from registration with the survey information, a computer software “best fit” alignment process was also done. This process locks the “as-built” model into its current location and uses the software to fit the “as-designed” model to the “as-built” model by minimizing error and maximizing the amount of track surface that is aligned to the design surface. The best fit process ignores potential errors such as:

- Errors in survey being utilized on site during scanning.
- Errors between the survey being completed on site and the original survey that was utilized during construction.
- Errors between the survey that was used during construction and the actual “perfect world” of the design information.

The construction audit of the Track includes a comparison of the “as-built” track to the “as-designed” in both the shape and location of the Track.

The best fit analysis examines how closely the shape of the Track matches the “as-designed” model with no emphasis on how true the location of the Track is to its designed location. A best fit approach can introduce errors in certain locations in order to get the largest overall area of the Track in the best possible alignment.

As the software generated best fit analysis did not improve the alignment between the two coordinate systems the best fit results for comparing the deviations between the as-constructed and as-designed track surfaces were not used in this report.

Documentation prepared by the Track designer was reviewed, including the drawings and specifications provided to the contractor for the construction of the Track, and photographs taken during construction.

A 3 Dimensional computer model of the “as-designed” Track was created from the data in the IGB documents. The “as-designed” surface was compared to the “as-constructed” concrete surface of the Track, at a moment in time, by overlaying the two surfaces. The comparison of the surfaces was presented in two ways.

First, a vertical plane was cut and a cross-section comparison was made every 2.5 m along the length of the Track. The second method of comparison was a 3 Dimensional contour map. Due to the size and software required to view the map, this comparison was compiled and loaded on a separate DVD accompanying this report. The same approach was used to compare the ice surface to the concrete Track surface, and to produce an ice profile.
The scans were created using a common local coordinate reference system. In order to carry out the “as-constructed” analysis, the scans were tied to the original design/construction coordinate system. The position of the reference monuments used for the construction of the Track were located by the survey team and compared to the survey provided by the Whistler Sports Legacies. A translation factor was calculated and the scan data translated into the design/construction coordinate system.

It is important to note the use of the term “a moment in time” – which means the comparisons reflect the data collected at a specific point in time. The Track is located in rugged terrain and the possible movement of survey monuments, as well as the varying environment, can contribute to variance in the alignment of the models.

The trajectory study was carried out by the Bromley Technologies team, including PES, Leeds University and CAPE. A key aspect of developing a track model is validation using real-time data. The first key task for the entire project was the acquisition of real-time data collected with Canadian National Team members sliding in all disciplines. An application to use athletes for data gathering was approved by SAIT’s Research Ethics Board.

Data acquisition (DAQ) hardware originally designed for a Bromley skeleton sled was used to acquire real-time dynamic data. The DAQ system was integrated into the saddle of the sled – its design ensured the system did not hinder the athlete. A second DAQ system developed by CAPE was calibrated to the Bromley system and integrated into luge and bob sleds, again ensuring that it did not interfere with the athlete. Data was collected on 28 runs over a five-day period at the end of March.

The scan of the ice completed by Epic Scan was used to create the Track model for the trajectory simulation software. The trajectory model was created by taking cuts of the ice scan surface every 0.5 m along the length of the Track, which produced a total of 3,034 individual ice section curves. Using a maximum spacing of 60 mm, 101 points were added, evenly distributed over every cross-section curve, resulting in a total of 306,434 points being applied to the cross sections. The geometric surface was then debugged for anomalies, such as discontinuities from the scanned data and uneven surfaces.

The trajectory software used free body particle (FBP) models to create a sled dynamic model (SDM) of the various sleds to study the trajectory envelope. The variables incorporated into the SDM’s are classified into two categories and include:

1. Physical data parameters
   a) ice friction coefficient
   b) aerodynamic drag coefficient
   c) sled weight
   d) section entry speed & angle

2. Track surface data points.

The SDM model was validated against the dynamic data gathered at the beginning of the study for all sliding disciplines. Over 270 trajectory simulations took into account:
1) Starting location  
2) Individual curves/sections  
3) Trajectory angles  
4) Velocity  

A re-creation of the February 12, 2010, fatal incident was carried out using video data provided by WSC.

In the summer of 2010, the International Olympic Committee (IOC) commissioned a study of the design model. IBG produced a report describing the model used to design the Track (Centrifugal Force, Speed and Travel Time Calculations for Luge and Bobsleigh Runs, IBG, Liepzeg, Germany, August 2010). A review of the IBG model by Dr. C. Glocker concluded the model was accurate in predicting the dynamic response of a 4-man bobsleigh travelling down a track. It studied the accuracy of the model compared to actual data from three sliding tracks: Cesana, Italy; Park City, USA; and Whistler, Canada. (Appraisal of the Track Speed Calculation Method by Ingenieurburo Gurgel (IBG), Glocker, C., Centre of Mechanics, Institute of Mechanical Systems, Swiss Federal Institute of Technology, Zurich, September 2010).

The scope of this study did not include an analysis of these reports, though the value of the sled parameters found in these reports were taken into account in determining the values used in the trajectory model in this study.

The Safety Audit was limited to the Track and facilities during winter on-track operations, and reviewed existing policies and procedures included in the WSC’s current safety management system. The safety and protective measures in place at the time of this study were evaluated to identify any gaps or opportunities for improvement.

During the review additional hazards were identified, but analysis was confined to items directly related to sliding Track operations.

An assessment of the current state of the safety program at the WSC Track was carried out using a Certificate of Recognition (COR™) Benchmark Audit. The COR™ program is an occupational health and safety accreditation program that verifies a fully implemented safety & health program which meets national standards.

The methodology included:

- Reviewing documented policy and management practices as related to Track activity.
- Identifying existing protective measures for location and application.
- Creating an incident plot of the Track to determine the frequency and severity of incidents related to training or competition to date.
- Working with the trauma and trajectory lead investigators to correlate existing measures with predicted incidents.
- Working with the trauma and trajectory lead investigators to identify gaps and opportunities for additional protective measures.

The reviewed data included policies and procedures developed for workers, volunteers and visitors, as well as copies of completed documents to verify processes were
followed. Observations of the facility were conducted in the spring of 2011 while the Track was still in use and included: athletes sliding; worker activity in clearing and preparing the Track; Track structure and design; operational activities; and, hazard control methods.

A second visit was made in June to observe the Track without ice, and to take pictures of the Track and safety barriers in place while the ice was out. Track barriers were measured and compared with documentation. Observations of the emergency measures and off-season worker activities were also made at this time.

The Safety Audit included a review of over 300 photographs taken by the team, as well as the homologation documents and more than 44,000 sliding records, 700 incident records and 400 drawings. The measurements were used to compare installed Track safety systems with the design specifications to determine if the safety barriers and other systems conformed to design specifications. More than 2,500 documents related to the safety management system – including procedures, policies and Emergency Response Plans – were also examined.

2.1.2 Assumptions and Limitations

Errors can be introduced into the alignment of the “as-built,” “as-designed” and ice profile data including:

- Differences in the extraction of targets by the scanning system.
- Differences between the surveyed targets and the scanned target locations.
- Differences in the alignment between the original site survey and the current site survey.
- Survey network errors over the larger footprint of WSC.
- Potential changes over time due to freezing, thawing, settling, etc.
- Accumulative error from the environment, survey tolerances, scanning tolerances, surfacing tolerances.

Redundancy was created in an effort to minimize the potential errors throughout the process and the steps taken to create redundancy were:

- Utilizing cloud-to-cloud alignment to assemble and align the individual scans.
- Implementing a thorough quality review of the scan alignment to verify all visible errors are corrected.
- Using common targets between scans from different scanners and different scan positions.
- Fitting cloud constraints and common targets to survey file as a redundant check of alignment.

In comparing the ice surface to the concrete surface some reports show the ice under the concrete in certain locations, which is obviously incorrect. An evaluation of these specific locations examined the errors between objects common to both the ice and concrete scans, such as structural steel over the track. In this examination, a typical error of 3 to 10 millimeters was found. These errors are also consistent with the errors
seen in aligning each data set (ice and concrete) with the survey file. This has been identified as a limitation of the scanning process.

The “as-built” drawings for the Track construction prepared by Stantec Architecture Ltd. are not available. As the Whistler Sliding Centre files for the project contain a number of drawings that were issued at various review stages, and several of the drawings were modified by addendum during the tender period for the project, we needed to assemble the information that was used by the contractor for construction of the Track.

The comparisons between the “as-designed” and “as-constructed” concrete surfaces in 3 Dimension and cross-section in the main appendix are influenced by construction tolerances, the accuracy of the surveys, concrete shrinkage, and temperature movements.

Only cross-sections provided to the contractor for construction have been used for comparison reporting.

The trajectory study test matrix was derived from the data generated by the trauma study team which did not highlight corner 16 as a priority in terms of incidents for the 4 and 2 man bobsleds. Therefore, simulations were not run for these sleds at this corner.

During the testing in March where the dynamic data was gathered, 4 man sleds were only allowed to be launched from the Damen (Ladies Luge) Start. The data to validate the 4 man bobsleds reflects the lower speeds and lower G Forces that would occur at a lower start.

Standard safety audits include data collection through interviews to verify and validate the accuracy of the documents and procedures reviewed. Current and former employees were interviewed to determine the COR™ benchmark score.

2.1.3 Findings and Observations

The organization and order of the design and construction information, such as drawings etc., was very difficult to follow. There were over 2,500 items made available to the study team.

Drawings and specifications for the Track and related facilities were prepared and issued for construction by Stantec Architecture Ltd. This documentation was revised by several addenda during the tender period.

Given the tolerances that can be achieved for this type of construction on the side of a mountain, in this team’s opinion, the as-constructed geometry of the WSC Track generally meets expectations.

The FIBT and FIL provided little detail on the homologation procedure in their regulations. An analysis of the Federation Internationale do Motocrylisme (FIM) Standards for Road Racing Circuits shows an entire section is dedicated to the inspection and homologation procedure for tracks (sec. 029.11, p36 ff). (http://www.fim-live.com/fileadmin/alfresco/111691_NCCR_ENG.pdf)

There may be areas of the Track that require modifications to ensure that sleds travel on a smooth surface in a safe trajectory. If the Track must be ground to make the
surface smoother, great care will need to be taken to avoid damaging the reinforcing steel and refrigeration pipes. If the thickness of the walls or ground slab of the Track must be increased in localized areas, the existing shotcrete must be carefully chipped away and new concrete added, as in the repair of deteriorated bridge decks.

The Safety Certificate of Recognition tool used to complete the COR™ audit resulted in a combined score of 68% for the completed audit. A score of 80% must be achieved in order to be awarded a Safety Certificate of Recognition.

2.1.3.1 Maximum Safe Velocity

The movement of a body traveling down a track is described by the location of the body in the track, its speed or velocity and the acceleration of the body as it travels down the track or around corners. The acceleration can be in a straight line as gravity pulls the body down the track or non-linear as the velocity of the object pulls it around a curve. As the body accelerates, the velocity increases and the forces the body experiences also increase. The force pulling the object to the centre of a curve is the centripetal force and the inertial force that feels like the body is being pushed into the curve is the centrifugal force.

As a body accelerates and decelerates the forces acting on the body are typically described as multiples of the force of gravity or “g-forces”. When a slider, whether they are riding on a luge, skeleton or in a bobsleigh, or a race car driver, or even a roller coaster rider travels down a track and around corners the magnitude of the forces the body could experience typically exceeds the force of gravity. These forces can be linear front to back, side to side or head to toe, or they can be rotational. A human body can tolerate significant levels of g-forces, though each person will have a different tolerance threshold which depends on many variables such as the location where the force is experienced and the period the load is applied. When a load is applied, energy is transferred to the body and an injury can result if the energy transferred exceeds the body’s capacity to absorb it.

In April 2001 the CART racing organization cancelled its debut race at the Texas Motor Speedway because a majority of drivers experienced disabling sensations (Voshell, M., High Acceleration and the Human Body, November 28, 2004 http://csel.eng.ohio-state.edu/voshell/gforce.pdf). It was determined that the velocities and subsequent g-forces that the drivers were exposed to were the primary contributors to the sensations.

In the Coroner’s report it was noted that with new calculations based on revised parameters for sled properties for trajectory modeling, ie. co-efficient of friction and drag co-efficient, the track designer felt that the existing track profiles could be used to a maximum speed of 161 kilometers per hour without the danger of a turn over.

There was nothing in the documentation provided to the Study team that showed how this maximum speed was determined and what assumptions were used that defined a turnover. There was also nothing to indicate this was a maximum safe velocity.

There is also no definition of a maximum safe velocity in either FIBT or FIL regulations. However, as stated earlier, in Appendix 4 of the FIBT regulations and Supplement 1 of the FIL regulations, maximum g-forces and maximum velocities are specified.
In Section 16.13 of the FIBT bob and skeleton regulations it states:

_The maximum time for which centrifugal force of ‘4G’ may occur is 3 seconds._

_The maximum centrifugal force allowed is ‘5G’; this centrifugal force must not last for more than 2 seconds._

_No centrifugal force in excess of ‘5G’ is allowed_

Is it important to note the use of the word “centrifugal.” The regulations are silent on the maximum load or impact force that a sled or athlete can be exposed to.

Supplement 1, Section 3.1.1 in the FIL regulations states:

_The gradient of the track should be designed in a way that a speed of approx. 80 km/h is reached approx. 250 m after the start. The average gradient of a track from the men’s start to the low point should not exceed 10%. The average gradient of the second half of the track should not exceed 8%. The calculated maximum speed must not exceed 135 km/h. The technically difficult track elements (labyrinth, left-left or right-right combinations) should be incorporated in the first two thirds of the track._

It was found that, in the FIL regulations, there was no mention of the maximum loads a sled or athlete was allowed to experience.

Without the definition of a maximum safe velocity, the Study team believes there is a significant gap in guiding the design of a track, or determining what the maximum safe velocity is for any track that is currently being used.

In general, the trajectory study has found that the majority of G-forces measured, and durations for maximum G-forces, are within the guidelines of the IF regulations. This was confirmed by the trajectory simulation model and the dynamic measurements used to validate the model. However, for all sliding disciplines, there are a number of occurrences where the forces ‘predicted’ are producing values above 5G’s.

The model also replicates a situation of no steering input from an athlete and under these conditions it was found that all sleds travelling through corner 16 will hit the inside wall on exit. The contact could be a brush with the side or a heavy impact. Bobsleds and skeleton sleds tend to hit the wall side-on with a glancing blow, whether they are in control or in a skid on exit. A luge sled has greater control with the curvature of its runners and may hit the wall at a greater angle or may climb up a wall.

Corners 12 and 13 are a challenging combination, where it is extremely difficult to avoid an impact on exit. For example, a skeleton sled entering corner 12 early may have a less severe impact exiting corner 12 and entering corner 13. It was found there is a geometrical “hump” designed into the ice surface between the corners, which can push a sled towards a later exit from corner 12 and later entry in corner 13. This can have the effect of tipping a sled onto its side. A more middle line through corner 12 produces a greater impact out of corner 12 which avoids the hump, resulting in a better line through corner 13. There have been a significant number of incidents with bobsleds through this section.
2.1.3.2 Rollover Barriers

In most sports, barriers are used to contain an athlete or their equipment if an unintended incident occurs. An element of this study was to assess the adequacy of the barriers in place around the Track and identify areas for adding, modifying or extending barriers based on the findings of the various specific studies. However, a key finding was the absence of a standard for rollover barriers in the Federations’ regulations.

A comparison of the FIBT and FIL regulations with the regulations of the Federation Internationale de Ski (FIS), in terms of barriers and testing, shows that the FIS is significantly more advanced than the FIBT and FIL in defining barrier standards. The FIS takes a systems approach to race course safety and produces an annual FIS safety material list of suppliers (http://www.fis-ski.com/data/document/simalist_16-07-12.pdf). In one case a vendor published the results of the field tests for their safety barriers. (http://www.barry.ca/publication/field-testing-of-barry-b-net-systems-30428-2003-04-30.pdf)

A similar comparison with the Federation Internationale de Motorcyclisme (FIM) found that significant detailed documentation on the design and testing of crash barriers (pages 8, 9, 41-43, http://www.fim-live.com/fileadmin/alfresco/111691_NCCR_ENG.pdf) was presented.

The International Bobsleigh and Tobogganing Federation (FIBT) and the International Luge Federation (FIL), along with the operators, take on the responsibility for improving the safety of tracks by adding safety barriers in response to conditions that occur during the use of the sliding facilities.

The requirements for safety barriers evolve and change over time in response to such things as variable sliding conditions, new sled designs and incidents that have occurred on tracks. This latter point became more acute given the circumstances and outcome of the crash of a four man bobsleigh at Altenberg in January 2012. (http://wap.sportsnet.ca/magazine/2012/05/04/sportsnet_magazine_bobsled_accident_welling/)

The results of the Bromely trajectory study indicate that properly operated sleds at Whistler will stay on the ice-covered concrete surface of the track. However, there is evidence that sleds have travelled across the safety barriers installed along the track.

Without proper standards, the Study Team limited its recommendations for rollover barriers to identifying locations along track where barriers should be considered.

2.1.4 Recommendations

For improved “Track Design and Modeling” it is recommended that:

1. The Whistler Sliding Centre investigate the use of Global Positioning Systems (GPS) and other technologies to continuously refine the trajectory model that was developed as part of this study.
2. The Whistler Sliding Centre should retain the original designer of the Track or an organization with equal knowledge and competence to engineer and document any modifications to the Track.

3. The original designer of the Track should take responsibility for reviewing the design and construction findings of this report and engineer improvements to address any deficiencies identified.

4. The FIBT and FIL should develop a more detailed procedure for track homologation, similar to the FIM procedure.

5. If the Track must be ground to make the surface smoother, we recommend that no more than 5 mm of shotcrete be removed. If more than this amount is removed, the concrete cover over the reinforcing steel and refrigeration pipes will be too thin and the long-term durability of the Track will be compromised.

6. It is recommended that a more stable line be created from the exit of corner 12 into the entry of corner 13 and that this can be achieved by:
   a. the ice profile in C12 be shaped, where possible to create a longer exit radius and thus more progressive and less extreme exit trajectory out of Curve 12 into Curve 13.
   b. the significance of the impact on sled trajectory of the designed bump at the exit from C12 to the entry of C13 should be reduced.

7. It is recommended that the profiles between C15 to C16 be fine tuned to enable more natural variability in the line of choice towards C16 so that they allow athletes to choose their entry line into C16 with the potential of reducing the centripetal accelerations (g forces) experienced through the initial part of C16.

8. Modelling of potential crash events be undertaken to examine “what-if” scenarios and provide insight into the potential for injury and the effect of potential safety measures.

9. The Whistler Sliding Centre continually evaluate the Track configuration and crash outcomes as they occur.

10. The FIBT and FIL provide more detailed track design criteria – beyond top speeds and g-force exposure – to guide track designers.

11. In order to provide transparency in the design of sliding tracks, the FIBT and FIL should validate the output from the trajectory simulation models: publish and annually review the range of values for the co-efficient of friction (CoF) and drag co-efficient used in the design and analysis of tracks; and annually review the output of the simulations in terms of “g-forces” and velocities using the revised, published CoF and drag values.
12. The FIBT and FIL should provide more specific guidance to track designers by clearly defining the basis of a maximum safe velocity.

13. The FIBT and FIL provide more detailed specifications for protective safety measures such as walls, barriers and crash equipment similar to that taken when specifying safety barriers for highways in Canada [CSA (2006)] and FIM (Standards for Road Racing Circuits 2012, p36 ff). The standard safety barrier designs should be developed from consideration of such things as:
   - Incidents that have occurred.
   - Marks from sleds travelling across the existing safety barriers on tracks.
   - Crash testing.
   - Trajectory modeling.
   - Structural analysis and design.

14. The operators of the Whistler track, under the direction of the Federations, should install the standard safety barrier system at all corners and locations along the length of the track where there is no control on the free flowing path of a sled.

2.2 Athlete Safety

As noted by the Coroner, the Track was not considered dangerous by the International Federations. The objective of Trauma Study was to perform retrospective biomechanical reconstructions and detailed injury analysis of previously-reported injurious or potentially injurious events. The primary goal of this analysis was to identify Track sections and/or trends in injury location or severity that could lead to changes in the Track or training procedures to improve athlete safety.

2.2.1 Methodology

The foundation the incident analysis was the construction of three databases. The run-sheet database was comprised of information gathered from the 1,600 run sheets supplied to the study team. The data recorded from the run sheets included:
   - run date
   - session reference
   - sliding sport
   - discipline
   - name (and partners name(s))
   - gender
   - athlete/public
   - start location
   - speed
   - start time
   - finish time
- crash (Y/N)
- crash details/location
- number of runs for an individual in a specific session
- comments and page number

The second database was developed from the control tower logs, accident reports, injury registration documents, medical encounter forms, patient care forms, sliding logs and other related documentation. The athletes' confidentiality was protected by assigning a study ID. The information compiled in this database included:

- discipline
- date
- session reference
- name(s)
- track location
- injured (Y/N)
- description of injury
- individual’s information (age, gender, weight and height)
- closed circuit television time

Each event was entered a single time regardless of the number of athletes injured (for disciplines with multiple riders). The database included only crashes and injuries that occurred on the Track during a training or competition run. Injuries sustained while walking the Track, sliding down the outrun, or in the start/finish areas were not included in this analysis.

To ensure consistency in identifying incident location, a specific procedure was developed. Incidents were recorded as occurring in the entrance of the turn, middle of the turn, or exit of the turn. If an incident occurred between two turns, the entrance to the succeeding turn was used. The Control Tower Log was viewed as the most accurate record if there were conflicts in reported incident sites, as control tower personnel can view and playback incidents on closed circuit television. In the absence of a Control Tower Log or if multiple locations were reported, the earliest Track location was used.

The third database was developed from medical records and captured data on injury severity.

An application to the University of British Columbia Clinical Research Ethics Board was approved in order to obtain medical records with the intent to carry out injury reconstructions to determine the breadth and severity of injuries sustained.

In order to create the Medical Record and AIS Database, a protocol was developed to ensure consistency in recording each event. Injuries were coded according to the Abbreviated Injury Scale (AIS) and the Injury Severity Score (ISS). This system is based on a consensus-derived global injury severity scoring system developed and administered by the Association for the Advancement of Automotive Medicine (AAAM). The AIS classifies each injury by body region according to its relative importance on a 6-point ordinal scale (1=minor, 2=moderate, 3=serious, up to 6=maximal).
A limited number of videos were available, but whenever possible, they were used as an analysis tool, along with speed trap data. With this information, velocity vectors of sliders before and after an impact to a wall or roof could be calculated and used to determine the magnitude of the impact.

Occurrences of ejection (slider leaves the track at speed), near ejection (slider obtains adequate height to pass outside the track but remains in the track), and partial ejection (a portion of the slider’s body, i.e. arm or leg, is ejected from the track but the majority of the slider’s body remains in the track) were also examined. These events were analyzed for the interaction that led to the ejection, near ejection or partial ejection and any resulting injuries. Recommendations pertaining to the evaluation of ejection during routine Track operation were also made.

2.2.2 Assumptions

The following assumptions were made about the data and reporting to ensure accuracy and consistency throughout the data sets:

- If a run listed the sport as bobsled but did not distinguish between the 2-man and 4-man disciplines, a 2-man run was assumed.
- If a run had more than one name listed, the first name was assumed to be the pilot of the sled.
- If a session contained a reference to a provincial sport organization, that session was assumed to include only runs by athletes. Otherwise, the session was assumed to be comprised of “public” runs.
- If two start locations were listed, the higher (closer to the top) start position was entered, and the second location was listed in the comments section.
- In many cases the slider’s sport and/or discipline was not recorded, in which case a sliding history was used to decide upon a common sport/discipline for that particular slider.
- If a slider's start location was not listed, that slider’s run times were used to determine a start location. If that slider had made no other runs, trends in the other sliding times from that session were compared.
- If there was no time recorded, the field was left blank. It was assumed the athlete did not crash.
- Any times listed as “NT” were assumed to be a timing error and not the result of a slider crash.
- It was assumed the data provided was accurate and that the individuals reporting did so to the best of their knowledge and expertise.
- When there were discrepancies in the record keeping as to the location of an incident it was always assumed that the highest curve recorded was the true location. This was only overruled when reasonable cause was given.
- It was assumed the sled of each athlete was in full working order and did not contribute to the incident under evaluation.
• It was assumed that only factors on and within the Track led to incidents (i.e. spectators, weather, wildlife, etc. were not factors).
• It was assumed the video data was accurately labeled regarding the date and athlete involved.
• It was assumed the data provided was accurate.
• It was assumed that the difference between the pre-impact velocity and the post-impact velocity, when the slider interacted with an ice wall or the roof, was minimal.
• It was assumed the body centerline of the athlete reflected the direction of the slider.

2.2.3 Results and Findings

More than 43,300 runs at the Whistler Sliding Centre were documented with “run sheets,” and that information was entered into the two databases described previously. There were 709 incidents on record – 1.64% of the runs taken resulted in an incident. A detailed analysis of the two databases resulted in the following findings:

The highest rate of track incidents considering all disciplines was 3.0 % and occurred when sliders started from the Lady Start 2, often termed Lower Ladies or Damen Start. Next was Lady Start 1 and Men’s Luge Start which resulted in 2.8 and 2.7 %, respectively.

When comparing the incident rate from Men’s Luge, Lady Start 1, and Lady Start 2 pre- and post-Feb. 12, 2010 there was a decrease in the rate of incidents from 3.0 % to 1.0 %. Although this drop was statistically significant, an analysis which was limited to Lady Start 1 and Lady Start 2 showed a more dramatic drop from 3.3 % to 1.0 % which indicates that other factors, such as ice conditions, track profile, experience or weather, other than start position, likely played a significant role in the decreased incident rate.

Of the total runs on the Track, athletes took over 94%, and the public less than 6%. Athletes had a 1.7% incident rate, while public sliders had an incident rate of 0.4%.

The vast majority of sliders (more than 75% of all sliders) slid on the track between 1 and 9 times. Less than 5% of the sliders have slid on the track more than 70 times with less than 20 sliders ever using the track more than 300 times.

The number of crashes that resulted in an athlete being referred to the clinic showed an interplay between risks associated with increasing exposure and the expected benefit of increasing experience. In general, the crash rate first increased with exposure and then decreased likely reflecting a benefit of experience.

When the incident data was analysed in terms of gender and discipline, it was found that the highest incident rate, (the number of crashes over the total number of runs for a particular gender-discipline combination), occurred with the 2-man bobsled. The male incident rate was 3.4% and the female incident rate was 2.9%. The male vs. female results for singles luge and skeleton were less than 1% for all cases.

In order to study the relationship between incidents and specific areas of the Track, a frequency plot of the number of incidents by location was created. In general, it was
found that the majority of incidents occurred on the lower portion of the Track, with 79% of the total incidents occurring in corner 13 or lower.

A total of 94 incidents – 0.2% of total runs – took place with sleds moving into, through, or out of corners 1 to 12. Almost half those incidents can be attributed to 2-man bobsled, 36.2% to singles luge, and 8.5% to 4-man bobsled. Skeleton and doubles luge accounted for only 9.6% of the total incidents in this area of the track.

A total of 170 incidents occurred moving into, through, or out of corner 13. Just over half were 2-man bobsled, 19.4% were singles luge, and 16.5% were 4-man bobsled. Skeleton and doubles luge accounted for only 10.6% of the total incidents that occurred in the area of corner 13.

In corner 14, a total of 44 incidents were documented with just over half attributed to singles luge, 27.3% to 2-man bobsled and 15.9% to doubles luge. Skeleton and 4-man bobsled accounted for 4.5% of the total number of crashes/injuries in this location.

Corner 15 recorded 60 incidents, with singles luge accounting for 55%, doubles luge 25%, and 2-man bobsled 13.3%. Skeleton and 4-man bobsled accounted for 6.7% of the total number of incidents in corner 15.

There were 43 documented incidents in corner 16, with singles luge accounting for 55%, 2-man bobsled 23.3%, and skeleton 11.6%. Doubles luge and 4-man bobsled accounted for 9.3% of the total incidents in corner 16.

In the outrun after corner 16, there were 28 recorded incidents. This included non-crashes that required medical attention due to the side-to-side “ping pong” effect. In this region of the Track, 68% of the incidents were linked to singles luge and 11% to skeleton. The remaining three disciplines accounted for the remainder of the incidents in the outrun.

The analysis showed less than 0.5% of the total runs taken resulted in injury. A total of 0.2% of sliders received medical care at the clinic after an incident.

Of the 62 incidents in which sliders were taken or referred to the clinic, 46 (74.2%) medical files were available for analysis.

Of the medically documented incidents, 52.2% were found to be classified as MAIS 1 injuries (minor), 43.5% to be MAIS 2 (moderate) and the remaining 4.3% to be unclassified because of a lack of detailed information or diagnoses in the medical records.

It was found that 59.1% of the MAIS 2 scores occurred at corner 13 or lower.

The risk of obtaining an abbreviated injury scale (AIS) injury of 2 (moderate injury) or greater on the Whistler Sliding Centre track was found to be less than 0.1%.

Of the clinically documented injuries, the most common were abrasions/ lacerations/ contusions, representing 52%.

The analysis of the possibility of a slider being ejected or partially ejected from the track identified two incidents. The occurrence of the partial ejection demonstrated the potential for a full ejection.
In a review of the International Federations’ regulations relating to equipment and medical response, the regulations were limited to procedures and general statements on equipment safety. Section 9 of FIBT regulations cover services at the track and refer to an “Injury Registration Document,” but there is no mention of the host track documentation or any documentation follow up. In Section 6 of the FIL regulations, the requirements and procedures for Medical Services are described. While regulations state the race doctor must certify in writing whether an athlete is allowed to compete after an injury, there is no mention of the host track documentation or any documentation follow up.

Both the FIBT (section 10.12) and FIL (section 2.3) reference helmets and the type of helmets that are allowed.

A detailed description of sled materials and assembly, for both bobsleigh and skeleton, is provided in section 14 of the FIBT regulations, but it is void of any reference to the definition of crash worthiness. Section 14.2 states:

“The bob manufacturers are responsible for the construction of sleds that can withstand, without damage, the stress of repeated runs on the bob tracks.”

A similar statement appears in section 14.1 of the skeleton regulation:

“Sled manufacturers are responsible for ensuring that the sled is constructed in such a way that it can withstand the strain of repeated runs on bob tracks without damage.”

Section 5.1 of the FIL regulations describes the dimensions and assembly of a luge sled but there is no mention of the crash worthiness.

In the documentation provided to the study team and in the Federation regulations there was no indication that there was a process in place to follow up on an incident(s) and take corrective action where appropriate. The corrective action could include improvements to the Track safety system, improved athlete preparation or equipment design.

A review of a FIS documentation and Formula 1 technical regulations shows a much more comprehensive, detailed approach to incident follow up and equipment design.

In Articles 16, 17 and 18 of the Formula 1 regulations (2012 F1 Technical Regulations, 9 March, 2012 and 2014 F1 Technical Regulations, 14 July 2011) the crash worthiness tests are highly detailed and descriptive of the objective of the test in terms of impact loading and duration of the impact.

The FIS has implemented an Injury Surveillance System and created an information document describing how to use the system (http://www.fis-ski.com/uk/medical/fis-injury-surveillance-.html) to document injuries and use the information to improve the safety of the sport. The FIS has enlisted the Oslo Sports Trauma Research Centre to manage the data.

An example of how the information was used is presented in a specific study conducted by the University of Salzburg, “A Quantitative Approach to Determine Key Injury Risk Factors in Alpine Skiing”, (http://www.fis-ski.com/data/document/fis-iss-final-report-
The results of the study led to changes in equipment design and the FIS published those changes on their website, ([http://www.fis-ski.com/de/disciplines/skialpin/nordische-kombination121.html?actu_id_1806=5261&actu_page_1806](http://www.fis-ski.com/de/disciplines/skialpin/nordische-kombination121.html?actu_id_1806=5261&actu_page_1806)).

### 2.2.4 Limitations and Implications of the Analysis

The trauma study, similar to the construction study, draws attention to the importance of good record keeping and document control. The Whistler Sliding Centre has an extensive record of crashes, which was invaluable to this study. In the process of creating the database, many limitations and inconsistencies with the entries became evident.

The 1.7% total incident rate is based on 710 crashes, reported on run sheets, in more than 43,000 runs. However, the Control Tower Logs and Accident Reports document 446 incidents, a difference of 263 incidents. While the overall findings won’t be affected, this discrepancy contributes to possible errors in the accuracy of the analysis.

The kinematic analysis was dependent on visual data or information taken from videos. With only 11 crash videos available for analysis, this aspect of the study was significantly limited. The analysis was further limited by video quality and poor camera angles. These limitations affected the team’s ability to recommend changes to the location and size of barriers and other safety devices.

The trajectory study identifies the potential for incidents relative to a range of inputs. Without being able to identify specific impact points, the dynamics of the impact, the frequency at a specific location, and pilot-correction or other contributions to an impact from videos, the recommendations in this study are restricted to identifying areas for more detailed analysis or design improvements.

The findings reported in the previous section are unique to the Whistler Sliding Centre Track. While requested by the study team, WSC staff were unable to obtain similar data from other tracks homologated by the FIBT and FIL. There is no way of knowing whether, if the data was available, it would be in a format that would permit a comparative analysis between tracks. Therefore, this study is limited to the data recorded for the WSC Track. The implication of this limitation is an inability to determine whether the incident rates of the WSC Track are higher or lower than any other track.
2.2.5 Recommendations

For improved “Athlete Safety” it is recommended that:

1. The Whistler Sliding Centre investigate sensors and other technologies as part of an Injury Surveillance System to carry out ongoing measurements of athlete exposure to forces and vibrations acting on the body.

2. The Whistler Sliding Centre implement the use of “visual indicators” on the track to eliminate the “white tube” effect athletes experience as they travel down a track.

3. The FIBT and FIL define a safety procedure, including measures for non-compliance, based on recording incidents, analyzing incident records and retaining incident records to assess the safety continuous improvement plan for all tracks.

4. The FIBT and FIL provide guidance on the use of “visual indicators” on the track to eliminate the “white tube” effect athletes experience as they travel down a track.

5. The FIBT and FIL conduct equipment crash worthiness and protection tests on all equipment, and consider equipment design criteria that would dissipate energy.

6. The FIBT and FIL define and implement a helmet embargo procedure for all athletes involved in incidents where the efficacy of helmet may be compromised.

7. The FIBT and FIL develop formal criteria defining an athlete’s competence to compete on a specific track.

8. The FIBT and FIL should create an Incident Surveillance System, based on the Federation Internationale de Ski (FIS) and incorporate knowledge gained from this report, as well as other studies of track accidents, when setting specifications for sleds and protective safety measures such as walls, barriers and crash equipment.
2.3  Track Operations

The WSC Track was built for sliding, specifically for luge, skeleton and bob sleds. At the time of this study, the Track is primarily used for athletic competitions, from club-sanctioned events and World Cup races to the 2010 Winter Olympic Games. The Track is also used for tourist sliding, where individuals can ride in or on a sled.

The Track must be approved for use by the appropriate bodies, such as the FIL, FIBT and the Government of British Columbia, before races can be held or tourists can experience sliding down the track.

It was not within the scope of this study to review the approval processes. In keeping with the Coroner’s recommendation, this study examined the Track in terms of its safe use and operation to protect athletes, workers and spectators.

Similar to the construction study presented in the first section, studying the use and operation of the Track crossed a number of the individual components. The safety audit and trauma study described in the previous sections were the primary sources of information used to assess and identify opportunities for improvement in the use and operation of the track. The Certificate of Recognition (COR™) Benchmark Audit, was used to assess the safety program and its implementation in day to day operations of the Track.

2.3.1  Findings

The Safety Certificate of Recognition (COR™) tool used to complete the audit resulted in a combined score of 68% for the completed audit. A score of 80% must be achieved in order to receive a Safety Certificate of Recognition.

During the first site visit in the winter, Track workers were interviewed. While they maintained the Track surface and blinds, it was observed they were in position to control access to the Track. They also communicated with the control tower to inform tower staff if the Track was clear prior to a run.

Workers were diligent in the preparation and cleaning of the ice surface. Maintenance of the ice filet radius at the vertical walls of the track is a key safety feature to prevent sleds from being launched from the track. The workers do not have a tool or template to determine if the filet meets recommended 10 cm radius.

The closed circuit television system (CCTV) is another method for track control. There were gaps observed in the coverage of the CCTV but the placement of the cameras appeared to be consistent with drawing number A0-17.161-0123 (P6). (Appendix E.2)

Internal controls are defined as controls added to prevent participants from leaving the track during an incident, such as barrier walls.

There were two different wall designs. One design consists of a roll-over barrier of limited height on the inside of a curve, intended to prevent a sled that bounces off the outside wall from exiting the track. A second barrier is designed for the outside of a curve, and may or may not include a roof to prevent a sled from climbing out of the curve.
Roll-over barriers were observed to be of differing heights and lengths along the Track. Placement of the barriers appeared to be consistent with the homologation recommendations. However, there was no documentation on the placement of barriers on drawings. There were no specifications to guide the engineering and construction of barriers.

Only the crash barrier constructed after the fatality on February 12, 2010, was documented; however, there were no design notes or calculations.

A key element of the safe use and operation of the Track is communication. Communication among all parties—Olympic Committees, managers, volunteers, staff, athletes, coaches and the general public—must be clear and consistent. This minimizes misunderstandings and ensures the greatest protection of all stakeholders.

The documents reviewed for this audit included: training materials for visitors and volunteers; safety committee meeting minutes; the WSC health and safety manual; hazard identification records; and the procedure for clearing the Track after workers enter.

The available documentation demonstrates effective and consistent communication. The training programs, safety manuals and procedures are documented and appear to address all levels of workers and volunteers.

For visitors to the Track, there is information provided explaining what should be done in the event of a bear encounter. There is also clear signage with specific site rules and pictograms.

This study found documentation to address issues of safety non-compliance during the design and construction of the Track, but no evidence of an accountability program in place once the construction was completed. There were no documents available to show if a process is in place to manage non-compliance with the procedures established for clearing or maintaining the Track.

A hazard is generally defined as any situation, condition or thing that has the capacity to cause loss or injury to people, materials, equipment and the environment. The identification and control of hazards is the basis of all safety programs, and a continuous process involving all levels of workers and management. The Whistler Sliding Centre is open, operated and used year round; hazards can change daily and will vary from season to season.

The documents provided by the WSC included completed hazard assessments with a risk analysis. It was found that hazards ranged from overexertion to exposure, wildlife encounters and driving. There was no evidence of follow-up action taken on the hazards identified.

Engineered controls were observed, including guardrails to control access to the sliding surface, poles and hooks to raise and lower sun shades, and road access to critical points at the facility.

The documentation showed administrative controls including: training on the recognition of cold injuries; procedures for wildlife encounters; and, procedures for clearing the Track when workers are crossing or removing debris during operations. It was also
observed that workers wore personal protective equipment including high-visibility work clothes designed for cold weather.

From the document review and site observations, it can be concluded that hazards have been identified and controlled for the employees.

Anytime there is an incident, near miss or loss, existing hazard controls must be reassessed and new controls instituted as required. This process was demonstrated when the WSC modified the location and height of the containment walls on the Track after incidents indicated an improperly controlled hazard.

The documentation reviewed included emergency response plans for ammonia leaks, injuries and wildlife encounters during the Olympics, when the Track is set up for training and public use, and in the summer when Track activities are shut down but the general public is still at the site.

A specific hazard for summer visitors is bear encounters. If visitors see a bear, they are instructed to “Notify Guest Services immediately.” During the spring site visit, when the Track was not in service, bears were observed breaking into the outrun area of the Track and the finish building. When calls were made to the Whistler Sliding Centre while Guest Services was open, there was no answer. This finding indicates a breakdown in emergency response.

During the spring site visit, the team observed two occurrences of visitors not complying with posted rules and entering the Track. This is an indication of an ineffective communication system.

A review of the documents included the procedures for clearing the Track after an incident, lock-out procedures and machinery operation. The documentation appears to be adequate for clearing the Track, and this was confirmed with observations made while the Track was in operation.

Documents provided by the WSC include the safety orientation programs for volunteers, workers and coaches. Other training records include on-the-track clearing procedures and worker training sign-off. There was limited information indicating training had occurred, and none indicating competence or effectiveness of the training.

The review of the Occupational Health and Safety documents, including incident investigation and hazard reporting forms, revealed that many of the forms and procedures were VANOC forms and procedures. Since VANOC is no longer responsible for the Track it is unclear if the procedures and policies used by VANOC are endorsed by the WSC.

The investigation into the Kumaritashvili accident was conducted primarily by external bodies. The team could not find any indication that the WSC has staff trained in incident investigation.

A primary source of information to ensure the safe use and operation of the Track are incident reports. The data analyzed by the trauma team gave a general indication of where many of the incidents occurred, and some idea of where to look to review the existing controls. There was no documentation indicating investigations were completed
on the incidents. Investigation reports would provide more direction on what controls can be implemented to minimize the reoccurrence of these incidents.

A track is designed to keep the participants on the track during a run, and to prevent the outside world from entering the track.

Over 300 photographs were taken to determine if the protective measures were sufficient to protect users, operators and spectators from known hazards. In the analysis, any clues or markings indicating a safety feature had been impacted were examined to determine the adequacy of the feature.

The controls for entry into the Track – including starting stations, buildings, shelters, bridges and tunnels – showed little or no deviation from the planned construction. The location of rails and other external barriers also appeared to be consistent with drawings when they were indicated.

Examination of the barriers showed traces of paint transfer – marks that indicated an impact by a sled or other vehicle.

There were no observed markings on barriers above corner 10, with the first markings on the roof of corner 11. The exit to corner 11 showed markings as high as 6 inches from the top of the roll-over barrier.

Marks were found primarily on the crash barriers in corners 12 and 13, with significant marking found on the roll-over barrier at the exit to corner 13.

There were a significant number of markings on the barriers in the outrun.

The Coroner’s report recommended a number of measures be implemented. From the team’s observations, it can be concluded that all items identified in the report were acted on.

An examination of the IF regulations shows detailed descriptions (Section 10 FIBT Skeleton and Bobsleigh; Section 3 - FIL regulations) on how to run an event, but no direction on the operation of a track in terms of incident response and record keeping.

The number of official training runs before an event is defined, and the FIBT stipulates that an athlete must complete two runs without a crash before being allowed to compete.

Section 1.4 in the FIBT skeleton and bobsleigh regulations describes the requirements for test competitions and training on new tracks. The right to participate and admission into an IF is described in sections 3 and 4 of the FIBT skeleton and bobsleigh regulations and section 1.3 the FIL regulations. Neither provides details on competency and defer to the National Sporting Organization (NSO) to assess competency and put forward names to compete in IF-sanctioned events. There is no regulation in either IF’s documents describing the progression of an athlete through the different start locations to the top of a track, or the number of runs taken as a measure of competency.
2.3.2 Limitations and Implications of the Analysis

Without access to near miss or loss reports, the team assumed the control measures in place are adequate.

There were no “worker on track,” near miss or incident reports. In the absence of these documents, it was assumed the procedures in place were adequate.

There were no completed documents to prove workers were tested for competence. As there were no incidents reported to identify deficiencies, we can only assume training was adequate. The lack of completed forms proving competency testing indicates WSC is not diligent in proving the workers are capable of performing their job-tasks safely.

The review of the hazard assessment process, including controls, was limited to the available documentation and observations of activities in late March 2011.

During the audit, the team was unable to verify details about changes to the safety procedures or Track modifications and the reasons for such changes.

No calculations were done on the existing barriers to determine if they were adequate to keep sleds in the Track, as that is not in the scope of this report.

2.3.3 Recommendations

For improved “Track Operations” it is recommended that:

1. The Whistler Sliding Centre work with the track designer to develop a filet ice measurement and cutting tool, similar to the standard groove cutting tool used at the bobsleigh and skeleton start, to continuously monitor the optimum ice filet radius along the length of the track.

2. The Whistler Sliding Centre develop a protocol to ensure the collection of important parameters within incident reports.

3. The Whistler Sliding Centre implement automated record-keeping of all incidents.

4. There should be communication between the control tower and the first responders after each incident to eliminate inconsistencies and reporting errors.

5. The Whistler Sliding Centre should collect data from workers around the track associated with near misses and incorporate that information into incident analysis.

6. Reporting be encouraged from Track users and those involved in Track activities, such as coaches and visitors.

7. The Whistler Sliding Centre implement and monitor a track etiquette protocol for all coaches, athletes and visitors, such as media and spectators, to ensure site rules, governing the viewing and recording of athletes sliding, the use of flash photography and reaching into or entering the sliding track or field of play, are enforced.
8. The Whistler Sliding Centre test all workers for competence in the tasks they are required to perform as part of their job duties.

9. Ongoing reviews of the emergency response system should be conducted throughout all operating phases and seasons of the year, internally and involving community emergency services. All emergency response drills should be documented and the plans reviewed to ensure the absence of gaps and an active, effective communication system.

10. The Whistler Sliding Centre train all staff involved in incident investigation, and assign trained staff to investigate all near misses and incidents at the facility.

11. The FIBT and FIL define a continuous improvement plan for all tracks that includes plans for Management reviews, audits, regular track maintenance and takes into account a continuous analysis of incident data as part of an Incident Surveillance System.

For improved “Document Control and Analysis” it is recommended that:

1. Representatives of the Whistler Sliding Centre should assemble the most current IBG Consulting Engineering documentation for the Track, and archive the remaining reports and drawings.

2. Representatives of the Whistler Sliding Centre should assemble the most current Stantec Architecture Ltd. drawings and specifications for the Track and related facilities, and archive the remaining documentation.

3. The Whistler Sliding Centre implement a continuous improvement plan that includes documentation around regular management reviews, audits, a regular track maintenance plan and takes into account a continuous analysis of incident data as part of an Incident Surveillance System.

4. The Whistler Sliding Centre create and implement a “Track is Clear” checklist including checks of ensure movable barriers are locked in place.

5. The Whistler Sliding Centre develop a visitor waiver or sign-off sheet to document that all visitors are provided with information about site hazards and property rules.

6. All applicable VANOC forms and policies be reviewed and converted to WSL forms and policies.

7. The Whistler Sliding Centre’s Change Management procedures include provisions for regular Management reviews, audits and more detailed documentation, describing the changes and confirming implementation.
2.4 Conclusions

In summary, it can be concluded that:

The group responsible for the design of the Track was competent in track design.

There was evidence in the design, construction and operation of the track to minimize unreasonable risk based on the guidance in the Federations’ regulations and the inherent level of risk in the sport.

The WSC Track was generally constructed within the design tolerances in terms of the intended shape of the track.

The Track was constructed in the intended design location.

Construction documentation needs to be better organized with only the latest document versions used for reference purposes.

The potential exists for high velocities and G forces that may exceed those specified in International Federations’ regulations.

The incident rate is less than 2% for over 43,000 runs.

There is less than a 0.5% risk of an incident leading to an injury and 0.2% requiring medical attention.

The incident performance can not be compared to the incident rate of other tracks.

The FIBT and FIL regulations describe the right to participate and admission into the International Federation (IF). The FIBT regulations describe the requirements for test competitions and training on new tracks. However, neither Federation provides details on competency (in terms of both skill and experience), as it relates to safety, and defer to the National Sporting Organization (NSO) to assess competency and put forward names to compete in IF-sanctioned events.

There is no regulation in either IF’s documents describing the progression of an athlete through the different start locations to the top of a track, or the number of runs taken as a measure of competency to travel down a track safely.

The FIBT and FIL should develop formal criteria defining an athlete’s competence to compete safely on a specific track.

Safety practices at the Track follow generally accepted standards with some opportunities for improvement in documentation.

The International Federations’ regulations should provide more detailed guidance on track design, a maximum safe velocity, rollover barrier design standards, safety measures, incident analysis, equipment safety and driver/slider competence and equipment.
CHAPTER 3 - TRACK SURVEY AND SCAN

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# TABLE OF CONTENTS

CHAPTER 3 - TRACK SURVEY AND SCAN ................................................................. 67

3.1 Track Survey ................................................................................................. 71
   3.1.1 Introduction ........................................................................................... 71
   3.1.2 Survey Methodology ............................................................................. 71
   3.1.3 Survey Assumptions ............................................................................. 72
   3.1.4 Survey Deliverables ............................................................................. 72
   3.1.5 Survey Recommendations ................................................................... 72

3.2 Track Scan .................................................................................................... 72
   3.2.1 Scan Introduction ............................................................................... 72
   3.2.2 Scanning Equipment and Field Process ............................................. 73
   3.2.3 How Survey Information is Obtained and Provided ............................ 74
   3.2.4 Registration of Individual Scans to Each Other for “Ice” and “Concrete” Data Sets ................................................................. 74
   3.2.5 Registration of “Concrete Scan” to Survey .......................................... 75
   3.2.6 Registration of “Ice Scan” to Survey .................................................. 75
   3.2.7 Best Fit Alignment Method ................................................................. 75
   3.2.8 Comparing the Utilization of Survey Information vs. Best Fit .......... 75
   3.2.9 Assessment of Potential Errors ............................................................ 76
   3.2.10 Assumptions While Scanning and Generating Point Cloud ............. 77
   3.2.11 Description of Deliverables ............................................................... 78
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3.1 Track Survey

3.1.1 Introduction

Terra Pacific Land Surveying offers a wide range of land surveying services through the expertise of two BC Land Surveyors, Larry Achtemichuk and Mike Bernemann, with combined experience of more than 40 years. Terra Pacific performs layouts of roadworks, commercial and industrial buildings, and pipeline rights of way. Terra Pacific specializes in monitoring and quantity surveys of slope movement, bridge stability, and ice rink shifting. With specialized software applications, Terra Pacific staff can prepare a variety of plans and perform calculations required by a wide variety of clients from home builders to engineering firms. Some major construction projects worked on by Terra Pacific include the Pitt River Bridge, the ICBC Central City Mall & Office Tower, Electronic Arts in Burnaby, the Richmond Skating Oval, and IKEA Coquitlam. Terra Pacific continues to monitor the cold storage facilities of Versacold and Evercold, as well as the 8 Rinks and Planet Ice rink complexes.

In February 2011 Terra Pacific was contacted by the Project Manager to provide survey services for a safety audit on the Whistler Sliding Centre. The purpose of the survey was to determine the thickness of the ice along the track. To determine this, the surface of the ice currently on the track would be measured and then, when the ice was removed, the concrete surface would be measured. After conferring with Project Manager on possible methods to achieve this, it was determined that a 3D scan of both surfaces would be the most cost effective and precise method. To accomplish this Epic Scan was invited as part of the team to do the track scanning and ice scanning.

The control survey was conducted from March 14 – 18th, 2011, and the scans were completed March 20 – 28th, 2011 for the ice surface scan and May 23-31st, 2011 for the concrete surface scan.

3.1.2 Survey Methodology

An independent control survey was completed by Terra Pacific prior to Epic Scan beginning their 3D scanning. This control survey set field points that would be required to orient the 3D scans to Terra Pacific's local-coordinate system. The survey was completed using the Topcon GPT3003 LW total station and TDS Recon with Survey Pro software to complete a closed loop of the 1.5km track. Using multiple sets of angles and distances, results were averaged and a horizontal misclosure of 8mm was obtained. Distributing the misclosure over the course of the traverse would give a plus or minus 3mm error for the horizontal coordinates of the control traverse. Using a Leica Sprinter 250 precise level and closing all loops to 5mm or better gave a plus or minus 2mm vertical error for the control points. The Topcon Hyperlite GPS was then used with three systems simultaneously to obtain coordinates that checked to within 5mm or better of the conventional survey. This was the base control survey that Epic Scan used to calculate the position of the scanner.

In June 2011 Terra Pacific returned to Whistler to locate the Doug Bush Survey Services Ltd. (Bush) control points which were then surveyed using multiple angles and distances. A least squares adjustment routine was used to calculate a best-fit between
Bush’s data and Terra Pacific's control points. The residuals on those points were 2cm or better. The elevation transformation was based on Bush’s survey control point #967 which was held at 795.890m. The best fit produced results with differences in coordinates in the range of 3mm to 50mm.

3.1.3 Survey Assumptions

No information was available as to how the Bush survey was conducted nor how it was tied to the design of the track so no comment can be made as to why the fit between the two data sets was not better. There is a possibility that some of the Bush points moved over time or may have been disturbed. There is inherent error in all surveys including instrumentation error, atmospheric conditions, sighting errors and human error. Terra Pacific completed the control survey using high precision instruments and took as many steps as possible to achieve the highest possible precision.

3.1.4 Survey Deliverables

Appendix A.1 - Control Traverse Data for Whistler Olympic Luge Track
Appendix A.2 - Control Coordinate Comparison After Helmerts Transformation
Appendix A.3 - Coordinate List for Helmerts Transformation Results
Appendix A.4 - Filed Notes for Precise Leveling Circuit

3.1.5 Survey Recommendations

An alternative method to verify the "as-built" location of the Track to the original design may be to survey points on the track support structure, such as bolt patterns, and then calculate a best fit between the field ties to those bolt patterns and the design location of the same bolt patterns.

It is also recommended that future tracks have an after construction as-built survey. This will aid in any comparisons that may be required for that track at any time.

3.2 Track Scan

3.2.1 Scan Introduction

Founded in 1999, Epic Scan is an industry leader in the terrestrial LiDAR (Light Detection and Ranging) industry. Only a handful of companies worldwide have a sole focus to provide LiDAR products and services. This focus has facilitated the development of a diverse knowledge in Archaeology, Architecture, Civil, Processing Facilities, Forensic, Marine, Reverse Engineering and several other unique applications. Due to the extensive diversity and unique nature of our projects, they have been featured on National Geographic, Discovery Channel, History Channel and several European stations.

Diverse application of the technology has been the key to having the necessary knowledge required for the safety audit and trajectory study. The project has required
the development, combination and implementation of tools and techniques utilized in traditional survey, LiDAR, Film industries, Automotive and Aeronautical Reverse Engineering.

Lead by Carlos Velazquez CEO & Ryan Woodward, Epic has consistently proven to be an industry leader. With a background in Mechanical Engineering, Carlos has spent 13 years educating and developing the LiDAR profession worldwide. Speaking at the LiDAR industry leading SPAR and Leica User Conferences has provided a platform to educate other professionals on the capabilities and possibilities of the LiDAR technology. Holding the chair of standards committee for the USIBD (U.S. Institute of Building Documentation), he develops and implements industry standards.

Ryan Woodward has spent 12 years managing, developing and executing LiDAR teams worldwide. His practical hands-on experience implementing terrestrial LiDAR for the field, and office, on hundreds of scanning projects provides a comprehensive understanding of its best application. This industry-leading experience and dedication in the diverse range of LiDAR projects is the key to Epic Scan’s success.

### 3.2.2 Scanning Equipment and Field Process

Epic Scan deployed two different ground based (terrestrial) LiDAR systems for the laser scanning at WSC. The Leica HDS 6000 phase based scanner was utilized for the scan positions along the track itself. The Leica HDS C10 time of flight scanner was utilized off of track to take overall shots of each turn and the surrounding areas. Paddle targets 6" in diameter were utilized within certain scans to associate the scan data to the survey coordinate system. These targets can be recognized by both scanners as well as the survey instrument.

Lines were painted on the ice in order to capture the ice surface as a comparison to the areas directly adjacent to the lines. The paint was slightly absorbed by the ice surface. An evaluation of the paint on the ice surface did not see a visible differentiation between the painted ice and the adjacent frosted ice. Because of the varying ice thickness, frost surface, and sun exposure it is very difficult to quantify if or how much laser penetration the ice was allowing. In areas such as the bobsleigh start where the ice was piled up in the corners the results were good with the laser on those surfaces.

From our experience this would indicate that the results in the areas where the ice was thinner and the frost was more consistent it would be likely to see even better results than with the laser reflecting off of the un-frosted surface. Laser penetration was difficult to measure due to the highly varying surface

A summary of the field procedures is as follows:

- Meet with local site management to discuss questions, concerns, and requirements,
- Walk Job Site to familiarize all team members with scope of work,
- Identify site survey points to be utilized for scan targeting and create map of survey point locations,
- Layout scan positions for both scanners and create scan locations map,
- Place targeting through area to be scanned that day,
- Verify that targeting will be visible to both scanners, and survey instrument,
• Create/Update target map and verify naming conventions to be used by all instruments,
• Began scanning and acquisition of spherical photos,
• Identify all date, scan name, and targets existing in each scan inside of field book,
• Verify all targets have been acquired by survey team prior to removal for the day,
• Verify all data has been downloaded and backed up from both scanners,
• Verify all images have been downloaded and backed up from camera,
• Import scan data to verify scan coverage and location.

3.2.3 How Survey Information is Obtained and Provided

In the case of the Whistler Sliding Centre project, Terra Pacific Land Surveys provided the onsite survey of the local coordinate system to Epic Scan. This included surveying in the targets that Epic Scan placed throughout the track in order to align the scan data to both the “scan” coordinate system and the “as-designed” coordinate system. The “scan” coordinate system is an arbitrary system that was used prior to the introduction of the “as-designed” coordinate system.

During the initial “ice” scan registration only the “scan” coordinate system was used to align the scan data. During the “concrete” scan, registration information was provided to Epic Scan for both the “ice” and “concrete” scan targets in the “as-designed” coordinate system. Subsequently all parties working with the scan data and as-designed model information were not able to work within the “as-designed” coordinate system due to the large coordinate values. This is a well-known issue when working within the 3D manipulation and CAD software’s. The decision was made to continue working in the “scan” coordinate system, and to have the as-designed 3Dimensional information provided in this coordinate system.

3.2.4 Registration of Individual Scans to Each Other for “Ice” and “Concrete” Data Sets

Once the individual scan data is imported there are two primary steps in doing an initial alignment:

Target Extraction – “Targets” are specifically designed to be read by both the laser scanner and by conventional surveying instruments. This allows the scan data to be aligned back to the desired coordinate system. The individual scans were manually reviewed to identify these “targets”. The software that was utilized has a function where it will automatically extract the centre of these identified targets. These are extracted and verified one at a time.

Cloud to Cloud Registration – Not every scan will have targets or sufficient targets to completely align the data in all three dimensions. However, the setup of the scan positions provided sufficient overlap for cloud to cloud registration. A second scanner with a larger range was also utilized to tie all of the targets within a turn and also provide overlapping data for the shorter range localized scans. This again allowed the creation of cloud to cloud constraints between the lower density overall scan and the higher density individual on-Track scans. A cloud to cloud constraint allows the software to
look at the common geometry between scans to best fit two scans together. In a cloud to cloud constraint the software is using millions of points to align individual scans.

3.2.5 Registration of “Concrete Scan” to Survey

Once the individual scans have been assembled utilizing common targets and geometry, the survey file is then registered. In this process the software takes the targets extracted from the point cloud and compares them to the same set of targets that were acquired by the survey instrument. The coordinates from the survey instrument are used to move the point cloud into the survey coordinates system based on these targets. The most critical items in this registration are the amount of error between these points and the geometry of the points used throughout the site. In Appendix A the “110920_WHISTLER_CONCRETE_GEOMETRY_MAP.pdf” describes the targets used to tie the ice scan data to the survey coordinate system. It also identifies the location, error, and overall geometry of the targets used.

3.2.6 Registration of “Ice Scan” to Survey

The same process is utilized when registering the “ice” scan to the survey file. The survey files were created for each set of scans at the time of the scanning. However, the points used at the site as the basis of this survey information are not the same for each trip. In Appendix A the “110921_WHISTLER_ICE_GEOMETRY_MAP.pdf” describes the targets used to tie the ice scan data to the survey coordinate system. It will also identify the location, error, and overall geometry of the targets used.

3.2.7 Best Fit Alignment Method

As a way of evaluating the “as-built” polygon surface against the “as-designed” surface, a “best fit” alignment of the cross sections was done to account for potential errors introduced in the process of aligning the current as-built surface to the design surface via the survey. This is the process of locking the as-built model into its current location and fitting the as-designed model to the as-built model. The software fits the models together to minimize error and maximize the amount of track surface that is aligned to the design surface.

3.2.8 Comparing the Utilization of Survey Information vs. Best Fit

When utilizing a conventional survey, the point cloud is located in space based on the values provided by the site survey. When aligning this resulting point cloud to the as-designed data the following can be potential sources of error:

- Errors in survey being utilized on site during scanning,
- Errors between the survey being completed on site and the original survey that was utilized during construction,
- Errors between the survey that was used during construction and the actual “perfect world” of the design information.
For the purpose of this project when utilizing the conventional survey, the goal is to find how the as-built track compares to the as-designed in both the shape of the track and the location of the track. The purpose of completing the best fit analysis is to look at how closely the shape of the track matches the as-designed model with no emphasis on how true the location of the track is to its designed location. When completing a best fit it is possible that the software will increase errors in certain locations in order to get the largest overall area of the track in the best possible alignment.

3.2.9 Assessment of Potential Errors

There are specific locations where errors can be introduced into the alignment of the data in the WSC project. They are as follows:

- Differences in the extraction of targets by the scanning system,
- Differences between the surveyed targets and the scanned target locations,
- Differences in the alignment between the original site survey and the current site survey,
- Survey network errors over the larger footprint of WSC,
- Differences in the design vs. as-built,
- Potential changes over time due to freezing, thawing, settling, etc.,
- Accumulative error from the environment, survey tolerances, scanning tolerances, surfacing tolerances,

Redundancy was created in the registration in an effort to minimize the potential errors throughout the process. The steps we take in creating redundancy are as follow:

- Utilizing cloud to cloud alignment to assemble the individual scans and align them,
- Implementing a thorough quality control of the scan alignment to verify all visible errors are corrected,
- Using common targets between scans from different scanners and different scan positions,
- Fitting cloud constraints and common targets to survey file as a redundant check of alignment.

The Track curves over a large area versus a long straight corridor, and the location of the Track on rugged terrain of a mountainside can be difficult to scan. The errors that may be introduced include variations in angles of incidence, variations in translucency of surfaces, variations in reflectivity of surfaces for the scan shots and from knitting the scans into one large composite.

The link between the "Ice Scan Dataset" and the "Concrete Scan dataset" is the control survey. The typical errors introduced in the control survey will be translated into the linkage between the data sets. The reference geometry maps include the accuracies related to laser scan data.

Frosted ice is not translucent and it provides the best possible surface in measuring the material. The effect of varying degrees of translucency of ice has on the laser scan is not well known or studied. In order to improve the accuracy of the laser scan results it
is recommended that more rigorous testing of the effect of varying degrees of translucency be tested in a controlled environment.

The software takes the large volume of cloud data points and applies complicated algorithms to create a surface. The software aligns each scan position and survey control and this is quantified in the geometry map that was developed. The only errors not included in the geometry map that the software would introduce would be related to non-existent data, interpolation between data points of minor spacing, and inaccurate information provided to create any component.

3.2.10 Assumptions While Scanning and Generating Point Cloud

The following are the assumptions made during the scanning and point cloud generation:

- Survey file provided meets the accuracy requirements for the project,
- Registration of concrete and ice surface to survey coordinate system meets the accuracy requirements for the project,
- Design surface meets the accuracy requirements for the project.
3.2.11 Description of Deliverables

The following are the deliverables from the survey and scanning of the WSC track:

- Ice Cross Sections – These are cross sections provided to Bromley located every 0.5m over the length of the track,
- Polygon Surface of “Ice” Scan – This is the triangulated surface generated of the ice scan point cloud,
- Concrete Cross-sections – These are cross-sections on the concrete scan located every 2.5m on the track,
- Polygon Surface of “Concrete” Scan – This is the triangulated surface created from the concrete point cloud,
- 3 Dimensional surface-to-surface Comparison Cross-sections – This is a comparison of the “as-built” concrete scan compared to the “as-designed” surface. The overall differences between the surfaces are displayed using a color differentiated map. 2 Dimensional cross sections located every 2.5 m identify the differences between the two surfaces,
- 3 Dimensional surface-to-surface Comparison Cross-sections – This is a comparison of the “ice surface” to the “as-built” concrete scanned surface. The overall differences between the surfaces are displayed using a color differentiated map. 2 Dimensional cross sections located every 2.5 m identify the differences between the two surfaces,
- 3 Dimensional Surface Comparison and Viewing Software - the “as-built” concrete to “as-designed” surface comparisons of each section of the track has been supplied as an individual file. These files can be viewed using Geomagic Review.
CHAPTER 4 - CONSTRUCTION AUDIT

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# TABLE OF CONTENTS

## CHAPTER 4 - CONSTRUCTION AUDIT

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>Introduction</td>
<td>85</td>
</tr>
<tr>
<td>4.1.1</td>
<td>Team Introductions</td>
<td>85</td>
</tr>
<tr>
<td>4.1.2</td>
<td>Terms of Reference</td>
<td>86</td>
</tr>
<tr>
<td>4.1.3</td>
<td>Track Description</td>
<td>86</td>
</tr>
<tr>
<td>4.2</td>
<td>Methodology</td>
<td>87</td>
</tr>
<tr>
<td>4.2.1</td>
<td>General</td>
<td>87</td>
</tr>
<tr>
<td>4.2.2</td>
<td>Track Construction</td>
<td>87</td>
</tr>
<tr>
<td>4.2.3</td>
<td>Specified Tolerances</td>
<td>107</td>
</tr>
<tr>
<td>4.2.4</td>
<td>Foundation Construction and Shotcrete Tolerances</td>
<td>112</td>
</tr>
<tr>
<td>4.2.5</td>
<td>As-Designed Track</td>
<td>113</td>
</tr>
<tr>
<td>4.2.6</td>
<td>As-Constructed Track</td>
<td>115</td>
</tr>
<tr>
<td>4.3</td>
<td>Assumptions</td>
<td>118</td>
</tr>
<tr>
<td>4.3.1</td>
<td>General</td>
<td>118</td>
</tr>
<tr>
<td>4.3.2</td>
<td>Assembly of Documentation for As-Designed Track</td>
<td>118</td>
</tr>
<tr>
<td>4.3.3</td>
<td>Shrinkage and Temperature Effects</td>
<td>120</td>
</tr>
<tr>
<td>4.3.4</td>
<td>Accuracy of As-Constructed to As-Design Track Surface Comparisons</td>
<td>122</td>
</tr>
<tr>
<td>4.4</td>
<td>Deliverables</td>
<td>127</td>
</tr>
<tr>
<td>4.4.1</td>
<td>As-Constructed to As-Designed Track Surface Cross-Sectional Comparison</td>
<td>127</td>
</tr>
<tr>
<td>4.4.2</td>
<td>As-Constructed to As-Designed Track Surface Differential Color Mapping</td>
<td>135</td>
</tr>
<tr>
<td>4.4.3</td>
<td>Best Fit As-Constructed to As-Designed Track Surface Cross-Sectional Comparison</td>
<td>136</td>
</tr>
<tr>
<td>4.5</td>
<td>Comments and Recommendations</td>
<td>137</td>
</tr>
<tr>
<td>4.6</td>
<td>REFERENCES</td>
<td>140</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

Figure 4.1 Alignment of the track control line that is equal to the IBG Consulting Engineering centerline in the vicinity of Curve C2 (from Stantec Architecture Ltd. Drawing A.2.5.5: A0-17.021-401). ................................................................. 88
Figure 4.2 Track profile in the vicinity of Curve C2 (from Stantec Architecture Ltd. Drawings A0-17.021-407 and A0-17.021-408). ................................................................. 89
Figure 4.3 Track foundation plan in the vicinity of Curve C2 (from Stantec Architecture Ltd. Drawings A0-17.031-03 and A0-17.031-04). ................................................................. 90
Figure 4.4 Typical section through the track (from Stantec Architecture Ltd. Drawing A0-17.031-26). .................................................................................. 92
Figure 4.5 Pendulum column foundation (from Stantec Architecture Ltd. Drawing A0-17.031-26). .................................................................................. 93
Figure 4.6 Pendulum wall foundation (from Stantec Architecture Ltd. Drawing A0-17.031-26). .................................................................................. 94
Figure 4.7 Fixed wall foundation (from Stantec Architecture Ltd. Drawing A0-17.031-26). .................................................................................. 95
Figure 4.8 Cross-section showing straight portions of track [adapted from IBG (2004), p. 14] .............................................................................................................. 96
Figure 4.9 Wall section showing refrigeration pipes and insulation [from IBG (2004), p. 17]. .............................................................................................................. 97
Figure 4.10 Jig profile drawings for the portion of the track leading to Curve C2 (from IBG Consulting Engineering Drawing WSC Phase 2 502.1) ................................................................. 98
Figure 4.11 Concrete profile drawings for the portion of the track leading to Curve C2 (from IBG Consulting Engineering Drawing WSC Phase 1 402.1) ................................................................. 98
Figure 4.12 Typical cross-section for curved portions of track [from IBG (2004), p. 16]. .............................................................................................................. 99
Figure 4.13 Suggested modifications to track at Curve C7 (from WSC files). ............... 108
Figure 4.14 Suggested modifications to track at Curve C9 (from WSC files). ............... 109
Figure 4.15 Track cross-sections in the vicinity of Curve C2 ........................................ 113
Figure 4.16 Track with mesh drawn between cross-sections in the vicinity of Curve C2. .............................................................................................................. 114
Figure 4.17 Track with mesh and surface drawn between cross-sections in the vicinity of Curve C2. .............................................................................................................. 114
Figure 4.18 Three-dimensional comparison between the as-designed and as-constructed track surfaces in the vicinity of Curve C2. ....................................................... 116
Figure 4.19 Comparison of the as-designed and as-constructed track surfaces at Section Sx 137.5 m. .............................................................................................................. 117
Figure 4.20 Comparison of the as-designed and as-constructed track surfaces at Section Sx 147.5 m. .............................................................................................................. 118
Figure 4.21 Vector diagram showing the shrinkage (S) and temperature (T) movements of the track at Curve C2. .............................................................................................................. 121
Figure 4.22 Doug Bush Survey Services Ltd. bench marks in the vicinity of Curve C2. .............................................................................................................. 123
Figure 4.23 Comparison between as-designed and as-constructed work points for the track surface at Station Sx 160 m for Curve C2. .............................................................................................................. 125
LIST OF PHOTOGRAPHS

Photograph 4.1 Construction of the foundation that supports the track (from WSC files). ................................................................. 91
Photograph 4.2 Close-up of the construction of the pendulum columns that support the track (from WSC files)................................................................. 91
Photograph 4.3 Straight portion of track with refrigeration pipes and reinforcing steel in place (from WSC files)................................................................. 99
Photograph 4.4 Shotcreting of straight portion of track (from WSC files) ................................................................. 99
Photograph 4.5 Finishing surface of wet shotcrete with a trowel (from WSC files) ................................................................. 100
Photograph 4.6 Final finishing surface of wet shotcrete with a broom (from WSC files) ................................................................. 100
Photograph 4.7 Refrigeration pipes in place for a curved section of the track (from WSC files) ................................................................. 102
Photograph 4.8 Reinforcing steel and refrigeration pipes in place for a curved section of the track (from WSC files) ................................................................. 102
Photograph 4.9 Section of the track after the shotcrete has cured (from WSC files) ................................................................. 103
Photograph 4.10 Section of track approaching Curve C2 (taken by Mackenzie Safety) ................................................................. 103
Photograph 4.11 Section of track at the entrance to Curve C2 (taken by Mackenzie Safety) ................................................................. 104
Photograph 4.12 Section of track in Curve C2 (taken by Mackenzie Safety) ................................................................. 104
Photograph 4.13 Section of track in Curve C2 (taken by Mackenzie Safety) ................................................................. 105
Photograph 4.14 Section of track in Curve C2 (taken by Mackenzie Safety) ................................................................. 105
Photograph 4.15 Section of track in Curve C2 (taken by Mackenzie Safety) ................................................................. 106
Photograph 4.16 Section of track leaving Curve C2 (taken by Mackenzie Safety) ................................................................. 106
Photograph 4.17 Removing a thin layer of shotcrete from the track surface with a light jack hammer (from WSC files) ................................................................. 110
Photograph 4.18 Track surface in a location where a thin layer of shotcrete was removed (from WSC files) ................................................................. 110
Photograph 4.19 Smoothing the track surface with mortar in a location where a thin layer of shotcrete was removed (from WSC files) ................................................................. 111
LIST OF TABLES

Table 4.2 Work point comparison between the as-designed and as-constructed concrete surfaces at the locations of the fixed wall foundations. .......................... 126
Table 4.3 Comparison between the as-constructed and as-designed concrete surfaces at cross-sections along the length of the track for Curve C2. ....................................... 128
Table 4.4 Percent of stations with vertical deviation of as-constructed profile in relation to as-designed profile within range ................................................................. 130
Table 4.5 Percent of stations with horizontal deviation of as-constructed profile in relation to as-designed profile within range ......................................................... 132
Table 4.6 As-constructed concrete profile comparison to as-designed profile. .............. 133
Table 4.7 Comparison of the track surface deviations for the unmodified (original) and "best fit" Epic Scan data................................................................. 137
4.1 Introduction

4.1.1 Team Introductions

Jim Montgomery and Jonathan Paul are the principal investigators at DIALOG for the Whistler Sliding Centre track construction audit.

Jim Montgomery has had an exemplary career that spans over 30 years. In 1973, he graduated at the top of his class at the University of Alberta. After obtaining post-graduate degrees at the University of Illinois, Urbana-Champaign, Dr. Montgomery joined the Department of Civil Engineering at the University of Alberta where he held positions as Assistant and Associate Professor from 1977 until 1981.

In 1981, Jim Montgomery became a principal in the structural engineering firm of Lamb McManus Associates Ltd., where he provided construction engineering services to contractors, and designed a number of bridges and buildings, including the 27 storey City Centre Project in Edmonton.

Jim Montgomery joined Cohos Evamy, in 1988. The firm changed its name to DIALOG in 2010. As Chief Engineer and as senior financial partner for more than 10 years, he has anchored the growth of the firm as it transitioned to a fully integrated design firm with a staff of 500 working in studios in Vancouver, Calgary, Edmonton and Toronto. At any given time, the firm is involved in more than $1 billion of design or construction projects.

At DIALOG, Jim Montgomery has been the structural engineering principal, leading a broad cross-section of significant building, bridge, and specialty engineering projects across Canada. Projects include the Public Safety and Emergency Preparedness Canada (PSEPC) National Headquarters in Ottawa, the Francis Winspear Centre for Music in Edmonton, the Markin/CNRL Natural Resources Engineering Facility and the National Institute for Nanotechnology at the University of Alberta, and the Robbins Pavilion/Lois Hole Hospital for Women at the Royal Alexandra Hospital. He was the executive in charge of the structural engineering work for the Edmonton Clinic North and South, buildings that occupy nearly five blocks in length in Edmonton. He is currently working on the design of the Walterdale Bridge replacement across the North Saskatchewan River in Edmonton, a signature through arch structure with a clear span of 240 m.

He has been responsible for a number of failure investigations, studies and arbitrations including the Triple Loop Roller Coaster Accident investigation for the Alberta Attorney General and the Board of Inquiry into the cause of the accident that killed three people and seriously injured a fourth. He also acted as an expert witness in the law suit that ensued following the accident.

Jim was APEGGA’s 2007 Centennial Leadership Award winner, the most prestigious award offered by the engineering profession in Alberta. Jim was also the recipient of the Consulting Engineers of Alberta (CEA) Lieutenant Governor’s Award for Distinguished Achievement in 2010.

Jonathan Paul holds a Diploma in Engineering Design and Drafting Technology with a Structural Major from SAIT Polytechnic. Aside from having the Structural Major, the
program provided a solid knowledge base in the areas of communications, engineering mathematics, surveying, as well as topographical, civil, mechanical, electrical, process pipe, HVAC, and environmental design and drafting. Jon joined DIALOG in the spring of 2007, and obtained his Certified Engineering Technologist (C.E.T.) designation through The Association of Science and Engineering Technology Professionals of Alberta (ASET) in 2010. Jon has also begun working towards obtaining a Project Management extension certificate through Mount Royal University, and intends to obtain a Project Management Professional (P.M.P.) designation in the upcoming years.

Jon is very detail orientated and takes pride in his work, promoting the quality of the structural drawings that are produced in the Calgary studio. He has been involved on a variety of projects including the Grande Prairie Shields Health & Education Centre, Chilliwack Secondary School, SAIT Polytechnics Trades & Technology Complex, SAIT Polytechnic Parking Garage, Suncor Mining Equipment Maintenance Expansion, and CrossIron Mills Shopping Centre.

4.1.2 Terms of Reference

The Board of Governors of the Southern Alberta Institute of Technology has been engaged by the Whistler 2010 Sports Legacy Society to conduct an independent evaluation of sled trajectories at the bobsleigh, luge and skeleton track at the Whistler British Columbia Sliding Centre.

As part of the consulting assignment, DIALOG has been subcontracted to provide a construction audit of the track. This work includes:

- A three-dimensional computer model of the as-designed track and the as-constructed track.
- A report summarizing our work, and comparing the as-designed and as-constructed track geometries. The report will express an opinion on whether the as-constructed track is within the required tolerances.

This chapter of the report summarizes the methodology, describes the assumptions, presents the deliverables, and sets forth the conclusions and recommendations for the construction audit.

4.1.3 Track Description

The Whistler Sliding Centre Track is 1700 m in length and has 16 curves in plan view with limited straight-aways between. Appendix B.1 to this report contains drawings and other technical information prepared by the track designer, IBG Consulting Engineering. The unnumbered WSC Drawing titled “Final Design – Ground Plan” prepared by that firm shows the overall geometry of track in plan view and longitudinal section. Drawing WSC 001 shows the polygon of the centerline of the track. Drawing WSC 003 shows the ground plan of the track, and Drawings WSC 04.1 and WSC 04.2 show the track in longitudinal section in more detail.

The elevation of the track varies from 934.866 m near the Bob start at Station Sx 0 m to a low of 786.043 m at Station Sx 1277.500 m. The slopes of the downhill portions of the
track vary between 4 and 20%. Each of the curves in plan view has a spiral section of varying radius to transition from the straight section at the entrance of the curve to the portion of the track with a circular curve, and a spiral section to transition to the next straight section at the exit from the curve. The radii of the circular sections of the curves vary from a minimum of 12 m at Curve C1 to a maximum of 1000 m at Curve C8.

The profile in cross-section varies along the length to accommodate the sleds as they travel through the straight and curved sections of the track. Drawing WSC 005 shows the profile at straight and various types of curved sections along the track.


4.2 Methodology

4.2.1 General

As part of the audit, we reviewed documentation that was prepared by the track designer, the drawings and specifications that were provided to the contractor for the construction of the track and selected photographs that were taken during constructions. Next, we relied on our experience in the construction of buildings and bridges to ascertain the tolerances that might be expected for foundation and shotcrete construction. Finally, we prepared a three dimensional model of the as-designed track surface, worked with Epic Scan to compare the as-constructed track surface to the as-designed surface, and worked with Epic Scan to estimate the thickness of the ice on the as-constructed track.

4.2.2 Track Construction

The track was constructed from drawings prepared by Stantec Architecture Ltd. for the Vancouver Organizing Committee for the 2010 Olympic and Paralympic Winter Games. Civil and structural specifications and drawings issued for review, tender and construction in late 2005 and early 2006 under Contract No. V-5051 show the geometry and construction details of the track. Appendix B.2 of the report contains a list of selected specification sections and drawings that were used to construct the track.

In this chapter of the report, we use Curve C2 of the track to illustrate construction details, methodology, survey results, and the like. Where appropriate, additional information for other sections of the track is included in the appendices.

Figures 4.1 and 4.2 show the track alignment and profile, respectively, in the vicinity of Curve C2. We assume that these geometrics were used by the contractor to layout the track.
Figure 4.1 Alignment of the track control line that is equal to the IBG Consulting Engineering centerline in the vicinity of Curve C2 (from Stantec Architecture Ltd. Drawing A.2.5.5: A0-17.021-401).
Figure 4.2 Track profile in the vicinity of Curve C2 (from Stantec Architecture Ltd. Drawings A0-17.021-407 and A0-17.021-408).

Figure 4.3 shows the foundation plan for a portion of the track in the vicinity of Curve C2. The track is supported on a series of pendulum column, pendulum wall and fixed wall foundations. Transverse expansion joints are located along the length of the track to allow movement to occur as it expands and contracts relative to the ground as a result of temperature changes. Neoprene pads with a thickness of 40 mm are placed on the tops of the pendulum column foundations to allow the track to move in any horizontal direction as temperatures change. Pendulum wall foundations oriented perpendicular to the longitudinal axis of the track are located near the expansion joints where it is necessary to restrain the movement of the track in the transverse direction.

Fixed wall foundations are located approximately midway between expansion joints to restrain the movement of the track in all directions. In Figure 4.3 the pendulum column,
pendulum wall and fixed wall foundations are denoted by PCF, PWF and FF, respectively.

Figure 4.3 Track foundation plan in the vicinity of Curve C2 (from Stantec Architecture Ltd. Drawings A0-17.031-03 and A0-17.031-04).
Photographs of the track construction are available from the Whistler Sliding Centre files for the project. The supports that transfer the loads from the track to the foundation are shown in Photographs 4.1 and 4.2 during construction.

Photograph 4.1 Construction of the foundation that supports the track (from WSC files).

Photograph 4.2 Close-up of the construction of the pendulum columns that support the track (from WSC files).
Figure 4.4 shows a typical section through the track between expansion joints. Figures 4.5, 4.6 and 4.7, respectively, show the pendulum column, pendulum wall and fixed foundation walls.

Figure 4.4 Typical section through the track (from Stantec Architecture Ltd. Drawing A0-17.031-26).
Figure 4.5 Pendulum column foundation (from Stantec Architecture Ltd. Drawing A0-17.031-26).
Figure 4.6 Pendulum wall foundation (from Stantec Architecture Ltd. Drawing A0-17.031-26).
Figure 4.7 Fixed wall foundation (from Stantec Architecture Ltd. Drawing A0-17.031-26).
Figure 4.8 shows the straight portions of the track that are U-shaped in cross-section and are constructed from shotcrete with a thickness of 150 mm. Shotcrete is the generic name used for concrete that is conveyed through a hose, and applied pneumatically and compacted at high velocity onto a surface. It is used for the construction of building components, tunnel liners, earth retaining walls and the like.

1. ground slab, 2. band wall, 3. band head, 4. insulation

Figure 4.8 Cross-section showing straight portions of track [adapted from IBG (2004), p. 14].

As shown in Figure 4.9, the ground slab and walls contain refrigeration pipes between layers of reinforcing steel to cool the exposed surface of the shotcrete track. IBG Consulting Engineering intended for the contractor to use 20 mm diameter jig bars with spacers between the layers of reinforcing steel as a reference to achieve the specified concrete thickness and cross sectional shape when placing and finishing the shotcrete.
The wall thickness is established from the following parameters:

1. 30 mm concrete cover
2. $\phi$ 10 mm, reinforcement steel; diagonal distributed
3. $\phi$ 10 mm, reinforcement steel; diagonal distributed
4. $\phi$ 33,7 mm icing steel pipe
5. (*) 16 or 20 mm distance, respectively
6. $\phi$ 10 mm, reinforcement steel; vertical distributed
7. $\phi$ 10 mm, reinforcement steel; horizontal distributed
8. woven mesh ( $\phi$ 0.8 mm wire, width 4.6 mm )
9. 27 or 23 mm concrete cover, respectively
10. jig, 20 mm round steel with spacers
11. 80 mm insulation
12. wall covering

Figure 4.9 Wall section showing refrigeration pipes and insulation [from IBG (2004), p. 17].

The Stantec Architecture Ltd. Drawing A0-17.031-000 referred to in Appendix B.2 lists the IBG Consulting Engineering jig and concrete profile drawings that the contractor was to use when fabricating jig bars, and placing and finishing shotcrete. Figures 4.10 and 4.11, respectively, show the jig and concrete profile drawings for the straight portion of track at Stations Sx 124 m and Sx 125 m leading to Curve C2. Appendix B.1 includes a listing of the most current set of the jig and concrete profile drawings for Curve C2.
Stantec Architecture Ltd. Drawing A0-17.031-000 indicates that the IBG Consulting Engineering reference drawings for the concrete profiles are for Phase 2 rather than Phase 1, and are 100 series rather than 400 series drawings. We have used the Phase 1 or Phase 2 400 series with the latest date of issue drawings in this report to ascertain the as-design geometry of the track surface.

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1 Stantec Architecture Ltd. Drawing A0-17.031-000 indicates that the IBG Consulting Engineering reference drawings for the concrete profiles are for Phase 2 rather than Phase 1, and are 100 series rather than 400 series drawings. We have used the Phase 1 or Phase 2 400 series with the latest date of issue drawings in this report to ascertain the as-design geometry of the track surface.
Photograph 4.3 shows the refrigeration pipes and reinforcing steel in place for a straight section of the track, prior to shotcreting. Photograph 4.4 shows the pneumatic placement of the shotcrete, and Photographs 4.5 and 4.6, respectively, show how the surface of the shotcrete is finished with a trowel and broom.

Photograph 4.3 Straight portion of track with refrigeration pipes and reinforcing steel in place (from WSC files).

Photograph 4.4 Shotcreting of straight portion of track (from WSC files).
Photograph 4.5 Finishing surface of wet shotcrete with a trowel (from WSC files).

Photograph 4.6 Final finishing surface of wet shotcrete with a broom (from WSC files).
Figure 4.12 shows the typical cross-section for curved portions that consist of spatial shell structures with continuously changing shapes to accommodate the trajectory of the sleds travelling on the track. The ground slab and walls in the curved portions are also constructed from shotcrete, with the walls having a thickness of 150 mm.

Figure 4.12 Typical cross-section for curved portions of track [from IBG (2004), p. 16].
Photographs 4.7 and 4.8, respectively, show the refrigeration pipes and reinforcing steel with pipes between in place for a curved section of the track.

Photograph 4.7 Refrigeration pipes in place for a curved section of the track (from WSC files).

Photograph 4.8 Reinforcing steel and refrigeration pipes in place for a curved section of the track (from WSC files).
Photograph 4.9 shows a portion of the track after the shotcrete has cured, but before shades, guardrails, and other amenities are constructed.

Photograph 4.9 Section of the track after the shotcrete has cured (from WSC files).

Photographs 4.10 through 4.16 taken in June 2011 show the track in the vicinity of Curve C2, from the top walking down.

Photograph 4.10 Section of track approaching Curve C2 (taken by Mackenzie Safety).
Photograph 4.11 Section of track at the entrance to Curve C2 (taken by Mackenzie Safety).

Photograph 4.12 Section of track in Curve C2 (taken by Mackenzie Safety).
Photograph 4.13 Section of track in Curve C2 (taken by Mackenzie Safety).

Photograph 4.14 Section of track in Curve C2 (taken by Mackenzie Safety).
Photograph 4.15 Section of track in Curve C2 (taken by Mackenzie Safety).

Photograph 4.16 Section of track leaving Curve C2 (taken by Mackenzie Safety).
4.2.3 Specified Tolerances

A key consideration in the current study is to ascertain whether the shotcrete track is constructed in the proper location and has a smooth surface that is within tolerance.

In describing the construction of the straight portions of the track, IBG (2004) on p. 25 required the contractor to measure “…the track bottom to check tolerances and evenness of concrete surface…” For the curved portions, IBG (2004) on page 29 required the contractor to survey “…the track bottom and curve wall to check evenness of concrete surface to meet specification”.

We have not been able to find any documents issued by IBG that specify the required tolerances for the construction of the track surface. A Whistler Sliding Centre representative [WSC (2011a)] contacted the design engineers to ascertain whether tolerances were specified for the construction of the track surface. IBG Consulting Engineering indicated that the specification of tolerances was not part of their work on the project.

Specification Section 03713 prepared by Stantec Architecture Ltd. for the track construction specifies acceptable tolerances for shotcrete. Appendix B.2 lists this and other relevant specification sections. Clause 3.2.4 of the shotcrete specification indicates that the acceptable tolerance for the build-up of the concrete surface to finish lines is 3 mm over a 1 m distance horizontally and a 400 mm distance vertically. The clause indicates that a 25 mm concrete cover is required over steel reinforcement. Clause 3.2.7 indicates that the sliding surface of the track is to be screeded and finished to a 3 mm tolerance over a 1 m distance horizontally and a 400 mm distance vertically.

The Stantec Architecture Ltd. specifications do not appear to give acceptable tolerances for the conformance of the surface along the length of the track to the shape of the design cross-sections, or the track to the design alignment and profile.

We have not been able to find any documentation indicating that as-built measurements were undertaken following the completion of construction. However, Figures 4.13 and 4.14, respectively, reproduced from the project files indicate someone requested that modifications be made to the exposed surface of the track at Curves C7 and C9 after the completion of construction.
Figure 4.13 Suggested modifications to track at Curve C7 (from WSC files).
Figure 4.14 Suggested modifications to track at Curve C9 (from WSC files).

Photographs 4.17, 4.18 and 4.19 indicate that some remedial work was undertaken on the track surface after the completion of construction.
Photograph 4.17 Removing a thin layer of shotcrete from the track surface with a light jack hammer (from WSC files).

Photograph 4.18 Track surface in a location where a thin layer of shotcrete was removed (from WSC files).
Photograph 4.19 Smoothing the track surface with mortar in a location where a thin layer of shotcrete was removed (from WSC files).
4.2.4 Foundation Construction and Shotcrete Tolerances

The pendulum column, pendulum wall, and fixed wall foundations for the track were constructed on the side of a mountain using cast-in-place concrete. It is unlikely that the as-built foundations are in the exact locations shown on the Stantec Architecture Ltd. design drawings. The position of the shotcrete track in space is likely influenced by the configuration for the as-constructed foundations.

The American Concrete Institute publishes guidelines and specifications for shotcrete design and construction. With respect to construction tolerances, ACI (1995) indicates the following:

“Specify tolerance based on function and appearance. Shotcrete is typically not held to the same tolerance as cast-in-place concrete. Sometimes no tolerances are specified, while sometimes shotcrete tolerances are increased by a factor of 2 times over the tolerances provided in ACI 117.”

ACI 117 [ACI (2010)] provides the construction tolerances for foundations, cast-in-place concrete for buildings, precast concrete, canal lining, cast-in-place bridges, pavement and sidewalks, and the like. Representative construction tolerances for cast-in-place concrete buildings are as follows:

“Deviation from elevation, top surface of slabs, formed suspended slabs, before removal of supporting shores +19 mm

Deviation from cross-sectional dimensions, thickness of elements, except slabs, where specified cross-sectional dimension is 305 mm or less +10 mm - 6 mm

Deviation from slope or plane, formed surfaces over distances of 3.05 m, all conditions, unless noted otherwise +0.3%

Random traffic floor finish tolerances as measured by manually placing a freestanding (unleveled) 3.05 m straightedge anywhere on the slab and allowing it to rest naturally upon the test surface. The gap under the straightedge and between the support points shall not exceed for 90% compliance:

Conventional 13 mm
Moderately flat 10 mm
Flat 6 mm"

The track was constructed by erecting formwork for the ground slab and installing wire mesh on the outside vertical wall surfaces, then placing reinforcing steel, refrigeration pipes, jig bars, anchor rods, embedded plates, and other cast-in items. Shotcrete was then conveyed through a hose, and applied pneumatically and compacted at high
velocity onto the forms and wire mesh at the outside vertical wall surfaces. Finally, the inside surface of the track was finished with a trowel and broom. It is inevitable that the as-built dimensions and locations of shotcrete members will differ slightly from those shown on the drawings, due to construction tolerances.

In our view, great care during construction is required to meet the surface finish requirements of Specification Section 03713 prepared by Stantec Architecture Ltd. for the track.

4.2.5 As-Designed Track

We have imported the geometry from the three dimensional Autodesk AutoCAD model into Autodesk 3ds Max so that the as-designed track can be surfaced between the cross-sections. The objective is to show the finished concrete surface of the track in three dimensions for comparison with the as-constructed track.

Figure 4.15 shows a series of cross-sections from the three-dimensional Autodesk AutoCAD model of the track in the vicinity of Curve C2. The cross-sections are oriented in a vertical plane, perpendicular to the centre line of the track when viewed in plan (see Appendix C.1 - Drawing WSC 005).

Figure 4.15 Track cross-sections in the vicinity of Curve C2.
The first step in the surfacing process is to draw a mesh between cross-sections. Figure 4.16 shows an example of the mesh for the track in the vicinity of Curve C2.

Figure 4.16 Track with mesh drawn between cross-sections in the vicinity of Curve C2.

The next step is to surface the mesh between the cross-sections. Figure 4.17 shows an example with the mesh and surface drawn between cross-sections for the track in the vicinity of Curve C2.

Figure 4.17 Track with mesh and surface drawn between cross-sections in the vicinity of Curve C2.

Appendix C.3 contains a complete model of the surfaced track.
4.2.6 As-Constructed Track

Epic Scan has completed a point-cloud survey that provides the as-constructed geometry of the surface of the track in three dimensions.

In a point-cloud survey, a laser scanner sends out a series of pulsed laser beams of light towards a surface. By recording the time for the beam of light to strike the surface and return, the scanner determines the distance to a point on the surface. By means of mirrors at the scanner, the horizontal and vertical angles of the beam of light are calculated. Knowing the position of the scanner in space and with the distance and angles to the point, the x, y and z coordinates of the point are determined and recorded by a three-dimensional visualization program. The three-dimensional shape is determined by assembling the coordinates for a number of points on the surface.

For the Whistler Sliding Centre track, Epic Scan set a laser scanner up at a number of positions along the length of the track and recorded the point-cloud survey data for the track in sections. Terra Pacific Land Survey Ltd. located the laser scanner in a local coordinate system at each set up position. Knowing the positions of the scanner, Epic Scan then assembled the point-cloud data to obtain a three-dimensional as-constructed computer model of the complete surface of the track.

Terra Pacific Land Survey Ltd. later related the local scan coordinate system to survey bench marks set up by Doug Bush Survey Services Ltd. for the construction of the track. Using the tie between the project coordinate system used for construction and the local scan system, Epic Scan has provided comparisons between the as-constructed three-dimensional surface of the track and the as-designed track surface in the project coordinate system. This allows the study team to ascertain the magnitude of any differences in geometry in three dimensions.

Figure 4.18 shows a view of the three-dimensional comparison between the as-designed and as-constructed track surfaces in the vicinity of Curve C2. The colour bar chart on the left side of the figure shows the deviations between the surfaces in millimeters. Positive deviations occur when the as-designed surface is within the as-constructed surface when viewed by a person travelling down the track.
Figure 4.18 Three-dimensional comparison between the as-designed and as-constructed track surfaces in the vicinity of Curve C2.

Figure 4.18 also shows locations where sections are cut through the three-dimensional model comparing the as-designed and as-constructed track surfaces. These sections are cut at the same locations as where concrete profile information was provided to the contractor for the construction of the track.

Figures 4.19 and 4.20 compare the as-designed and as-constructed track surfaces at Sections Sx 137.5 m and Sx 147.5 m, respectively. In these figures, the solid purple/red line represents the cross-section of the as-constructed track and the line of varying colour between the dots represents the cross-section of the as-designed track. The colour bar chart on the left side shows the deviation between the as-designed and as-constructed cross-sections in millimeters. Positive deviations occur when the as-designed surface is within the as-constructed surface when viewed by a person travelling down the track.

The maximum positive and negative deviations for the cross-section are tabulated in the table at the bottom of the figures.

By means of the colour bar chart, it is possible to estimate the amount that the as-constructed cross-section is out of position in the horizontal and vertical directions from the as-designed cross-section. By comparing the shape of the cross-sections, comments can be made on whether or not the as-constructed shape conforms to the as-designed shape.
Figure 4.19 Comparison of the as-designed and as-constructed track surfaces at Section Sx 137.5 m.
Appendix C.4 contains comparisons between the as-designed and as-constructed surfaces along the entire length of the track.

4.3 Assumptions

4.3.1 General

In developing the three-dimensional computer model for the as-designed track, we reviewed drawings that were issued by IBG Consulting Engineering and Stantec Architecture Ltd. at various times during the design and tender period for the construction of the facility. In preparing the point-cloud surveys of the track, the project team measured the ice and as-constructed concrete surfaces at two different times under field conditions. This subsection of the report describes the assumptions that were made in assembling data and developing the three-dimensional computer models to compare the as-constructed and as-designed concrete surfaces, and the ice and as-constructed concrete surfaces.

4.3.2 Assembly of Documentation for As-Designed Track

In the initial stages of the study, we needed to resolve three outstanding issues to develop three-dimensional computer models of the as-designed track.
The first is that there appeared to be incomplete and conflicting information concerning the track geometry in the Whistler Sliding Centre project files. This is understandable as drawings and other documents were issued for review and construction at a variety of times by the track designer, IBG Consulting Engineering. For example, Drawing WSC 005 defining the dimensions for the cross-sections along the length of the track given in computer files was not available. Also, Drawings WSC 04.1 and WSC 04.2 gave elevations for the centre line along the length of the track that are in conflict with those given in a Microsoft Excel spreadsheet.

Through communication with IBG Consulting Engineering, a Whistler Sliding Centre representative [WSC (2011b)] was able to obtain Drawing WSC 005. The representative determined that the entire track was lowered by 1 m after Drawings WSC 04.1 and WSC 04.2 were first issued so that cuts and fills could be balanced by the earthworks contractor during the construction of the track. If the elevations on Drawing WSC 04.1 and Drawing WSC 04.2 are reduced by this amount, the elevations on the drawings and the spreadsheet are generally in agreement.

The second reason is that as-built drawings for the track construction prepared by Stantec Architecture Ltd. are not available. As the Whistler Sliding Centre files for the project contain a number of drawings that were issued at various review stages, and several of the drawings were modified by addendum during the tender period for the project, we needed to assemble the information that was used by the contractor for construction of the track.

The third reason is that we received conflicting information relative to the track geometry. In the week of June 20, 2011 a representative of the Whistler Sliding Centre [WSC (2011b)] forwarded to our firm a three dimensional Autodesk AutoCAD model of the track from IBG Consulting Engineering. The model connects together cross-sections at 0.5 m stations along the length of the as-designed track.

We found discrepancies between the WSC, Phase 1 or Phase 2, 400 series, concrete profile drawings that were issued to the contractor for construction and the cross-sections in the IBG Consulting Engineering three-dimensional model of the track. The IBG Drawing Review Notes included in Appendix C.5 describe the discrepancies that generally occur at the entrances and exits to the curved portions of the track. This appendix also includes a listing of the concrete profile drawings for the entire length of the track.

We have used the three-dimensional Autodesk AutoCAD model of the track from IBG Consulting Engineering to create the three dimensional as-designed surface of the track, but we have corrected the cross-sections in the model to be consistent with the WSC, Phase 1 or Phase 2, 400 series, concrete profile drawings. We have used the 0.5m stations to create the surface, but only cross-sections that were provided to the contractor for construction have been used for comparison reporting, typically at every 2.5 m.
4.3.3 Shrinkage and Temperature Effects

The position of the track in space is affected by concrete shrinkage and temperature. When the shotcrete track lost moisture by evaporation on drying after the initial set of the concrete, it shrank. Also, the track continually expands and contracts, respectively, between expansion joints as the temperature increases and decreases.

To ascertain the influence that shrinkage and temperature effects might have on the geometry of the as-built track, we have developed a simple stick structural model of the Curve C2 portion of the track between expansion joints. The structural model assumes that the track is restrained from movement at the fixed wall foundation (see Figures 4.3, 4.4, and 4.7) and restrained from movement in the transverse direction by the pendulum wall foundations adjacent to the expansion joints (see Figure 4.6).

Figure 4.21 shows a vector diagram of the movement of the Curve C2 portion of the track assuming shotcrete shrinkage of $300 \times 10^{-6}$ mm/mm and a temperature reduction of 25 °C from the time of construction to the current time when the track is in service in the winter. The combined longitudinal shrinkage and temperature movements of the track near the expansion joints are relatively large, but the transverse movements along the length of the track are relatively small.

It has been assumed that concrete shrinkage and temperature effects can be neglected. Nevertheless, shrinkage and temperature movements may influence the comparisons between the as-designed and as-constructed track geometry.
Figure 4.21 Vector diagram showing the shrinkage (S) and temperature (T) movements of the track at Curve C2.
4.3.4 Accuracy of As-Constructed to As-Design Track Surface Comparisons

When the point-cloud survey was undertaken, Terra Pacific Land Surveying Ltd. located the data in a local scan coordinate system. They indicate that [Terra Pacific (2011)]:

An independent control survey was completed by Terra Pacific prior to Epic Scan beginning their 3D scanning. This control survey set field points that would be required to orient the 3D scans to Terra Pacific’s local coordinate system. The survey was completed using the Topcon GPT3003 LW total station and TDS Recon with Survey Pro software to complete a closed loop of the 1.5km track. Using multiple sets of angles and distances, results were averaged and a horizontal misclosure of 8cm was obtained. Distributing the misclosure over the course of the traverse would give a plus or minus 3mm error for the horizontal coordinates of the control traverse. Using a Leica Sprinter 250 precise level and closing all loops to 5mm or better gave a plus or minus 2mm vertical error for the control points. The Topcon Hyperlite GPS was then used with three systems simultaneously to obtain coordinates that checked to within 5mm or better of the conventional survey. This was the base control survey that Epic Scan used to calculate the position of the scanner.

At the time of construction, Doug Bush Survey Services Ltd. installed a number of survey bench marks in the vicinity of the track in the same coordinate system that IBG Consulting Engineering used for design. The location of the track was set out from these bench marks. Representatives of the Whistler Sliding Centre had Doug Bush Survey Services Ltd. resurvey the bench marks this year. A drawing showing the Bush bench marks is contained in Appendix C.6. Figure 4.22 shows the resurveyed bench marks in relation to the as-designed track in the vicinity of Curve C2.
In June 2011 Terra Pacific was notified by the Project Manager that it would now be necessary to integrate Terra Pacific’s control survey with the control points set previously by Doug Bush. A return trip to Whistler on the 27th of June was necessary to find Bush’s control points which were then surveyed using multiple angles and distances. A least squares adjustment routine was used to calculate a best-fit between Bush’s data and Terra Pacific’s control points. The residuals on those points were 2cm or better. The elevation transformation was based on Doug Bush’s survey control point #967 which was held at 795.890m. The best fit produced results with differences in coordinates in the range of 3mm to 50mm.

As indicated in Table 4.1 below, there are a number of discrepancies between the two surveys. Terra Pacific Land Surveying Ltd. indicated that a tight survey up the Whistler Sliding Centre mountain side would be within 10 mm, but that a survey of this type could be out by 20 mm or more. In addition, the bench marks could easily have been disturbed between the initial Bush survey at the time of track construction and the resurvey this year.
Table 4.1 Coordinate comparison between surveys undertaken by Terra Pacific Land Survey Ltd. and Doug Bush Survey Service Ltd.

As indicated in Section 4.2.2 Track Construction, there are fixed wall foundations along the length of the track where movement is restrained in all directions. We have compared the as-designed position of the track surface with the as-constructed position determined from the Epic Scan data above the fixed wall foundations. Figure 4.23 shows two work points on the cross-section at Station Sx 160 m where comparisons are made for Curve C2. The as-designed and as-constructed concrete surfaces are relatively close in position to each other at these work points.
Figure 4.23 Comparison between as-designed and as-constructed work points for the track surface at Station Sx 160 m for Curve C2.
Table 4.2 below tabulates the differences between as-designed and as-constructed work points located at the fixed wall foundation locations along the length of the track. Work Point 1 is located on the surface of the curved wall 1500 mm above the point on the ground slab where the Profile Line (PL) intersects the top of concrete (see Drawing WSC 005). Work Point 2 is located where the Profile Line (PL) intersects the top of concrete at the ground slab.

<table>
<thead>
<tr>
<th>WSC Station Number</th>
<th>Work Point 1 Difference</th>
<th>Work Point 2 Difference</th>
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<td>Northing (m)</td>
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<td>0.005</td>
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<tr>
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</tr>
<tr>
<td>SX 1071.0 [CURVE C13]</td>
<td>0.003</td>
<td>0.057</td>
</tr>
<tr>
<td>SX 1143.0 [CURVE C14]</td>
<td>-0.002</td>
<td>0.019</td>
</tr>
<tr>
<td>SX 1214.5 [CURVE C15]</td>
<td>0.007</td>
<td>0.025</td>
</tr>
<tr>
<td>SX 1292.0 [CURVE C16]</td>
<td>-0.006</td>
<td>-0.002</td>
</tr>
<tr>
<td>SX 1349.0 [CURVE C16]</td>
<td>0.002</td>
<td>0.024</td>
</tr>
</tbody>
</table>

*Values represent position of as-built (scan) in relation to as-designed data.

Table 4.2 Work point comparison between the as-designed and as-constructed concrete surfaces at the locations of the fixed wall foundations.

The comparisons between the as-designed and as-constructed concrete surfaces in three-dimensions and cross-section in Appendix C.4 are influenced by the accuracy of the surveys.

It has been assumed that survey inaccuracies will not have a significant impact on the concrete/ice surface comparisons.
4.4 Deliverables

4.4.1 As-Constructed to As-Designed Track Surface Cross-Sectional Comparison

**General.** We have used the comparisons between the as-constructed and as-designed track surfaces at cross-sections in Appendix C.4 to estimate the vertical and horizontal offsets of the track at various locations along the length of the track. We have also used the comparisons to ascertain whether the as-constructed cross-section has the profile that was specified by the track designer at these locations, and whether the track surface is relatively smooth.

**Raw Data.** Table 4.3 summarizes typical comparisons for sections along the length of Curve C2. The second and third columns in the table tabulate the maximum and minimum deviations of the as-constructed track profile from the as-designed profile at the cross-section under consideration.

Columns four and five give, respectively, an indication of how much the as-constructed section is offset in the vertical and horizontal directions from the as-designed section. The direction of the horizontal offset (either left or right) is determined when the observer looks down the track.

The sixth column indicates whether there appears to be any anomalies in the scanned data for the as-constructed concrete surface. Stations listed as “Data inaccuracy” have deviation values that appear to lack accuracy. We have ignored the inaccurate deviations in ascertaining how much the as-constructed sections are offset from the as-designed.

The seventh column comments on the smoothness of the concrete surface, and indicates whether the as-constructed profile conforms to design. Stations listed as “Does not conform” have an as-constructed cross-sectional shape that does not match the as-designed shape.

Stations listed as “Rough” in the seventh column have an as-constructed surface finish that appears to deviate from the smooth as-designed surface at one or more locations as the observer moves around the perimeter of the cross-section. For the ground slab and walls, respectively, the as-constructed surface finish is “Rough” if the deviations are up and down, or left and right relative to the as-designed cross-section.

The final column indicates whether safety barriers have been installed in the field to extend the profile of the section.
Table 4.3 Comparison between the as-constructed and as-designed concrete surfaces at cross-sections along the length of the track for Curve C2.
At the bottom of Table 4.3 are presented for Curve C2 the number of stations where the as-constructed and as-designed concrete surfaces are compared, the range of offsets of the profile in the vertical direction, and the range of offsets in the horizontal direction. For a total of 37, 70 % and 24 % of the as-constructed cross-sections are up (higher) than the as-designed by 0 to 20 mm and 20 mm to 40 mm, respectively, and data are not available at 6 % of the stations. Note from the fourth column in Table 4.3 that the as-constructed track for Curve C2 is always higher than the as-designed.

Table 4.3 also indicates for Curve C2 that 11 %, 32 % and 3 % of the as-constructed cross-sections are to the left of the as-designed by 0 to 20 mm, 20 mm to 40 mm and 40 mm to 60 mm, respectively, and that 3 %, 30 % and 16 % are to the right by 0 to 20 mm, 20 mm to 40 mm and 40 mm to 60 mm, respectively. Horizontal profile deviation data are not available at 5 % of the stations. Note from the fifth column in Table 4.3 that the as-constructed track is offset to the left at the upper portion of Curve C2 and to the right at the lower portion.

Neglecting the stations where there are data inaccuracies (sixth column), data are unavailable (seventh column) or there are scan problems (seventh column), the seventh column in Table 4.3 indicates that cross-sectional shape does not conform to the as-designed for five of the stations (14 %). The as-constructed surface appears rough when compared to as-designed at eight stations (22 %).

Appendix C.4 contains similar comparison tables for the entire length of the track.

**Vertical Offsets.** Table 4.4 tabulates the ranges of the vertical offset of the as-constructed track from as-designed at various locations along the length. The tabulated information indicate that the track is generally constructed higher than design by up to 40 mm or more at the top (from the Bob Start to Curve C10) and lower than design by up to 60 mm at the bottom (from Curve C11 to Outrun 4).

A review of the tables in Appendix C.4 indicates that the vertical offsets transition relatively smoothly in magnitude and in the upward or downward direction from station to station along the length of the track. This indicates that unexpected bumps or dips are not built into the track.
The Bromley team have identified a "hump" in the track between the exit from Curve C12 and the entrance into Curve C13 that they are recommending be reduced in significance. From the data tabulated for Curve C12 between Stations Sx 963 m and Sx 1040 m and Curve C13 between Stations Sx 1040 m and Sx 1107 m (see Appendix C.5), it does not appear that there are large vertical offsets of the as-constructed track from as-designed in this region. This indicates that the “hump” is likely not related to the improper construction of the track, but was intended in the original design.

<table>
<thead>
<tr>
<th>Location</th>
<th>Number of Stations</th>
<th>Vertical Profile Deviation (%)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Up</td>
<td>0 to 20 (mm)</td>
<td>20 to 40 (mm)</td>
<td>40 to 60 (mm)</td>
<td>&gt; 60 (mm)</td>
<td>Down</td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Bob Start</td>
<td>33</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Men’s Start</td>
<td>22</td>
<td>36 54 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Curve C1</td>
<td>27</td>
<td>15 81 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Curve C2</td>
<td>37</td>
<td>70 24 6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ladies Start 1</td>
<td>11</td>
<td>9 82 6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ladies Start 2</td>
<td>5</td>
<td>20 60 20</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>30</td>
<td>70 30 30</td>
<td></td>
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<td></td>
</tr>
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<td>64 36</td>
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<td></td>
</tr>
<tr>
<td>Curve C5</td>
<td>25</td>
<td>4 96</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Junior Start 1</td>
<td>8</td>
<td>13 25 25 25</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Curve C6</td>
<td>42</td>
<td>5 93</td>
<td></td>
<td></td>
<td></td>
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<td>Junior Start 2</td>
<td>7</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Curve C7 (1 of 2)</td>
<td>29</td>
<td>52 41 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Curve C7 (2 of 2)</td>
<td>27</td>
<td>77 4 15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>21</td>
<td>85 10</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Curve C9</td>
<td>31</td>
<td>81 16</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>31</td>
<td>74 26</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Curve C11</td>
<td>47</td>
<td>28 4 64 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>100</td>
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<td></td>
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<td></td>
</tr>
<tr>
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<td>28 72</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Curve C14</td>
<td>31</td>
<td>13 77 10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Curve C15</td>
<td>33</td>
<td>6 94</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Curve C16 (1 of 2)</td>
<td>31</td>
<td>55 45</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Curve C16 (2 of 2)</td>
<td>27</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outrun 1</td>
<td>35</td>
<td>6 94</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outrun 2</td>
<td>34</td>
<td>3 23 65</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Outrun 3</td>
<td>35</td>
<td>83 11</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Outrun 4</td>
<td>29</td>
<td>10 83</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td>789</td>
<td>25 28 7 15 13 9 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.4 Percent of stations with vertical deviation of as-constructed profile in relation to as-designed profile within range
**Horizontal Offsets.** Table 4.5 tabulates the ranges of the horizontal offset of the as-constructed track from as-designed at various locations along the length. The tabulated information indicates that the track is generally constructed with offsets to the left or right of design of less than 60 mm, with some areas where the offsets are greater than this amount.

A review of the tables in Appendix C.4 indicates that the offsets occur relatively smoothly in the right or left directions along the length of the track. Column twelve in Table 4.5 indicates the direction of the as-constructed offset from as-designed along the length of the track.
<table>
<thead>
<tr>
<th>Location</th>
<th>Number of Stations</th>
<th>Horizontal Profile Deviation (%)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Left 0 to 20 (mm)</td>
<td>20 to 40 (mm)</td>
</tr>
<tr>
<td>Bob Start</td>
<td>33</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Men’s Start</td>
<td>22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Curve C1</td>
<td>27</td>
<td>7</td>
<td>19</td>
</tr>
<tr>
<td>Curve C2</td>
<td>37</td>
<td>11</td>
<td>32</td>
</tr>
<tr>
<td>Ladies Start 1</td>
<td>11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ladies Start 2</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Curve C3</td>
<td>30</td>
<td>47</td>
<td>10</td>
</tr>
<tr>
<td>Curve C4</td>
<td>39</td>
<td>25</td>
<td>23</td>
</tr>
<tr>
<td>Curve C5</td>
<td>25</td>
<td>4</td>
<td>76</td>
</tr>
<tr>
<td>Junior Start 1</td>
<td>8</td>
<td>38</td>
<td>37</td>
</tr>
<tr>
<td>Curve C6</td>
<td>42</td>
<td>5</td>
<td>16</td>
</tr>
<tr>
<td>Junior Start 2</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Curve C7 (1 of 2)</td>
<td>29</td>
<td>10</td>
<td>21</td>
</tr>
<tr>
<td>Curve C7 (2 of 2)</td>
<td>27</td>
<td>4</td>
<td>33</td>
</tr>
<tr>
<td>Curve C8</td>
<td>21</td>
<td>10</td>
<td>71</td>
</tr>
<tr>
<td>Curve C9</td>
<td>31</td>
<td>23</td>
<td>19</td>
</tr>
<tr>
<td>Curve C10</td>
<td>31</td>
<td>13</td>
<td>19</td>
</tr>
<tr>
<td>Curve C11</td>
<td>47</td>
<td>4</td>
<td>26</td>
</tr>
<tr>
<td>Curve C12</td>
<td>33</td>
<td>42</td>
<td>55</td>
</tr>
<tr>
<td>Curve C13</td>
<td>29</td>
<td>34</td>
<td>17</td>
</tr>
<tr>
<td>Curve C14</td>
<td>31</td>
<td>32</td>
<td>68</td>
</tr>
<tr>
<td>Curve C15</td>
<td>33</td>
<td>39</td>
<td>12</td>
</tr>
<tr>
<td>Curve C16 (1 of 2)</td>
<td>31</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Curve C16 (2 of 2)</td>
<td>27</td>
<td>7</td>
<td>15</td>
</tr>
<tr>
<td>Outrun 1</td>
<td>35</td>
<td>80</td>
<td>17</td>
</tr>
<tr>
<td>Outrun 2</td>
<td>34</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Outrun 3</td>
<td>35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outrun 4</td>
<td>29</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td>789</td>
<td>14</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 4.5 Percent of stations with horizontal deviation of as-constructed profile in relation to as-designed profile within range.
Cross-Sectional Shape. Table 4.6 indicates the percentage of stations along the length of the track where the as-constructed cross-sectional shape does not match the as-designed. In preparing this table from the data in Appendix C.4, stations are not included where there are data inaccuracies, data are unavailable or there are scan problems. The table indicates that the cross-sectional shape does not conform at a total of 9% of the stations along the length of the track.

Surface Roughness. Table 4.6 also tabulates the percentage of stations along the length of the track where the as-constructed surface appears rough. In preparing the table, stations are not included where there are data inaccuracies, data are unavailable or there are scan problems. The table indicates that the surface is rough at a total of 15% of the stations along the length of the track.

<table>
<thead>
<tr>
<th>Location</th>
<th>Number of Stations</th>
<th>Does Not Conform (%)</th>
<th>Rough (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bob Start</td>
<td>33</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Men's Start</td>
<td>22</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Curve C1</td>
<td>27</td>
<td>26</td>
<td>26</td>
</tr>
<tr>
<td>Curve C2</td>
<td>37</td>
<td>14</td>
<td>22</td>
</tr>
<tr>
<td>Ladies Start 1</td>
<td>11</td>
<td>36</td>
<td>9</td>
</tr>
<tr>
<td>Ladies Start 2</td>
<td>5</td>
<td>60</td>
<td>20</td>
</tr>
<tr>
<td>Curve C3</td>
<td>30</td>
<td>23</td>
<td>3</td>
</tr>
<tr>
<td>Curve C4</td>
<td>39</td>
<td>18</td>
<td>15</td>
</tr>
<tr>
<td>Curve C5</td>
<td>25</td>
<td>0</td>
<td>32</td>
</tr>
<tr>
<td>Junior Start 1</td>
<td>8</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>Curve C6</td>
<td>42</td>
<td>10</td>
<td>17</td>
</tr>
<tr>
<td>Junior Start 2</td>
<td>7</td>
<td>29</td>
<td>14</td>
</tr>
<tr>
<td>Curve C7 (1 of 2)</td>
<td>29</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>Curve C7 (2 of 2)</td>
<td>27</td>
<td>11</td>
<td>7</td>
</tr>
<tr>
<td>Curve C8</td>
<td>21</td>
<td>0</td>
<td>14</td>
</tr>
<tr>
<td>Curve C9</td>
<td>31</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>Curve C10</td>
<td>31</td>
<td>0</td>
<td>19</td>
</tr>
<tr>
<td>Curve C11</td>
<td>47</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Curve C12</td>
<td>33</td>
<td>24</td>
<td>18</td>
</tr>
<tr>
<td>Curve C13</td>
<td>29</td>
<td>21</td>
<td>17</td>
</tr>
<tr>
<td>Curve C14</td>
<td>31</td>
<td>16</td>
<td>26</td>
</tr>
<tr>
<td>Curve C15</td>
<td>33</td>
<td>9</td>
<td>39</td>
</tr>
<tr>
<td>Curve C16 (1 of 2)</td>
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<td>6</td>
<td>35</td>
</tr>
<tr>
<td>Curve C16 (2 of 2)</td>
<td>27</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Outrun 1</td>
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<td>20</td>
</tr>
<tr>
<td>Outrun 2</td>
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<td>9</td>
</tr>
<tr>
<td>Outrun 3</td>
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<td>11</td>
</tr>
<tr>
<td>Outrun 4</td>
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<td>0</td>
</tr>
<tr>
<td>TOTAL</td>
<td>789</td>
<td>9</td>
<td>15</td>
</tr>
</tbody>
</table>

Table 4.6 As-constructed concrete profile comparison to as-designed profile.
**Discussion.** As indicated in Section 4.2.3, the specifications for the project list acceptable tolerances for the finishing of the shotcrete track. The specifications do not appear to give acceptable tolerances for the conformance of the surface along the length of the track to the shape of the design cross-sections, or the track to the design alignment and profile.

Section 4.2.4 indicates that shotcrete construction is generally held to tolerance requirements that are less stringent than the requirements for cast-in-place construction. We have not been able to find any technical documentation that specifies acceptable tolerances for the shape of cross-sections or the alignment and profile of sliding centre tracks.

Given the tolerances that can be achieved for this type of construction on the side of a mountain, recognizing that the comparisons may be influenced by the accuracy of the surveys, concrete shrinkage and temperature movements, and noting that the alignment and profile are relatively smooth along the as-constructed track length, in our opinion the as-constructed geometry of the track generally meets expectations.

There may be areas of the track that require modifications so that sleds travel down on a smooth surface in a safe trajectory. Consideration should be given to modifying the surface of the concrete track at the stations where the tables in Appendix C.4 indicate the following:

- The as-constructed section is offset in the vertical or horizontal directions from the as-designed section by more than 40 mm (see columns four and five in the tables). For Curve C2 the horizontal offset is greater than this amount at Stations Sx 152.5, 172.5, 182.5, and 197.5 through 205 (Table 4.3).
- The as-constructed cross-section “Does not conform” to the as-designed shape (see column seven). For Curve C2 the cross-section “Does not conform” at Stations Sx 165 through 192.5 (Table 4.3).
- The as-constructed surface finish is described as “Rough” (see column seven). For Curve C2 the surface is “Rough” at Stations Sx 125, 127.5, 132.5, 137.5, 152.5, 157.5, 160 and 197.5 (Table 4.3).

Since they will be expensive, modifications to the as-constructed track should only be made where deemed necessary by a technical organization with expertise in the design of sliding tracks.

**Safety barriers.** The Bromley team has indicated that suitable safety barriers or retaining walls are required in locations along the length of the track where there is no control on the free flowing path of a sled. They indicate that safety barriers are required at number of locations (see Trajectory Study, section 6.7).

The comparison tables in Appendix C.4 indicate that safety barriers have been installed at many locations along the track. However, additional safety barriers should be installed at the locations noted in the Trajectory Study, section 6.7.

The Bromely study does not indicate the size and extent of safety barriers needed as their mathematical model does not predict post impact trajectories.
4.4.2 As-Constructed to As-Designed Track Surface Differential Color Mapping

Appendix C.4 also contains three-dimensional visualizations that provide an indication of the deviations of the as-constructed and the as-design surfaces along the length of the track. This allows the reader to take a virtual walk down the track to ascertain whether the concrete surface is relatively smooth and to get an indication of whether the shape conforms to design.

Figure 4.24 shows snapshot views of the track from the three-dimensional visualization of the track in the vicinity of Curve C2.

Figure 4.24 Views of the three-dimensional deviations between the as-constructed and as-designed track surfaces in the vicinity of Curve C2.
4.4.3 Best Fit As-Constructed to As-Designed Track Surface Cross-Sectional Comparison

In reviewing the comparisons between the as-constructed and as-designed surfaces in Section 4.4.1, it was initially thought that an unwanted shift in the scan coordinate system relative to the project coordinate system might be affecting the measurement results. Epic Scan has completed an additional comparison between the as-constructed and as-designed track surfaces using a "best fit" analysis.

In this analysis, the entire as-constructed track in the scan coordinate system is shifted relative to the as-designed track in the project coordinate system with the objective of minimizing the deviations between the two surfaces. Appendix C.7 contains the best fit comparisons between the track surfaces.

The comparisons in Appendix C.7 indicate that the as-constructed surface appears to be further away from the as-designed track surface in the regions of Curves C2 and C3 for the best fit. However, the deviations appear to be less in other areas of the track.

Table 4.7 compares the average deviations for the various regions of the track. This table indicates that on average the as-constructed to as-designed track surface deviations are less for the unmodified (original) Epic Scan data than for the best fit data.

A computer software generated best fit analysis does not improve the alignment between the two coordinate systems. The average deviations between the as-constructed and as-designed track surfaces did not reduce with the best fit analysis (Table 4.7). Consequently, we have not used the best fit results for comparing the deviations between the as-constructed and as-designed track surfaces in this report.
Table 4.7 Comparison of the track surface deviations for the unmodified (original) and "best fit" Epic Scan data.

4.5 Comments and Recommendations

From consideration of our review of the track design drawings and specifications, the accuracy of field surveys, construction tolerances, deviation comparisons between the as-constructed and as-designed concrete, we have the following comments and recommendations:

Document Management  The design of the track by IBG Consulting Engineering evolved over a period of time, with technical reports describing the project and drawings showing the track geometry being issued at various stages of completeness. Representatives of the Whistler Sliding Centre should assemble the most current IBG Consulting Engineering documentation for the track, and archive the remaining reports and drawings.
Drawings and specifications for the track and related facilities were prepared and issued for construction by Stantec Architecture Ltd. This documentation was revised by several addenda during the tender period. Representatives of the Whistler Sliding Centre should assemble the most current Stantec Architecture Ltd. drawings and specifications for the track and related facilities, and archive the remaining documentation.

**As-Constructed to As-Designed Track Surface Cross-Sectional Comparison**

Given the tolerances that can be achieved for this type construction on the side of a mountain, in our opinion the as-constructed geometry of the Whistler Sliding Centre track generally meets expectations.

Measurements indicate that, although there are offsets of the as-constructed track in the vertical and horizontal directions from the as-designed track, the alignment and profile is relatively smooth along the length of the track. Except at the location noted below, the Bromley team has not identified areas of the track where sudden changes in the profile or alignment will adversely affect sleds travelling down the track.

Although measurements indicate that the concrete surface is rough in certain locations, the proper placement and maintenance of the ice surface on the track during the operating season can mitigate the adverse affects of the rough concrete surface.

There may be areas of the track that require modifications so that sleds travel down on a smooth surface in a safe trajectory. Consideration should be given to modifying the surface of the concrete track at the stations where the tables in Appendix C.4 indicate the following:

- The as-constructed section is offset in the vertical or horizontal directions from the as-designed section by more than 40 mm (see columns four and five in the tables).
- The as-constructed cross-section “Does not conform” to the as-designed shape (see column seven).
- The as-constructed surface finish is described as “Rough” (see column seven).

Consideration should be given to reducing the significance of the "hump" in the track identified by the Bromley team between the exit from Curve C12 and the entrance to Curve C13.

If the track must be ground to make the surface smoother, we recommend that no more than 5 mm of shotcrete be removed. If more than this amount is removed, the concrete cover over the reinforcing steel and refrigeration pipes will be too small and the long-term durability of the track will be compromised. If the thickness of the walls or ground slab of the track must be increased in localized areas, then the existing shotcrete must be carefully chipped away and new concrete added in much the same way as for the partial and full depth repair of deteriorated bridge decks. Great care will need to be taken to avoid damaging the reinforcing steel and refrigeration pipes if partial or full depth repairs are undertaken.
We were not able to find anything in the project documentation indicating that as-built measurements of the track surface were made, or that the original track designer signed off on the as-built geometry. Our view is that the track designer for sliding facilities needs to confirm that the as-constructed track generally conforms to the design intent. We recommend that IBG Consulting Engineering review the measurements of the as-constructed track surface recorded in this report to confirm that the construction meets the design intent.

If required by IBG Consulting Engineering, it will be to the advantage of the Whistler Sliding Centre to have the contract documents for any modifications to the geometry of the track prepared by the original track designer. The original designer or their local affiliate should follow through with field review to ascertain that any modifications generally conform to the design intent.

**Safety barriers** The International Bobsleigh and Tobogganing Federation (FIBT) and the International Luge Federation (FIL), along with the operators, take on the responsibility for improving the safety of tracks by adding safety barriers in response to conditions that occur during the use of the sliding facilities. The requirements for safety barriers evolve and change over time in response to such things as variable sliding conditions, new sled designs and incidents that have occurred on tracks.

We are of the opinion that the Federations should develop designs for standard safety barrier systems for installation at corners and locations along tracks where there is no control on the free flowing path of a sled. This approach is similar to that taken when specifying safety barriers for highways in Canada [CSA (2006)]. The standard safety barrier designs should be developed from consideration of such things as:

- Incidents that have occurred.
- Marks from sleds travelling across the existing safety barriers on tracks.
- Crash testing.
- Trajectory modeling.
- Structural analysis and design.

The safety barriers should start at appropriate distances before and after, respectively, the start and end of the curves.

The results of the Bromely trajectory study indicate that properly operated sleds at the WSC track will stay on the ice-covered concrete surface of the track. However, there is evidence that sleds have travelled across the safety barriers installed along the track.

The adequacy of the existing safety barriers along the length of the Whistler track should be addressed. As a minimum, consideration should be given to adding safety barriers at the exit from Curve C14/entry to Curve C15.

The operators of the Whistler track, under the direction of the Federations, should install the standard safety barrier system at all corners and locations along the length of the track where there is no control on the free flowing path of a sled.
4.6 REFERENCES

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CHAPTER 5 - RETROSPECTIVE TRAUMA STUDY

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# TABLE OF CONTENTS

## CHAPTER 5 - RETROSPECTIVE TRAUMA STUDY

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1</td>
<td>Lead Investigators</td>
<td>145</td>
</tr>
<tr>
<td>5.2</td>
<td>Observations and Recommendations Summary</td>
<td>146</td>
</tr>
<tr>
<td>5.2.1</td>
<td>Observations</td>
<td>146</td>
</tr>
<tr>
<td>5.2.2</td>
<td>Recommendations</td>
<td>149</td>
</tr>
<tr>
<td>5.3</td>
<td>Timeline to Date</td>
<td>150</td>
</tr>
<tr>
<td>5.4</td>
<td>Project Deliverables</td>
<td>151</td>
</tr>
<tr>
<td>5.5</td>
<td>Methodology</td>
<td>152</td>
</tr>
<tr>
<td>5.5.1</td>
<td>Run Sheet Database</td>
<td>152</td>
</tr>
<tr>
<td>5.5.2</td>
<td>Incident Database</td>
<td>153</td>
</tr>
<tr>
<td>5.5.3</td>
<td>Medical Record and AIS Database</td>
<td>154</td>
</tr>
<tr>
<td>5.5.4</td>
<td>Detailed Injury Analysis</td>
<td>156</td>
</tr>
<tr>
<td>5.5.5</td>
<td>Assumptions</td>
<td>157</td>
</tr>
<tr>
<td>5.6</td>
<td>Data Summaries and Analysis</td>
<td>159</td>
</tr>
<tr>
<td>5.6.1</td>
<td>Medical record review</td>
<td>159</td>
</tr>
<tr>
<td>5.6.2</td>
<td>Crash by Gender</td>
<td>159</td>
</tr>
<tr>
<td>5.6.3</td>
<td>Crash by Start Location</td>
<td>160</td>
</tr>
<tr>
<td>5.6.4</td>
<td>Crash/Injury by Experience</td>
<td>163</td>
</tr>
<tr>
<td>5.6.5</td>
<td>Public vs. Athlete</td>
<td>166</td>
</tr>
<tr>
<td>5.6.6</td>
<td>Crash/Injury Frequency by Location</td>
<td>167</td>
</tr>
<tr>
<td>5.6.7</td>
<td>Injury Type</td>
<td>171</td>
</tr>
<tr>
<td>5.6.8</td>
<td>Detailed Injury Analysis</td>
<td>172</td>
</tr>
<tr>
<td>5.6.9</td>
<td>Helmets Used in Sliding Sports</td>
<td>180</td>
</tr>
<tr>
<td>5.7</td>
<td>Issues Encountered</td>
<td>181</td>
</tr>
<tr>
<td>5.8</td>
<td>Recommendations</td>
<td>183</td>
</tr>
<tr>
<td>5.9</td>
<td>Bibliography</td>
<td>184</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

Figure 5.1: Number of male incidents (LEFT) and female incidents (RIGHT) versus discipline................................................................. 160
Figure 5.2: The percent of crashes at each start location................................. 161
Figure 5.3: The percent of crashes at each start location on the Track for Men's luge. ................................................................................................................... 162
Figure 5.4: Men's Luge Injury Severity for Different Start Positions .................. 162
Figure 5.5: Overall experience of sliders on the track ..................................... 163
Figure 5.6: Effect of experience on injury rate as a function of the sliders' cumulative experience ................................................................. 164
Figure 5.7: Effect of experience on injury rate as a function of the sliders' cumulative experience ................................................................. 165
Figure 5.8: Injury severity compared to slider experience for incidents with clinical documentation ................................................................. 165
Figure 5.9: Track usage broken down by runs by athletes and runs by public sliders. 166
Figure 5.10: Overall percent of crashes normalized by total runs by athlete sliders and public sliders ................................................................. 166
Figure 5.11: Incident frequency by corner location on the Track for all disciplines..... 167
Figure 5.12: Injury severity and frequency based on track location ...................... 168
Figure 5.13: Incident and injury summary for each corner on the track. Circle size represents frequency ................................................................. 170
Figure 5.14: Injury severity summary for each corner on the track ...................... 170
Figure 5.15: Injury type as determined through medical documentation provided by the WHCC and VANOC WPC ................................................................. 171
Figure 5.16: Injury type as documented through the Incident Database .............. 171
Figure 5.17: Video still frames overlaid to illustrate entrance and exit angles as well as the line of reference. (ref. C16) ................................................................. 173
Figure 5.18: Vector summation to produce the Delta V vector ............................ 173
Figure 5.19: Bromley simulation of a single luge with no steering input interacting with the wall at the exit of turn 16 ................................................................. 174
Figure 5.20: Bromley simulation of Nodar Kumaritashvili trajectory through curve 16. 175
Figure 5.21: Bromley simulation of Nodar Kumaritashvili trajectory through the exit of curve 16 ........................................................................................................... 175
Figure 5.22: Comparison of C16 exit kinematics for athletes N Yakushenko and N Kumaritashvili competing approximately a year apart ............................ 178
Figure 5.23: Modifications to the protective barrier/wall (red arrow) at the exit of turn 16. ................................................................................................. 179
Figure 5.24: Proportion of incidents documented with an incident report .......... 182
5.1 Lead Investigators

**Dr. Peter Cripton**

Dr. Peter Cripton is an Associate Professor and holds the Patrick Campbell Chair in Design in the Department of Mechanical Engineering at the University of British Columbia. He is also the Co-Director of the Orthopaedic and Injury Biomechanics Group. Dr. Cripton’s research interests are primarily focused on prevention, rather than treatment: an injury that never happens, as he points out, needs no repair or therapy. To this end, he works on spine, hip, impact and spinal implant biomechanics, all focused on either preventing injury or minimizing it as it happens. He also works a great deal with geriatric and pediatric models, looking at ways of preventing injury to very old and very young people. He and his team are developing improved mechanical models of spines for crash test dummies and other injury testing, and are using advanced magnetic resonance imaging (MRI) techniques to better understand spinal cord injury. He is also working with the US Department of Defense on setting safe transfer limits for medical evacuations and with the Whistler Sliding Centre on understanding and preventing injuries to athletes using that facility.

**Mr. Darrin Richards**

Mr. Richards is the President of Synaptic Analysis Consulting Group, Inc., a Vancouver company that specializes in accident reconstruction and injury biomechanics. He has degrees in Mathematics, Mechanical Engineering, Bioengineering, and is a registered Professional Engineer in both Canada and the United States. Mr. Richards has spent the last 15 years of his career investigating, analyzing, and conducting tests to study incidents involving human injury.

Mr. Richards’ work has included the investigation and reconstruction of automobile, bicycle, motorcycle, skiing, snowboarding, snow tubing, bobsledding, construction site, and sport accidents. He has used computational models and has run hundreds of crash tests with anthropomorphic test devices (ATDs) to evaluate injury.

Mr. Richards’ research has primarily focused on accident dynamics, injury biomechanics, helmet safety, and restraint systems. Results from Mr. Richards’ research have been published in peer-reviewed journals and presented at national and international conferences. He has received awards from the International Society for Skiing Safety (ISSS) for his work on head injuries in snowboarding and from the Society of Automotive Engineers (SAE) for his work on occupant kinematics in rollover accidents.
5.2 Observations and Recommendations Summary

5.2.1 Observations

This study analyzed runs from the Whistler Sliding Centre from track inception to March of 2011 for which documentation was available. In all, over 43,200 runs were compiled and analyzed. Data was recorded in the form of approximately 1600 Run Sheets in which each page contained details from multiple runs on a given day. In addition, track incidents were recorded by 327 Control Tower Logs and 111 Accident Reports, as well numerous sliding logs, injury registration documents, patient care and medical encounter forms, and 11 videos. Medical records pertaining to 46 incidents were also obtained from the Whistler Health Care Centre and VANOC Whistler Polyclinic. From this information, three databases were constructed:

(i) Run Sheet Database – documents all runs on the track.
(ii) Incident Database – documents incidents and crashes.
(iii) Medical Record and AIS Database – documents severity for incidents with clinical documentation

Overall, incidents occurred in less than 1.7 % of the runs on the track based on Run Sheet data. Accident Reports, Control Tower Logs or similar, were completed for less than 1.1 % of all sliders on the track. However, when the analysis is limited to incidents in which an injury (minor and/or major as opposed to an incident or crash which may not have caused an injury) was documented, the risk was reduced to less than 0.5 %. When the analysis is limited to cases where the slider was sent or referred to clinic, generally an indication of a more severe injury, the risk was reduced to less than 0.2 %. This injury severity was quantified for 46 of the 62 incidents sent or referred to clinic and the risk of obtaining an abbreviated injury scale (AIS) injury of 2 (moderate injury) or greater is further reduced to less than 0.1%.

The highest rate of track incidents, based on start location, was 3.0 % and occurred when sliders started from the Lady Start 2, often termed Lower Ladies. Next was Lady Start 1 and Men’s Luge Start which resulted in 2.8 and 2.7 %, respectively, of the sliders experiencing a track incident. It is also noteworthy that less than 0.5 % of the starts from Tourist start resulted in incidents.

The majority of the incidents on the track occurred on the lower portion of the track. Both the Run Sheet Database and database compiled from incident reports demonstrate that 75% or more of the incidents took place in corner 13 or lower.

Analysis of the run sheet data demonstrates that over 94% of the runs on the track were performed by athletes. Public sliders to date represent less than 6% of the total number of sliders. Of the athlete sliders, 1.7% [700/40623=1.7%] were involved in incidents, whereas only 0.4% [10/2547=0.4%] of the public sliders were involved in incidents.

The vast majority of sliders (more than 75% of all sliders) slid on the track between 1 and 9 times. Less than 5% of the sliders have slid on the track more than 70 times with less than 20 sliders ever using the track more than 300 times. We analysed the number of crashes that resulted in an athlete being referred to the clinic and noted an interplay between risks associated with increasing exposure and the expected benefit of
increasing experience: the crash rate generally first increased with exposure and then decreased likely reflecting a benefit of experience.

After February 12, 2010, the date of Mr. Kumaritashvili’s fatal crash, Men’s Luge Start was no longer used. In order to analyze the effect this had on the rate of incidents, a deeper analysis was undertaken which was limited to Men’s Luge in order to eliminate any confounding effects of gender and different sleds. A comparison of the incident rate from the upper three starts on the track combined (Men’s Luge, Lady Start 1, and Lady Start 2) pre- and post-Feb. 12, 2010 revealed a decrease in the rate of incidents from 3.0 % to 1.0 %. Although this drop was statistically significant, an analysis which was limited to Lady Start 1 and Lady Start 2 showed an even more dramatic drop from 3.3 % to 1.0 % indicating that factors (such as ice conditions, track profile, experience or weather) other than start position likely played a significant role in the decreased incident rate.

When the overall data for Men’s Luge was examined and not stratified by date, a comparison of the incident rate from Men’s Start to the incident rate from Lady Start 1 and Lady Start 2 combined only resulted in a small decrease in the number of incidents from 2.8 % to 2.5 %, and this difference was not statistically significant.

Kinematic analysis of specific incidents was undertaken, but was limited by video quality and poor camera angles. The dynamic model created by Bromley can be used to analyze the trajectory of a sled prior to impact, but because of model limitations cannot be used to analyze the collision dynamics of a crash.

In order to measure severity of injuries occurring in track incidents, medical documentation was obtained from the Whistler Health Care Centre (WHCC) and the VANOC Whistler Polyclinic (VANOC WPC). Using the AIS and Injury Severity Score (ISS), documented injuries were classified. The Maximum Abbreviated Injury Score (MAIS) was used as a representation of crash severity. We obtained medical records for 74% of the incidents sent or referred to the clinic and found 52.2% of these to be classified as MAIS 1 injuries, 43.5% to be MAIS 2 and the remaining 4.3% to be unclassified because of a lack of detailed information or diagnoses in the medical records.

The medical records provided by the WHCC and VANOC WPC allowed our team to identify all injuries for individuals treated at the clinics, quantify severity for each injury using the AIS and ISS, and identify trends for injury severity based on crash location, injury type, discipline, slider experience and start location. Four incidents in particular were identified in our severity analysis as noteworthy due to their mechanism of injury. These include a Bobsled rollover in corner 16 which a slider impacted the track side wall with his head, resulting in a suspected spinal injury, a luge incident in which the slider “caught” their leg resulting in a dislocation, a bobsled incident in which the slider hit their face on the sled and sustained a facial laceration, and a luge accident in which the slider was ejected from the track, resulting in fatality. Our procedures for analyzing the medical records place a paramount importance on patient confidentiality and we performed the medical record analysis with the approval of the UBC Clinical Research Ethics Board and the Vancouver Coastal Health Privacy office (UBC CREB Number H11-02121; Vancouver Coastal Health Research Study # V11-02121).
Of the clinically documented injuries, the most common were abrasions/lacerations/contusions, representing 52%. Strain/sprain/tear injuries and concussion/head injuries were the next most prevalent representing 15.7% and 14.7% respectively. Fractures and miscellaneous injuries represented 9.8% and 7.8% respectively.

All documents, including videos, were reviewed for the potential of track ejection. A video from the pre-February 12, 2010 time period showed potential for ejection/partial ejection from the track at the exit of curve 16. The detailed analysis illustrates the importance of proper barriers and the extreme potential for injury when ejection occurs. The analysis of the partial ejection demonstrated the potential for a full ejection and illustrates the importance of reviewing all track incidents, in an on-going and detailed fashion, to identify incidents with the potential for ejection and to take immediate steps to mitigate this potential.
5.2.2 Recommendations

Our retrospective trauma study draws attention to the importance of good record keeping. WSC has an extensive database of accidents, which was invaluable to this study. However, many deficiencies and shortcomings in the records were observed during the analysis and this has placed some limitations on our findings. It is recommended that WSC develop a protocol to ensure the collection of important parameters, such as name, start location, crash location, description of injury, and other fields that we have discussed in this document. It is recommended that the record keeping be done in an automated fashion perhaps with a computer or tablet computer interface. One such way would be to develop a database program that would systematically log data and would allow for statistics to be automatically compiled at any time. This approach could perhaps be extended to include specific fields that could be populated on sport specific emergency department triage forms that physicians could fill out.

Many discrepancies were observed between the Control Tower Logs and Accident Reports. In order to eliminate these errors it is recommended that there should be communication between the control tower and the first responders after each incident so that parameters such as the accident location and cause of accident can be agreed upon. The communication can be as simple as a radio discussion or an in person meeting. The goal is to eliminate errors before they are input to the database.

It is recommended that WSC continually review crashes, incidents and injuries that occur on the track. Past incidents can provide invaluable information about potential future crashes. Furthermore, once a database is up and running it is recommended that the accident trends and statistics be continually monitored to identify and mitigate any potential for track ejections or high speed impacts.

An in depth retrospective study was undertaken for this project. It is suggested that a future prospective analysis of track accidents would provide additional insight. It is recommended that modelling of potential crash events be undertaken to examine “what if scenarios”. Utilizing trajectory outputs of interest from the Bromley model as an input to a mathematical model of the human body could provide invaluable insight into the potential for injury and the effect of potential safety measures.

Because of the high risk of fatal or catastrophic injury associated with athlete ejection, our strongest recommendation is that all plausible attempts be made at the WSC to continually evaluate the track configuration and the outcomes of crashes as they occur. Regular review of all crashes on the track (perhaps on a daily basis) is recommended with a specific focus on identifying potential ejections. When a potential ejection is identified it should be a priority to take action to eliminate the potential for ejection before sliding resumes. There are likely many ways to prevent track ejections and it is beyond the scope of our study to investigate or recommend any detailed methods to accomplish this. The results of our analyses clearly indicate the need to take all plausible measures to prevent athlete ejection and to remain vigilant on this front.
5.3 Timeline to Date

Phase 1:

<table>
<thead>
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<td>Data Collection at Whistler Sliding Centre</td>
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<tr>
<td>Week 2</td>
<td>Data Processing/Review of incident reports</td>
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<tr>
<td>Week 3-7</td>
<td>Tabulate all incident data from track for all disciplines of sliding</td>
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<tr>
<td>Week 8-14</td>
<td>Analysis of injuries and mechanisms of injuries from tabulated data. Prepare and submit midterm report to Whistler. Meetings to obtain detailed medical records and prepare ethics protocol for same.</td>
<td>COMPLETE</td>
</tr>
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<td>Week 15-20</td>
<td>Continue to perform detailed analysis of injuries and mechanisms of injuries / Break down injuries by location, severity, discipline and athlete experience. Use this data to identify specific injuries of specific interest. Revisit track if necessary to assess injury biomechanical analysis. Work with Bromley to obtain speed and acceleration information to assist in analysis.</td>
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<td>Week 21-24</td>
<td>Plot of raw and normalized (to total # runs) incident frequency and severity for each section of the track for each sliding sport.</td>
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<td>Tabulate preliminary results and report preliminary opinions to Whistler</td>
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<td>Week 25-30</td>
<td>Generate summary tables / Technical review of biomechanical injury analysis / Refine analyses where necessary / Outline Report</td>
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<td>Week 30-32</td>
<td>Generate report / Technical review of report.</td>
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</tbody>
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Phase 2:

<table>
<thead>
<tr>
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<tr>
<td>Week 48</td>
<td>Obtain medical records from Whistler Health Care Centre and VANOC Whistler Polyclinic</td>
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<td>Week 49</td>
<td>Redact all names and dates from medical records (record custodian only)</td>
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<tr>
<td>Week 49-59</td>
<td>Analysis and severity scoring of medical records</td>
<td>COMPLETE</td>
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<td>Week 60-61</td>
<td>Generate final report / Technical review of final report</td>
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<td>Week 62</td>
<td>Submit Final Report</td>
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5.4 Project Deliverables

The objective of our study is to perform retrospective biomechanical analysis of the previous reported injurious or potentially injurious events on the WSC track. We are using the principles of injury biomechanics [6,8] to identify the injury mechanisms associated with these events. The overarching objective is to identify any section-specific or discipline specific trends in injury location or severity that would indicate changes to the track or training procedures that would be appropriate to prevent incidents or injuries in future.

This report summarizes, discusses and interprets the relevance of the past track incidents. In the report, (i) luge, (ii) skeleton, and (iii) bobsled are individually investigated. The spectrum and severity of injuries that have been sustained during historical incident events at various locations on the track are also investigated. A plot of incident frequency and severity for each section of the track has been generated to help identify any critical sections of the track for detailed analysis. The report also discusses the effect of the various start positions, gender, experience, discipline and the effects of protective barriers or walls on the risk of injury. Particular injury mechanisms and helmet efficacy are identified and discussed.
5.5 Methodology

5.5.1 Run Sheet Database

5.5.1.1 Database Construction

The Run Sheet Database is comprised of data collected from approximately 1600 run sheets provided by the Whistler Sliding Centre. A database template was created with fields that included:

- Date
- Session reference
- Sport
- Discipline
- Name
- Partners name(s)
- Gender
- Athlete/public
- Start location
- Speed
- Start time
- Finish time
- Crash (Y/N)
- Crash details/location
- Number of runs for that individual for that session
- Comments
- Page number

These details were entered for every run down the track as the run sheet data allowed. When all of the data was entered, several days were spent cleaning the data to ensure quality and eliminate as many discrepancies as possible (some general assumptions were made which are discussed in the assumptions portion of this report). To allow for ease in referencing the original run sheet documents, each sheet was scanned and correlated to each database entry by page number.

5.5.1.2 Database Analysis

This database was interrogated to generate statistics of interest and was compared to the control tower records and Incident Database in order to identify trends. Start location was correlated to crash location to identify any particular locations that led to higher incident frequency. This database was used to generate statistics pertaining to gender, athlete vs. public sliders, and slider experience.
5.5.2 Incident Database

5.5.2.1 Database Construction

In order to create the Incident Database, a protocol was developed to ensure consistency in recording each event. This database included the following fields:

- Discipline
- Date
- Session reference
- Name(s)
- Location
- Injured (y/n)
- Description of injury
- Age
- Gender
- Weight
- Height
- Injury Description
- Injury Categorization

The relevant data was compiled using Control Tower Logs, Accident Reports, Injury Registration Documents, Medical Encounter Forms, Patient Care Forms, Sliding Logs, videos and all other supporting documentation. Any slide for which a report was filled out was entered into the Incident Database. Some reports were for relatively minor incidents where sliders did not actually come off of their sled and/or injuries were considered to be minor in nature. Other incidents consisted of serious crashes in which the sliders came off their sled and sustained more severe injuries. One goal of this database was to identify locations on the track where incidents are especially prevalent, thus each event was entered only once regardless of the number of athletes injured (in the case of the disciplines with multiple riders on each sled). However, the database does include the names of all sliding partners listed in the mentioned supporting documentation. The database only includes crashes/injuries that occurred on the track during a training or competition run (athlete or public). Injuries sustained walking the track, sliding back down the outrun or in the start or finish areas were not included in this analysis.

To document each incident location, a specific procedure was followed to ensure consistency. As was allowed by the records, the incident was recorded as occurring in the entrance of the turn, middle of the turn, or exit of the turn. In the case where an incident occurred between two turns, the entrance to the succeeding turn was used. When a contradiction in the reported site was encountered, the Control Tower Log was taken to be the most accurate documentation. This was due to the fact that the control

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2 This protocol was developed due to discrepancy in reporting two incidents that occurred at the track entrance of the women's start ramp. As the ramp enters the track between corners two and three, the location was entered as the entrance to corner 3.
tower personnel reporting the crash would have the ability to view and play back the incident on the closed circuit television. In the absence of the Control Tower Log or in the event that there were multiple different locations recorded in the various records, the earliest track location was used. This was based on the assumption that the highest recorded position likely corresponded to the first sighting of the crash/injury by any of the people recording the incident. When a crash or injury occurs, the event generally propagates down track. It was the goal of this database to document the location of the initial incident. However, the location data was specific to the crash/injury and did not document the location where the athlete made a mistake or any event that may have preceded the incident. In the cases where video evidence was available this was also used to determine crash location.

5.5.2.2 Database Analysis

The Incident Database was interrogated to analyze the crash location, the effect of start position, severity of injuries (as determined by referral to clinic), and the types of injuries sustained by sliders. To evaluate injury data, each incident documented was first categorized on a binary scale (yes/no) to indicate whether the athlete(s) sustained an injury. The injuries were further classified by location and type. These categories included head, neck, back, torso, and extremity. Injuries were also categorized as concussion, fracture, contusion, laceration, and abrasion based on the track documentation (further injury analysis is discussed in the Medical Record and AIS Database section of this report). It was also noted whether the injured slider(s) was sent or referred to clinic and this was used as an initial measure of injury severity. The absence of detailed track medical records (except the records obtained from the WHCC and WPc) in some cases means that there was no medical confirmation that the injury recorded or suspected by the first responder had, in truth, been sustained. In some cases sliders were referred to a clinic but instead, presumably, presented at alternative treatment providers, were seen by team physicians or did not seek medical treatment beyond that provided by the trackside first responder.

This database was also used to identify gender specific trends in sliding sports with both male and female participation (2 man bobsled, single luge and skeleton).

5.5.3 Medical Record and AIS Database

5.5.3.1 Database Construction

In order to create the Medical Record and AIS Database, a protocol was developed to ensure consistency in recording each event. We coded injuries according to the Abbreviated Injury Scale (AIS) and the Injury Severity Score (ISS).

The AIS is an anatomically-based, consensus-derived global injury severity scoring system developed and administered by the Association for the Advancement of Automotive Medicine (AAAM). The AIS classifies each injury by body region according to its relative importance on a 6-point ordinal scale (1=minor, 2=moderate, 3=serious, up to 6=maximal). In some cases where there was insufficient information to assign a severity to an injury, the AIS scale classifies injuries as 9 which allows tracking of
trauma by body region but without assignment of severity. AIS is the basis for the Injury Severity Score (ISS) calculation for patients with multiple injuries. The term MAIS refers to the Maximum Abbreviated Injury Score (MAIS) taken by selecting the highest AIS injury (i.e.: most severe) for a particular patient with multiple injuries. For example, if an individual had an AIS 1 injury to the foot and an AIS 3 injury to the shoulder the MAIS would be 3.

The AIS provides standardized terminology and ranks of injury severity. Current AIS users include health organizations, motor vehicle crash investigators, and researchers for epidemiological studies.

The Injury Severity Score (ISS) is an anatomical scoring system that provides an overall score for patients with multiple injuries. Each injury is assigned an AIS score and is categorized into one of six body regions (Head, Face, Chest, Abdomen, Extremities (including Pelvis), and External). The highest AIS score in each body region is used for the ISS calculation. The highest AIS severity code in each of the three most severely injured ISS body regions is squared and added together to calculate the ISS score. For example, if an individual had an AIS 1 injury to the hand, an AIS 3 injury to the head, an AIS 2 injury to the chest and an AIS 2 injury to the arm, the ISS score would be 17 \((3x3)+(2x2)+(2x2)\).

This database included the following fields:

- Redacted Injury Narrative
- AIS [Head]
- AIS [Face]
- AIS [Chest]
- AIS [Abdominal or Pelvis Contents]
- AIS [Extremities or Pelvis Girdle]
- AIS [External]
- MAIS
- ISS

The relevant data was compiled using medical documents provided by the Whistler Health Care Clinic (WHCC) and the VANOC Whistler Polyclinic (VANOC WPc). In order to maintain patient confidentiality, a protocol was developed to ensure only injury relevant information was extracted from the medical records and this received approval from the Clinical Research Ethics Board at UBC and from the privacy office of Vancouver Coastal Health [UBC CREB Number: H11-02121; Vancouver Coastal Health Authority Research Study #: V11-02121]. A study custodian was assigned to be the only person with access to the patient’s records. This custodian assigned a randomized study ID to each record and removed all personal and date information associated with the patient. The redacted records were then given to the research team to investigate each of the records and to assign an AIS score for each injury sustained, as well as a MAIS score and an ISS score for each incident. Once the research team had reviewed each score, the medical records were then returned to the custodian and the severity scores were linked back to the incident and run sheet databases.
5.5.3.2 **Database Analysis**

The Medical Record and AIS Database was developed to allow investigation of injury severity compared to slider experience, discipline, start location, crash location, and injury type. Injury type was categorized in one of the following categories: head/concussion, abrasion/laceration/contusion, fracture, sprain/strain/tear, and miscellaneous. Similar to the previous databases, each incident was represented as opposed to each slider. In some cases more than one slider was injured in the same incident and in these cases the MAIS and ISS values were taken as the maximum among all of the sliders scores, from the single sled, involved in the incident.

In order to quantify injury severity, the AIS was used initially and further scored using the MAIS, and the ISS. In all cases, no inferences were made and each injury was coded strictly based on the diagnosis from a medical doctor. As the AIS is very specific, when the medical records were vague, a strict approach in accordance with the AIS was taken. Issues encountered in this analysis involved indistinguishable writing, uncertain diagnoses, and inconsistent diagnoses between medical professionals (section 5.0 elaborates on these issues).

5.5.4 **Detailed Injury Analysis**

Specific incidents were analyzed based on the information available. Only a limited number and selection of videos were available. However, whenever possible, these were used as an analysis tool. Specific data such as speed trap data and injury data were also utilized whenever possible. The dynamic model created by Bromley was utilized to recreate incidents where videos were available.

5.5.4.1 **Kinematic Analysis**

A detailed kinematic analysis of crash events was undertaken using the available videos and speed trap data. Delta V, which is defined as the vectoral change in velocity, was computed from the available videos. The location of the video cameras, the quality of the video, and the limited number of views available for each incident limited the accuracy of this analysis. As such, a sensitivity analysis was conducted to determine if the accuracy of the velocity vector angles allowed for a meaningful prediction of the Delta V.

5.5.4.2 **Trajectory Modelling**

The trajectory model was created by Bromley Technologies Ltd. The model utilized the equations of motion to create a forward dynamic simulation. Ice geometry was imported into the model based on ice scans as part of the overall project. The code simulates the particle motion of a body moving down the track with no steering input. Model variables include mass, coefficient of friction, and aerodynamic drag. The model allows the sled’s trajectory to be modelled from any starting location by specifying the velocity and direction at the onset of the simulation.
For the purposes of the Trauma Study, statistical analysis pertaining to crash data were forwarded to Bromley so that the analysis could be focused on areas with the highest crash activity. In addition, videos of crashes involving walls and/or roofs were forwarded to Bromley so that they could be virtually recreated. The model is very effective at determining the pre-crash trajectory of a slider. However, it's capabilities are limited from the standpoint of modelling a crash event. Determination of parameters such as coefficient of restitution, sled stiffness, and impact energy dissipation are critical to an accurate impact analysis and were beyond the scope of the trajectory model.

5.5.4.3 Analysis of Track Ejection

All video records, Control Tower Logs and incident reports were evaluated to identify instances of ejection (slider leaves the track at speed), near ejection (slider obtains adequate height to pass outside of the track but remains in the track) and partial ejection (a portion of the slider’s body, i.e. arm or leg, is ejected from the track but the majority of the slider’s body remains in the track). Where any of these instances were identified, analysis was conducted to identify the interaction that resulted in the vertical motion of the slider. The injuries that resulted from the ejection, near ejection or partial ejection were also evaluated to estimate the consequences of track ejection.

5.5.4.4 Medical Record and AIS Analysis

Medical records were analysed to identify basic mechanisms of injury for each athlete in the medical record and AIS database. Mechanisms of particular concern were identified, further analysed and are discussed below in section 5.6.8.4 Medical Record and AIS Analysis.

5.5.5 Assumptions

To perform our analysis, several assumptions were made about the data and reporting to allow accuracy and consistency throughout the data sets.

5.5.5.1 Run Sheet Database Assumptions

- It was assumed the data provided was accurate and that the individuals reporting did so to the best of their knowledge and expertise.
- When runs were encountered which listed the sport as bobsled but there were no factors which distinguish between the 2 man and 4 man disciplines, 2 man was assumed unless otherwise recorded.
- For runs that had more than one name listed (i.e.: 2 Man, 4 Man or doubles luge), the first name listed was taken to be the pilot of the sled.
- If the session reference contained a provincial sport organization (ie. BCBSA, CLA etc.), that session was taken to include all athletes. Otherwise, the session was taken to be all ‘public’ runs.
- If there are two start locations listed, the higher (closer to the top) start position was entered and the second was entered in the comments section.
• In many cases the slider’s sport and/or discipline was not recorded in which case sliding history was used to decide upon the sport/discipline for that particular slider.
• If a slider's start location was not listed, that individual’s run times were used to determine a start location.
• If there was no time recorded, the field was left blank. It was assumed that the athlete did not crash.
• Times listed as 'NT' were assumed to be a timing error and not considered to be the result of a slider crash.

5.5.5.2 Incident Database Assumptions
• It was assumed the data provided was accurate and that the individuals reporting did so to the best of their knowledge and expertise.
• When there were discrepancies in the record keeping as to the location of an incident it was always assumed that the highest curve recorded was the true location. This was only overruled when reasonable cause was given.
• It was assumed that transportation to the medical clinic represented cases of more severe injuries.
• It was assumed the sled of each athlete was in full working order and did not contribute to the incident under evaluation.
• It was assumed only factors on and within the track led to the incidents (i.e. spectators, weather, wildlife, etc. were not factors)

5.5.5.3 Medical Record and AIS Database Assumptions
• It was assumed the data provided was accurate and that the individuals reporting did so to the best of their knowledge and expertise.
• Discrepancies in the diagnoses were evaluated on an individual basis and the medical professional which was considered to have the most objective basis for diagnosis, given the nature of the injury, was used for coding.
• Each case documented all injuries sustained and no injury was overlooked.
• Ambulance reports were generally not used as a diagnosis tool unless injuries were superficial and corresponded to AIS 1 (eg. Lacerations or abrasions)

5.5.5.4 Detailed Injury Analysis Assumptions
• It was assumed the video data was accurately labelled for the specific date of occurrence and athlete involved.
• It was assumed that the difference in the magnitude between the pre-impact velocity and the post-impact velocity when the slider interacted with an ice wall or the “roof” was minimal.
• It was assumed the body centreline of the athlete reflected the direction of the slider.
5.6 Data Summaries and Analysis

At the initiation of this study in May 2011, there had been over 43,200 runs at the Whistler Sliding Centre. All runs have been documented with “run sheets”. For each slider on the track an entry is made on the run sheet kept at the control tower. The data from the run sheets has been compiled and analyzed for the purpose of this analysis. The run sheets document information such as gender, start location, incident location, sled type, whether the run is part of a competition or whether the slider is a tourist, and whether there was an incident during the run. The radio code for a crash during a slide is 10-80 and is used on the run sheets to denote such. In addition, WSC maintains a Control Tower Log of all incidents that involve injury as well as an Accident Report. We have used the term Accident Report interchangeably with incident report in this document. The Control Tower Log is completed by the control tower and the Accident Report is generally completed by first aid personnel who attended to the injured slider. The following sections analyse the compiled data from these two databases (Run Sheet and Incident Database). In addition, this section contains a more detailed analysis of specific cases for which video footage was available.

In order to measure severity of injuries occurring in track incidents, medical documentation was obtained from the Whistler Health Care Centre (WHCC) and the VANOC Whistler Polyclinic (VANOC WPc). This data was compiled as outlined in section 5.5.3 Medical Record and AIS Database and is presented in the following sections.

5.6.1 Medical record review

We obtained medical records for 74% of the incidents referred to the clinic [46 of 62 cases] and found 52.2% of these to be classified as MAIS 1 injuries, 43.5% to be MAIS 2 and the remaining 4.3% to be unclassified (AIS 9) because of a lack of detailed information or diagnoses in the medical records. We classified Mr. Kumaritashvili’s fatal injury as an AIS 9 (unspecified) because neither the medical records that we had access to nor the BC Coroner’s report on Mr. Kumaritashvili’s death contained enough specific information on the injuries that he sustained to allow definitive coding by the AIS rules. This same situation (not having enough information available to definitively code an injury for AIS) occurred one other time for a less severe injury than Mr. Kumaritashvili’s.

Of the clinically documented injuries, the most common were abrasions/lacerations/contusions, representing 52%. Strain/sprain/tear injuries and concussion/head injuries were the next most prevalent injury in those clinically documented representing 15.7% and 14.7% respectively. Fractures and miscellaneous injuries represented 9.8% and 7.8% respectively (see Figure 5.15).

5.6.2 Crash by Gender

Figure 5.1, which was tabulated from the Run Sheet Database, depicts the number of incidents for males and females in the discipline of 2 man bobsled, single luge, and skeleton. It is noted that females do not partake in 4 man bobsled or doubles luge, thus
these disciplines were excluded from this analysis. When the number of incidents are broken down by gender and discipline, it is observed that the highest incident rate occurred for the 2 man bobsled with the male incident rate (number of crashes per total number of runs in that gender/discipline combination) at 3.0 % and the female incident rate at 2.4 %, respectively. For single luge the incident rate for male and female sliders was 1.9 and 1.8 %, respectively. For skeleton, the incident rate was less than 1 % for both male and female sliders.

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Figure 5.1: Number of male incidents (LEFT) and female incidents (RIGHT) versus discipline.

5.6.3 Crash by Start Location

Figure 5.2 depicts the crash totals for each start location based on the Run Sheet Database. The crash totals are expressed as a percentage of the total number of runs from that location. The highest rate of track incidents considering all disciplines was 3.0 % and occurred when sliders started from the Lady Start 2, often termed Lower Ladies or Damen Start. Next was Lady Start 1 and Men’s Luge Start which resulted in 2.8 and 2.7 %, respectively. These differences were not statistically significant. It is also noteworthy that less than 0.5 % of the starts from Tourist start resulted in incidents. It should be noted that Figure 5.2 is based on all crashes (10-80s) recorded in the run sheets and these numbers do not reflect injury rates. Nevertheless these numbers are important because each time there is a crash, the potential for injury increases considerably.

After February 12, 2010, the date of Mr. Kumaritashvili’s fatal crash, Men's Luge Start was no longer used. In order to analyze the effect this had on the rate of incidents, a deeper analysis was undertaken which was limited to Men’s Luge in order to eliminate any confounding effects of gender and different sleds. A comparison of the incident rate from Men’s Luge, Lady Start 1, and Lady Start 2 pre- and post-Feb. 12, 2010 revealed a decrease in the rate of incidents from 3.0 % to 1.0 %. Although this drop was statistically significant, an analysis which was limited to Lady Start 1 and Lady Start 2 showed a more dramatic drop from 3.3 % to 1.0 % indicating that factors (such as ice conditions, track profile, experience or weather) other than start position likely played a significant role in the decreased incident rate.
When the overall data for Men’s Luge was examined and not stratified by date, a comparison of the incident rate from Men’s Start to the incident rate from Lady Start 1 and Lady Start 2 combined only resulted in a small decrease in the number of incidents from 2.8 % to 2.5 %. This difference was not statistically significant.

Figure 5.3 shows the incident rates for Men's luge from the various start positions. It is noteworthy that there was no statistically significant difference in the incident rate between any of the upper starting positions on the track (Bobsled Start, Men's Start, Lady Start 1, Lady Start 2). Figure 5.3 also shows the incident rate for cases where the luge was referred to the medical clinic for treatment. The numbers in this category were small and also did not demonstrate a statistically significant difference between the upper four start positions. Figure 5.4 further examines the cases sent/referred to clinic and shows the severity of injury for the documented injuries. It is important to recognize that of the male lugers with clinical documentation, all were coded as MAIS 2.

![Crash Totals for All Start Locations](image)

Figure 5.2: The percent of crashes at each start location.  
(Note: Expressed as a percent of the number of runs from that start location. When a start location is listed as a curve this represents that the slider started within the track at this location.)
Figure 5.3: The percent of crashes at each start location on the Track for Men’s luge. (Note – This is expressed as a percent of the number of runs from that start location. The figure also shows the percent of crashes where slider was referred to the clinic for the each start position. When a start location is listed as a curve this represents that the slider started within the track at this location.)

Figure 5.4: Men’s Luge Injury Severity for Different Start Positions Based on Incidents Sent to Clinic

(Note – The crash frequency where the slider was referred to the clinic for each start position as well as the severity based on MAIS score is presented. Of the 12 sliders...
sent to the clinic, there were no cases with an MAIS score of 1 (all MAIS 2). When a start location is listed as a curve, this represents that the slider started within the track at this location.)

5.6.4 Crash/Injury by Experience

Crash data versus slider experience is important because it allows a correlation between crash statistics and skill level. The vast majority of sliders (more than 75% of all sliders) slid on the track between 1 and 9 times as depicted in Figure 5.5. Less than 5% of the sliders have slid on the track more than 70 times with less than 20 sliders ever using the track more than 300 times.

Figure 5.5: Overall experience of sliders on the track.

(Note – The figure shows that 1985 sliders slid between 1 and 9 times and that the number of runs taken for a particular sliders drops significantly for sliders with 10 runs of experience or more.)

Analysis of the number of crashes that resulted in an athlete having a documented injury is presented in Figure 5.6 - Figure 5.8. The number of crashes that involved sliders that had slid a minimum of 29, 59, 89 runs, and further multiples of 30, was normalized by the number of sliders that had slid at least that number of times with or without a crash. This analysis revealed an interplay between risks associated with increasing exposure to the track through increasing multiples of runs taken and the expected benefit of increasing experience: the crash rate as a percentage of cumulative runs taken generally first increased with exposure and then decreased likely reflecting a benefit of experience. Because the number of sliders that slid more than 200 times on the track is very low (44) it is difficult to interpret the data on the extreme right of Figure 5.6 and Figure 5.7 and we recommend further study of the experience of athletes with multiple hundreds of runs on the track before definitive conclusions are drawn for athletes with this level of experience. Figure 5.8 is a further magnification of Figure 5.7 to show the severity of the injurious incidents identified.
All figures show that, with low exposure, the number of injuries recorded is low relative to the large number of sliders that slid at least nine times on the track. The injury rate rises once the sliders have slid at least 30 times on the track and remains near its maximum until the sliders have slid at least 150 times on the track.

Figure 5.6: Effect of experience on injury rate as a function of the sliders’ cumulative experience.
Figure 5.7: Effect of experience on injury rate as a function of the sliders’ cumulative experience.

Injury Severity vs. Slider Experience for Incidents with Clinical Documentation

Figure 5.8: Injury severity compared to slider experience for incidents with clinical documentation.
(Note - The percentage data labels indicate the percent of total injuries reported for each BIN. This image is a further magnification of the injurious incidents shown in Figure 5.6 and Figure 5.7 above.)

5.6.5 Public vs. Athlete

Analysis of the run sheet data (Figure 5.9) demonstrates that over 94% of the runs on the track are taken by athletes. Public sliders to date represent less than 6% of all the slides on the track. It should be noted that a slide is only counted once even if there were 4 public sliders in a 4 Man Bobsled. Athletes were more than 4 times more likely to crash than public riders(Figure 5.10).

![Athelete vs. Public Runs](image)

Figure 5.9: Track usage broken down by runs by athletes and runs by public sliders.

![Crashes: Athlete vs. Public](image)

Figure 5.10: Overall percent of crashes normalized by total runs by athlete sliders and public sliders
5.6.6 Crash/Injury Frequency by Location

The Run Sheet Database and the Incident Database were used to assess the location of incidents on the track. Figure 5.11 depicts the incidents at each corner as a percentage of the total number of runs done on the track as recorded in the Run Sheet Database. The figure shows, (i) the number of incidents as documented in the Run Sheet Database, (ii) the number of incidents for which there was a crash report, (iii) the number of incidents in which the crash report or the first responders report document an injury, (iv) the number of incidents that were sent or referred to the medical clinic, and (v) the number of incidents that resulted in an MAIS code of 2. The results were totalled for all disciplines and were plotted for each corner. Corner 17 refers to the outrun portion of the track.

Of the 710 incidents recorded in the Run Sheet Database only 500 reported the location of the incident. It is unclear where the location of the incident was not reported due to inexact record keeping or because of the minor nature of the injuries in these particular cases. For example, if a person sustained a minor abrasion or bruise on their extremity, the location may not have been deemed important. Of the 446 incidents for which an incident report was completed, 442 contained information about the location of the incident.

![Overall Crash/Injury Frequency vs. Track Location](image)

*Note: 17 represents the outrun

Figure 5.11: Incident frequency by corner location on the Track for all disciplines. (Note - Incidents are plotted as a percent of all runs in the years studied. Incidents resulting in an MAIS 2 were also included in this figure.)
In Phase 1 of this analysis no medical records were available for review. Prior to obtaining the medical records, the severity of each crash or incident was measured solely on referral or transport to the medical clinic. Phase 2 allowed for full review of the medical records to code each documented injury using the AIS and ISS scales. Figure 5.11 depicts that the majority of all incidents occurred in corner 13 or lower. The Run Sheet Database and the Incident Database indicate that 75% and 78% of incidents occurred in corner 13 or lower. An analysis that was limited to sliders referred to clinic indicated that 69% occurred in corner 13 or lower (Figure 5.11-Figure 5.14). Of the 62 incidents in which sliders were taken or referred to the clinic, we were able to obtain 46 (74.2%) medical files. Once these records were scored for injury severity, it was found that 59.1% of the MAIS 2 scores occurred at corner 13 or lower. Figure 5.11 also depicts that injuries occurring at corner 16 tend to be of greater severity than those at other corners. This is also illustrated in Figure 5.14 below, where the number of occurrences is represented by circle size in each corner of the track.

This analysis also allowed us to extend our previous investigation of crash frequency by location to include injury severity based on AIS and ISS coding. Although this analysis was limited to the incidents for which medical documentation was available, data trends were still observed. In particular, of all the injuries coded using the AIS, 74.5% were AIS 1, 23.5% were AIS 2 and 2% were unclassified. Furthermore, of the 46 incidents with medical documentation, 54.3% were coded at MAIS 1 and 45.7% were coded as MAIS 2. In regards to incident location, 24.4% of all incidents coded occurred at or below corner 13 and were scored as a MAIS 2. Figure 5.12 illustrates the distribution of the incidents sent/referred to clinic and the severity of each incident documented.

*Note: 17 represents the outrun

Figure 5.12: Injury severity and frequency based on track location.
(Note - The data used in the AIS analysis was limited to incidents sent to clinic for which there was medical documentation. Incidents are plotted as a percentage of all runs in the years studied.)

5.6.6.1 Corners 1 through 12

The Incident Database indicates that 94 incidents occurred into, through, or out of corners 1 to 12, 45.7% were 2-man bobsled, 36.2% were single luge, and 8.5% were 4-man bobsled. Skeleton and doubles luge accounted for only 9.6% of the total incidents. From the total number of incidents, injuries were documented in 43.6% while only 20.2% resulted in transport to the medical clinic. Of the 94 total documented incidents in corners 1 to 12, the medical records identified 7 cases with an MAIS 1 score and 9 cases with an MAIS 2 score.

5.6.6.2 Corner 13

Of the 170 incidents documented in the Incident Database that occurred into, through, or out of corner 13, 53.5% were 2-man bobsled, 19.4% were single luge, and 16.5% were 4-man bobsled. Skeleton and doubles luge accounted for only 10.6% of the total incidents. From the total number of incidents, injuries were documented in 37.1% while only 9.4% resulted in transport to the medical clinic. Of the 170 total incidents in corner 13, the medical documents identified 7 incidents that resulted in an MAIS score of 1 and 2 incidents scored as an MAIS 2.

5.6.6.3 Corner 14

The Incident Database documented a total of 44 incidents in corner 14 with 52.3% of those being singles luge, 27.3% being 2-man bobsled and 15.9% being doubles luge. Skeleton and 4-man bobsled accounted for 4.5% of the total number of crashes/injuries in this location. Of the 44 incidents, injuries were documented in 25% with 9.1% resulting in transport to the medical clinic. Of the cases for which medical documentation was available, 2 cases resulted in and MAIS 1 and 2 cases resulted in MAIS 2, of the 44 total incidents in corner 14.

5.6.6.4 Corner 15

The Incident Database documented sixty incidents in corner 15, of which 55% were singles luge, 25% were doubles luge and 13.3% were 2-man bobsled. Skeleton and 4-man bobsled accounted for only 6.7% of the total number of incidents. Injuries were documented in 28.3% of the total number of incidents with 11.7% resulting in transport to the medical clinic. Of the 60 total incidents in corner 15, 2 resulted in MAIS 1 scores and 3 resulted in MAIS 2 scores, based on the medical documentation.

5.6.6.5 Corner 16

The Incident Database contained 43 incident in corner 16, of which 55.8% were single luge, 23.3% were 2-man bobsled and 11.6% were skeleton. Doubles luge and 4-man bobsled accounted for 9.3% of the total incidents. Injuries were documented in 62.8%
of incidents with 23.3% resulting in transport to the medical clinic. Of the 43 incidents in corner 16, the medical documentation revealed 4 cases resulting in MAIS 1 scores and 4 cases resulting in MAIS 2 scores.

5.6.6.6 Outrun (17)

The Incident Database documented 28 incidents in the outrun, of which 67.9% were singles luge and 10.7% were skeleton. The remaining 21.4% can be attributed to the other three disciplines. Of the 28 incidents, injuries were documented in 46.4% with 21.4% resulting in transport to the medical clinic. It should be noted that many of the injuries that occurred in the outrun were due to the side to side ‘ping pong’ effect which generally did not result in a crash. These non-crash incidents were also included in our database. Of the 28 incidents in the outrun, the medical documentation allowed our team to code 3 as MAIS 1 and 1 as MAIS 2.

Figure 5.13: Incident and injury summary for each corner on the track. Circle size represents frequency

Figure 5.14: Injury severity summary for each corner on the track.
(Note - The scaling has been increased from Figure 5.13 so that incidents can be better visualized.
5.6.7 Injury Type

From the Medical Record and AIS Database, our team was able to identify trends in injury type which can be seen in Figure 5.15. Figure 5.16 shows the types of injuries from analysis of the Incident Database and was included to give a broader interpretation of injuries sustained. It should be noted that the documentation used in the Incident Database injury type analysis was not completed by physicians and as such, is not valid for scoring AIS or ISS.

![Injury Type from Medical Record and AIS Database](image)

**Figure 5.15: Injury type as determined through medical documentation provided by the WHCC and VANOC WPc.**

![Injury Types from Incident Database](image)

**Figure 5.16: Injury type as documented through the Incident Database.**

(Note - This has a larger sample as not all of these injuries were taken/referred to clinic but it should be noted that the documents used to categorize these injuries were not completed by physicians and therefore cannot be used to code AIS severity.)
5.6.8 Detailed Injury Analysis

To further understand the incidents and injuries that have occurred on the track, and to guide future analysis, individual incidents were examined whenever detailed information was available. Track records, video footage, track time, speed data, medical records, and simulation data, were all utilized to perform a detailed analysis with the goal of better understanding injury mechanisms.

5.6.8.1 Kinematic Analysis

A common methodology, utilized in automotive accident reconstruction, is to perform a kinematic analysis whereby the severity of the collision is defined by the magnitude of the change in velocity or Delta V. The vectoral difference between the pre- and post-impact velocity vectors is defined as the Delta V. Video documentation and speed trap data were used to determine the pre- and post-impact velocity vectors for sliders. Figure 5.17 depicts a luger's pre- and post-impact velocity vectors for a roof contact in curve 16. Figure 5.18 illustrates the entrance and exit vectors as well as the Delta V. In this particular incident the athlete was transferred to the clinic by ambulance. Quantification of the Delta V allows the incident to be evaluated from a biomechanical engineering perspective to assess the motions and injury potential based on known injury tolerance data.

In total we were given 11 videos that captured crashes or roof/wall contacts. In all cases, the incidents were captured from only one camera angle limiting the accuracy with which the pre- and post-impact velocity vectors could be determined. A sensitivity analysis showed that the resolution of this analysis technique is intimately tied to the accuracy in predicting the angle of the velocity vectors. The oblique low resolution camera views did not allow velocity vectors to be determined with the accuracy required for the above analysis.
Figure 5.17: Video still frames overlaid to illustrate entrance and exit angles as well as the line of reference. (ref. C16)

Figure 5.18: Vector summation to produce the Delta V vector.
(Note - The above diagram is for illustrative purpose and does represent actual magnitudes or direction.)

5.6.8.2 Trajectory Modelling

The dynamic model created by Bromley was used to analyse varying trajectories at the curves of interest. One focus of these analyses was to conduct trajectories through the exit of turn 16 such as the one depicted in Figure 5.22 (N Yakushenko and N Kumaritashvili crashes). A range of incoming velocity vectors was utilized by the Bromley investigators. The model calculated the slider velocity and trajectories through the turns as illustrated in Figure 5.19 to Figure 5.21. The Bromley investigators have informed us that their model does not accurately model slider impact with the track walls.
or ceiling and nor does it accurately model any airborne phases. In both instances this is because the physics of the impacts or of the airborne phase of the slider motion have not been studied in any depth previously and these phases could not therefore be incorporated into the model. The fact that the trajectory models only accurately depict the incoming velocity of any impact with the ceiling or walls means that the delta-V described above, that was associated with any particular impact, could not be quantitatively determined for the trauma analysis. Nevertheless, the modelling allowed for a direct comparison between different impacts at the exit of corner 16. A luge with no steering input interacted very differently with the wall than did Nodar Kumartishavili during his fatal crash (compare Figure 5.19 to Figure 5.21). It is plain to see that the risk of both injury and of the luge beginning to “mount” the wall at the exit of curve 16 (thereby imparting a vertical motion to the slider) increases as the impact angle varies from a more glancing and obtuse impact angle to a more perpendicular and acute angle. This is entirely consistent with the delta-V diagram above. Clearly the magnitude of the delta V vector increases as the angle between V1 and V2 increases (Figure 5.18).

Figure 5.19: Bromley simulation of a single luge with no steering input interacting with the wall at the exit of turn 16.

(Note - The sequential motion of the red shape indicates the motion of the luge and the blue line indicates the trajectory history.)
Figure 5.20: Bromley simulation of Nodar Kumaritashvili trajectory through curve 16. (Note - The red line indicates the particle’s trajectory.)

Figure 5.21: Bromley simulation of Nodar Kumaritashvili trajectory through the exit of curve 16. (Note – Path shows the interaction with the track wall at the exit to turn 16. The red line indicates the particle’s trajectory.)
5.6.8.3 Analysis of Track Ejection

The materials and incidents reviewed clearly indicated the high risks of severe injury and death that are associated with athlete ejection from the track. According to BC Coroner Dr. Pawlowski [8], Mr. Kumaritashvili was fatally injured during and after ejection from the track adjacent to the exit to corner 16. Dr. Pawlowski found that Mr. Kumaritashvili sustained injuries in his left arm and lower torso from interaction with “the low wooden barrier” on the slider’s left exiting turn 16. He sustained his fatal traumatic head injuries when he experienced what Dr. Pawlowski described as “The most severe point of impact” which “was the collision against the metal post that occurred outside of the track and resulted in abrupt deceleration, causing the traumatic head injuries.” (bold italics added for emphasis). As can be clearly seen in the sequence of photos presented in Figure 5.22 below, Mr. Kumaritashvili interacted with the ice wall to slider’s right at the exit of turn 16 and this interaction resulted in significant vertical and leftward motion as Mr. Kumaritashvili rebounded from his impact with the ice wall. This vertical and leftward motion allowed him to interact with and ultimately cross over the top of the wooden barrier or wall to his left and he ultimately continued outside the track and struck the metal roof support column with the back of his head.

We analysed a similar but less severe set of slider kinematics that had occurred approximately a year before Mr. Kumaritashvili’s fatal crash. This is presented alongside Mr. Kumaritashvili’s kinematics for comparison in Figure 5.22. Ms. Yakushenko also experienced an upward and (slider’s) leftward motion after rebounding from the ice wall at the exit of turn 16. The impact with the ice wall was less energetic than was the case for Mr. Kumaritashvili which resulted in a less severe rebound and Ms. Yakushenko was retained in the track although her left leg was ejected from the track for a short distance. It is significant to note that we do not have a Control Tower record or an Accident Report to document Ms. Yakushenko’s crash so we do not know if she was injured. Sometime after the Yakushenko incident there were higher barrier/walls added on both sides of the exit of turn 16 and this is illustrated in the top two images of Figure 5.23. This barrier/wall was increased in size after Mr. Kumaritashvili’s fatal crash to the configuration shown in the bottom of Figure 5.23.

Preventing ejection of the athlete from the track is clearly of utmost importance to prevent fatal and potentially fatal incidents during luge sliding. If the athlete is retained in the track there is no mechanism for any part of their body to engage with any other structure at a closing speed approximating their travel speed (often upwards of 140 km/hr). Within the track, the athlete can interact with smooth slippery surfaces such as the ice track, ice side walls or the smooth surfaces of the upper retaining wall (termed the roof) or the safety barrier/walls that extend upwards from the ice side walls. These structures have no mechanism to engage the athlete’s torso or extremities or to result in the high speed impacts and decelerations that can occur when an athlete is ejected from the track. The results of our injury analysis are consistent with this: except for the fatality of Mr. Kumaritashvili that occurred as a result of track ejection, we recorded a spectrum of lower severity injuries including fractures of the extremities, contusion/laceration of extremities and torso, sprain/strain and head impacts with possible concussion. This is also consistent with published luge injury data which indicates the majority of injuries in luge are contusions and strains with a minority of
fractures and concussions being the most serious injuries.[2,4] In the 2010 Vancouver Olympics, luge was among the lowest risk for injury (with less than 5% of athletes suffering injury) of any sport.[4]

Because of the high risk of fatal or catastrophic injury associated with athlete ejection, our strongest recommendation is that all plausible attempts be made at the WSC to continually evaluate the track configuration and the outcomes of crashes as they occur. Regular review of all crashes on the track (perhaps on a daily basis) is recommended with a specific focus on identifying potential ejections (the Yakushenko incident being a case in point). When a potential ejection is identified it should be a priority to take action to eliminate the potential for ejection before sliding resumes. The change in barrier/wall configuration at the exit of turn 16 after the Yakushenko incident would be consistent with this goal, although we have no specific knowledge of the timing and motivation for the track configuration changes that occurred at the WSC. There are likely many ways to prevent track ejections and it is beyond the scope of our study to investigate or recommend any detailed methods to accomplish this. The results of our analyses clearly indicate the need to take all plausible measures to prevent athlete ejection and to remain vigilant on this front.
Figure 5.22: Comparison of C16 exit kinematics for athletes N Yakushenko and N Kumaritashvili competing approximately a year apart.
5.6.8.4 Medical Record and AIS Analysis

Four incidents in particular were identified in our severity analysis as noteworthy due to their mechanism of injury or the severity of injury sustained. Our procedures for analyzing the medical records place a paramount importance on patient confidentiality and we performed the medical record analysis with the approval of the UBC Clinical Research Ethics Board and the Vancouver Coastal Health Privacy office.

Incident 1 involved an October 2008 incident in which a 29 year old male slider in a two man bobsled suffered a facial laceration after his bobsled rolled and his helmet visor came off and he may have struck his face on the sled. This is noteworthy in that it points out that surfaces on the sliding equipment should be designed to avoid sharp edges that could injure a slider if the slider contacts it.
Incident 2 involved a January 2009 incident in which a 22 year old male slider in a four man bobsled that flipped in corner 16 and, according to the ambulance run sheet, the slider impacted their “head/neck on the track side wall”. This slider complained of neck pain and tingling fingers. This was coded as a suspected “spinal injury with deficits” by the attending EMS provider. He was eventually diagnosed with neck strain but this incident is noteworthy because the complaints are similar to a clinical entity known as cervical cord neuropaxia. Neurapraxia of this type is reported to occur in American football and other collision sports and often occurs due to an impact to the top of the helmet, or head-first impact, causing compression of the cervical spine. This is a mechanism known to cause spinal cord injury (SCI) and cervical cord neuropaxia is often thought of as a near miss of an SCI [3]. This incident is of concern because it raises the possibility that SCI could occur in head first impacts against the track side wall when bobsleds roll over. Injury prevention steps should be considered for this worrisome potential mechanism of devastating cervical spine and spinal cord injury.

Incident 3 involved an October 2009 incident in which a 25 year old male Luger dislocated his hip after impacting it into the roof of the sliding centre. There are also notes that he may have “caught” his leg on the roof of the sliding centre. This is noteworthy because it underlines the importance of designing the track so that no part of the athlete’s body can engage or “catch” on any part of the track. There is no definitive mechanism identified with this specific injury and we did not see evidence of locations where a slider could have a part of their body engage with or catch on the roof of the Whistler track. However, this incident suggests a potential injury mechanism and both the plausibility of the mechanism itself and its prevention should be considered.

Incident 4 is that in which Mr. Nodar Kumaritashvili was fatally injured and we have discussed this injury in detail in the section immediately preceding this one.

### 5.6.9 Helmets Used in Sliding Sports

The helmets worn by sliding athletes are designed to meet the requirements of the specific discipline. For example, luge helmets have a special visor which wraps under the chin and skeleton helmets have a chin bar to protect from ice impact. However, all sliding helmets have some features in common. Every helmet has a hard outer shell, an energy absorbing liner, and a retention system. Review of the medical records revealed several instances in which helmet damage was documented. This is important because the energy absorbing liner is designed to manage the energy from an impact through permanent deformation. To our knowledge all of the helmets used in sliding sports utilize liner material designed for a single impact. These types of liners are effective in preventing head injuries [7,9,11], and do so by dissipating energy and decreasing peak accelerations. Once this type of liner is damaged it is imperative they be replaced as the effectiveness is greatly diminished once damaged.

Sliding sport helmets can be expensive because of the unique designs and the small market. Sliders should be educated on the importance of replacing their helmet after it is involved in an impact. Liner damage may not be readily visible, however this does not mean it is not present. Compression of the liner can be hard to detect.
should be replaced after a head impact even if the helmet is intact with no visible damage.

5.7 Issues Encountered

Over the course of this project several limitations of the current databases were identified. All databases were created primarily from handwritten sheets of paper. Documents often contained misspelled names and critical information such as start position and crash location were often missing. In addition there were inconsistencies between the various records reviewed. Often times there were inconsistencies between the Control Tower Logs, Accident Reports, and Run Sheets.

There is a large discrepancy between the number of incidents compiled for the “Incident Database” and the “Run Sheet Database” (see Figure 5.24). Overall, the Run Sheets indicate there were 710 incidents over the past four seasons, whereas the records reviewed for the Incident Database only have reports for 446 incidents. This leaves 264 incidents with no documentation. It may be that there were only minor or no injuries in these 264 cases, but it is unclear how that determination is made. Overall, it is not clear when an incident justifies further documentation. In addition, there are likely situations where the incident records under-report the number of injuries. For example, if a person experienced concussive type symptoms the day following an incident with no other obvious injuries, it is unlikely that their injury would show up in WSC records.

Figure 5.24 depicts that the proportion of incidents for which an incident report was filled-out changed quite significantly from 2008/2009 to 2009/2010. In 2007/2008, 2008/2009, 2009/2010, 2011/2012 the percent of incidents for which there was documentation of injury was 59, 82, 38, and 94 percent, respectively. It should be noted that the run sheet data analysed in this study contained 2125, 13835, 15301, and 12005 runs for the 2007/2008, 2008/2009, 2009/2010, and 2011/2012 seasons, respectively. It is unclear whether there were less severe incidents because of changes between seasons or whether the requirements to fill-out an incident report changed from one season to the next.

Crash data versus rider experience is difficult to quantify because the number of runs by each slider must be sorted in a database of over 43,000 entries. The run sheet data contains misspelled names as well as missing first and last names making it difficult to accurately sort the data. It was beyond the scope of our project and not possible to be able to completely clean the databases of misspelled names.

In many cases, the documentation we have is incomplete and is difficult to draw conclusions from. Only 25% of the incidents were documented with a ‘Whistler Sliding Centre Accident Report’ which generally provides information such as start location, whether the athlete was transported to the clinic, and anthropometric data. Missing data in the run sheets (i.e. start locations, sport, discipline, session reference, incident location) left gaps in the database and decreases the strength of conclusions. For example, there were 210 incidents recorded in the Run Sheet Database for a crash or incident that location was not given.

Inconsistency in record keeping is another limitation of the current data set. Discrepancies between the Accident Reports and the Control Tower Logs often made it
difficult to determine the location of the incident. The protocol for defining incident location was developed for consistency when encountering this issue, but we feel that this procedure may not be accurate in every case.

Analysis of the medical documentation also involved several challenges. One issue that was frequently encountered was a discrepancy between the radiological report and the physicians. This ambiguity was resolved on an individual basis and the medical professional which was considered to have the most objective basis for diagnosis, given the nature of the injury, was used for coding. In many of cases, the documents were hand written and the writing was difficult to interpret. In these cases, all supporting documentation was examined in order to identify all possible injury locations and mechanisms. Some medical records also documented uncertain injuries requiring further follow up or simply noted with a question mark. A conservative (coding as less injurious) approach was taken for these cases as the AIS specifies that no inferences can be made without explicit diagnoses.

![Documentation of Track Incidents](image)

**Figure 5.24:** Proportion of incidents documented with an incident report.  
(Note – This was generally a Control Tower Log or an Accident Report) vs. incidents where the only documentation was in the form of the in the Run Sheet with no further details or description of the incident.)
5.8 Recommendations

Our retrospective trauma study draws attention to the importance of good record keeping. WSC has an extensive database of crashes, which was invaluable to this study. However, many deficiencies and shortcomings were observed during the analysis. It is recommended that WSC develop a protocol to ensure the collection of important parameters, such as name, start location, crash location, description of injury, and other fields that we have discussed in this document. This approach could perhaps be extended to include specific fields that could be populated on sport specific emergency department triage forms that physicians could fill out. These forms should include fields to record specifics of the mechanism of injury and details of the incident (such as helmet damage). It is recommended that the record keeping at the track be done in an automated fashion. One such way would be to develop a database program that would systematically log data and which would allow for statistics to be automatically compiled at the end of the season. It would be ideal if these were computerized allowing for auto complete and simplifying entry.

Many discrepancies were observed between the Control Tower Logs and Accident Reports. In order to eliminate these errors it is recommended that there should be communication between the control tower and the first responders after each incident so that parameters such as the accident location and cause of accident can be agreed upon. The communication can be as simple as a radio discussion or an in person meeting.

It is recommended that WSC continually review accidents that occur on the track. Past incidents can provide invaluable information about potential future crashes. Furthermore, once a database is up and running it is recommended that the accident trends and statistics be continually monitored.

While it is beyond the scope of this project to investigate the effect of sled design on the risk of trauma, it is recommended that this be an area of future research. The crash worthiness of sleds including the advantages/disadvantages of an energy dissipating sled design should be studied. It is expected that this would involve design, computer modelling and crash testing of sleds.

While not directly part of this evaluation, it is recommended that the FIBT and FIL incorporate knowledge gained from this retrospective trauma study as well as from other studies of track accidents when setting specifications for protective safety measures such as walls, barriers and crash equipment.

While an in-depth retrospective study was undertaken for the purpose of this project, it is suggested that a prospective analysis of track accidents would provide additional insight. It is recommended that modelling of potential crash events be undertaken to examine ‘what-if?’ scenarios. Utilizing trajectory outputs of interest from the Bromley model as an input to a mathematical model of the human body could provide invaluable insight into the potential for injury and the effect of potential safety measures.

Because of the high risk of fatal or catastrophic injury associated with athlete ejection, our strongest recommendation is that all plausible attempts be made at the WSC to continually evaluate the track configuration and the outcomes of crashes as they occur.
Regular review of all crashes on the track (perhaps on a daily basis) is recommended with a specific focus on identifying potential ejections. When a potential ejection is identified it should be a priority to take action to eliminate the potential for ejection before sliding resumes. There are likely many ways to prevent track ejections and it is beyond the scope of our study to investigate or recommend any detailed methods to accomplish this. The results of our analyses clearly indicate the need to take all plausible measures to prevent athlete ejection and to remain vigilant on this front.

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CHAPTER 6 TRAJECTORY STUDY

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TABLE OF CONTENTS

CHAPTER 6 TRAJECTORY STUDY ................................................................. 185
6.1 Introduction .......................................................................................... 191
6.2 Bromley Technologies – History .......................................................... 191
   6.2.1 Management Overview ............................................................... 192
   6.2.2 The Project Team ........................................................................ 193
6.3 Project Deliverables ............................................................................. 193
6.4 Digital Modelling of the Whistler Track Geometry ................................. 194
   6.4.1 Introduction .................................................................................. 194
   6.4.2 Methodology of geometry preparation and importation into the trajectory software .......................................................... 194
   6.4.3 Geometry Debugging: ................................................................. 197
   6.4.4 Overlaid/Duplicate files ............................................................... 197
   6.4.5 ‘Reversed’ Section files ............................................................... 198
   6.4.6 ‘No Walls’ .................................................................................... 199
   6.4.7 Missing Section files ................................................................. 200
6.5 Sled Dynamics Model ........................................................................... 205
   6.5.1 Overview .................................................................................... 205
   6.5.2 SDM Objective ........................................................................... 205
   6.5.3 SDM Input Data ......................................................................... 205
   6.5.4 SDM Design ............................................................................. 206
6.6 Trajectory Study .................................................................................. 208
   6.6.1 Run Test Matrix ........................................................................ 208
   6.6.2 SDM Parameter Review ............................................................... 210
   6.6.3 SDM Filtering Conditions ........................................................... 212
   6.6.4 SDM Results Format ................................................................ 216
   6.6.5 On Track Study (March 2011) - SDM Model validation .................. 216
6.7 Results ................................................................................................. 225
   6.7.1 Descriptive Terms ..................................................................... 225
   6.7.2 Sample Analysis ....................................................................... 225
   6.7.3 Summary of 4 Man Bobsleigh Trajectory Findings ...................... 234
   6.7.4 Summary of Results for Singles Luge .......................................... 245
   6.7.5 Summary of Two Man Bobsleigh Trajectory Findings ................. 258
   6.7.6 Summary of Skeleton Trajectory Findings .................................. 270
6.7.7 Summary of Doubles Luge Trajectory Findings ................................................. 283
6.8 Fatal Accident Re-Creation .................................................................................. 293
6.8.1 Overview ........................................................................................................... 293
6.8.2 SDM Input Parameters ...................................................................................... 293
6.8.3 Results ............................................................................................................... 294

LIST OF FIGURES

Figure 6.1: Illustration of the application of points to the ice profile cross section curves. ............................................................................................................................................................. 195
Figure 6.2: Illustration of the trajectory software recreating the track geometry by forming panels defined by the point sets created from the scanned ice data. ............ 196
Figure 6.3: Illustration of a duplicated point set data file. The image is the geometry created by the trajectory software. .............................................................................. 197
Figure 6.4: Illustration of an overlaid point set data file. .............................................. 198
Figure 6.5: Illustration of a ‘reversed’ point set data file. ............................................. 198
Figure 6.6: Illustration of a ‘reversed’ point set data file. ............................................. 199
Figure 6.7: Illustration of a ‘reversed’ point set data file. ............................................. 199
Figure 6.8: Illustration of the results of a discontinuous cross sectional curve. .......... 200
Figure 6.9: Illustration of the results of a discontinuous cross sectional curve. .......... 200
Figure 6.10: Illustration showing the effect of a missing point data file on the geometry created by the trajectory software. ................................................................. 201
Figure 6.11: Illustration showing a distortion in the ice profile geometry that had to be removed. ..................................................................................................................... 202
Figure 6.12: Illustration showing the IBG design section (red), the ice geometry section curve (white) and the 101 points (blue) applied to the ice geometry at IBG station SX = 435.5 (ref. Upper Section) ................................................................. 203
Figure 6.13: Curve showing over 200 individual sections .......................................... 204
Figure 6.14: Plot of raw unfiltered data as outputted from the SDM ......................... 213
Figure 6.15: Plot of a 10 Hz filter ............................................................................... 214
Figure 6.16: Plot of a 2 Hz filter ................................................................................. 215
Figure 6.17: Graphical comparison between measured split times and model prediction ......................................................................................................................... 221
Figure 6.18: Measured ‘g’ force data - Charles Wlodarczak Run 1 (15th March 2011) 222
Figure 6.19: Photograph of CAPE Portable Data Acquisition System Installed on Singles Luge Sled .................................................................................................................. 224
Figure 6.20: Overlay of the SDM trajectories - C1 Entry 4 Man Bobsleigh ................. 227
Figure 6.21: Overlay of the SDM trajectories - C1 Exit Reverse 4 Man Bobsleigh ...... 228
Figure 6.22: ‘g’ Force & Velocity Speed Plot – Early entry line C1 4 Man Bobsleigh  .. 229
Figure 6.23 : 'g' Force and Velocity Plot – Middle entry line C1 4 Man Bobsleigh ...... 230
Figure 6.24 : 'g' Force and Velocity Plot – Late entry line C1 4 Man Bobsleigh ......... 231
Figure 6.25 : ‘g' Force and Velocity Plot – Early entry line +10% entry speed C1 4 Man Bobsleigh .................................................................................................................... 232
Figure 6.26: Velocity plot and g-force map for 4 man bobsleigh .............................. 237
Figure 6.27: Distance against Time plots of the SDM model performance vs the Gold medal performance from the 2010 Vancouver Olympic Games ........................................ 240
Figure 6.28: Velocity plot and g-force map for singles luge ................................. 248
Figure 6.29: Distance against Time plots of the SDM model performance vs the Gold medal performance from the 2010 Vancouver Olympic Games ................................... 252
Figure 6.30: G - Map of a full simulated run for Two Man Bobsleigh (average of the early entry and middle entry line trajectories) ........................................................................ 263
Figure 6.31: Distance against Time plots of the SDM model performance vs the Gold medal performance from the 2010 Vancouver Olympic Games .................................... 265
Figure 6.32: G - Map of a full simulated run for Skeleton (average of the early entry and middle entry line trajectories) ............................................................................. 275
Figure 6.33: Distance against Time plots of the SDM model performance vs the Gold medal performance from the 2010 Vancouver Olympic Games .................................... 277
Figure 6.34: G - Map of a full simulated run for Doubles Luge (average of the early entry and middle entry line trajectories) ............................................................................. 286
Figure 6.35: Trajectory of luge through section Curve 14 – C15 ............................ 295
Figure 6.36: Trajectory of luge through section Curve 15 – C16 ............................ 295
Figure 6.37: Trajectory of luge through section Curve 15 – C16 ............................ 296
Figure 6.38: Zoomed in image of the exit trajectory from curve 16 and the following impact into the wall ...................................................................................................... 297
LIST OF TABLES
Table 6.1: Trajectory Run Matrix for the Sled Disciplines ........................................... 209
Table 6.2: Timing interval / speed trap location points .................................................. 218
Table 6.3: Training split times and speeds provided by the Whistler Track .................... 220
Table 6.4: Tabulated comparison between measured split times and model prediction ................................................................................................................ 220
Table 6.5: comparison of measured ‘g’ force data vs. model prediction middle, lower and finish sections ....................................................................................................... 223
Table 6.6: Sled Dynamics Model (SDM) parameters .................................................. 226
Table 6.7: SDM Trajectory Data for C1 4 Man Bobsleigh ............................................ 233
Table 6.8: Summary of SDM predicted Speed and ‘g’ accelerations .......................... 234
Table 6.9: Sled Dynamics Model (SDM) parameters for Singles Luge ....................... 245
Table 6.10: Summary of SDM predicted ‘g’ and velocities for singles luge from the ‘Ladies start’ ................................................................................................................ 245
Table 6.11: Sled Dynamics Model (SDM) parameters ................................................ 258
Table 6.12: Summary of SDM predicted Speed and ‘g’ accelerations for Two Man Bobsleigh ................................................................................................................... 258
Table 6.13: Sled Dynamics Model (SDM) parameters for Skeleton ............................ 270
Table 6.14: Summary of SDM predicted Speed and ‘g’ accelerations for Skeleton .... 270
Table 6.15: Sled Dynamics Model (SDM) parameters ................................................ 283
Table 6.16: Summary of SDM predicted Speed and ‘g’ accelerations for Doubles Luge ......................................................................................................................... 283
Table 6.17: Parameters used for re-creation of the fatal accident ............................... 293
Table 6.18: Predicted ‘g’ force exposure for the accident recreation ....................... 294
6.1 Introduction

On March 4, 2011 the Whistler Sports Legacy Society (WSLS) awarded the Southern Alberta Institute of Technology (SAIT) a contract to carry out a comprehensive study of the Whistler Sliding Centre (WSC) track. The study proposed was broken out into five components,

- A report on the “as is” constructed track versus the design.
- A survey of the track to verify gradient changes and position, the structural components and the shape of the concrete and an estimate of the ice profile.
- A report on the potential trajectories, including the velocities and pressures that a sled experiences as it travels the length of the track.
- A retrospective report on the trauma athletes experienced as a result of incidents on the track.
- A report on the safety measures set up on and around the track to protect athletes, spectators and employees from injury if an athlete loses control of their sled.

Bromley Technologies Ltd was the partner chosen to carry out component three – ‘To report on the potential trajectories, including velocities and pressures a sled could experience as it travels the length of the track’.

6.2 Bromley Technologies – History

Bromley Technologies Ltd was incorporated in the year 2000 by Company Directors and brothers; Professor Kristan Bromley, PhD, BEng and Richard Bromley BEng who have over 27 years collective experience within the aerospace, Olympic winter sport, performance engineering & academia sectors.

Between 2000 and 2011 Bromley Technologies has been dedicated to the research, development and manufacture of high performance Skeleton & Bobsleigh technologies in parallel to research programmes focusing on sled research and bobsleigh track dynamics. This has included research collaborations with three leading UK Universities, Nottingham, Bath, and Leeds.

Bromley products have won medals in the last three consecutive Olympic Winter Games and have supported athletes in winning over 70 medals through FIBT competitions. The company’s customer base includes teams and athletes from Switzerland, Russia, USA, Canada, Austria, Norway, France, UK, Japan, Latvia, Italy, Romania, Netherlands, Australia, Sweden & Iraq.

The company is located on the new Advanced Manufacturing Park (AMP) Technology Centre, Rotherham, near Sheffield, UK.
6.2.1 Management Overview

Professor Kristan Bromley: Director / Founder, Age 40

Prof. Kristan Bromley is a three-time Olympian and the 2008 World Champion in the sport of Skeleton. Kristan is one of Great Britain’s most successful winter sport athletes having won over 30 medals in world competitions, having been ranked world number one in 2004 & 2008.

In 2008 Kristan made sporting history by becoming the first man in the sport’s 100 years to win the ‘Triple Crown’ of world titles, the European Championships, World Cup Series and the World Championships.

Kristan is also an award winning design engineer with a 12 year high profile career with BAESYSTEMS having worked on Eurofighter and Airbus engineering projects, where he gained considerable experience in advanced composites design and manufacture processes and non-destructive testing (NDT). Sponsored by BAE and Nottingham University Kristan completed a world leading PhD study in Skeleton Bobsleigh Performance. Kristan subsequently managed research collaborations between Bromley Technologies Ltd and Bath University and more recently Sheffield Hallam University, where Kristan holds a Visiting Professor chair.

Richard Bromley, Director / Founder, Age 36

Responsibilities: Research into Sled Dynamics, Skeleton Sled Design & Manufacture.

Co-founder of Bromley Technologies, Richard is a proven structural dynamics and systems engineer, having graduated with a Mechanical Engineering degree from Hull University.

Richard held research positions at Bath University and Sheffield Hallam University between 2004 – 2009, where he worked on the science and engineering behind the bobsled sports.

Richard played a key role as technical race engineer to the British Skeleton Olympic Performance programme having supported the national team in the 2002, 2006 and 2010 Olympic Winter Games as a race sled engineer and technical support engineer.

Richard currently leads the Bromley ‘works’ programme as the lead race engineer.

Richard leads a current collaborative research partnership with the 5* Mechanical Engineering department at Leeds University.

Bromley Technologies’ unique mix of diverse advanced engineering experience, research activity, sled development programmes and Olympic athlete pedigree, makes it perhaps one of the world’s leading authorities and ‘applied engineering’ bodies in the sport of Skeleton and the Bobsleigh sports.
6.2.2 The Project Team

Bromley Technologies secured the support of two subcontractors, Leeds University and PES Ltd, both commissioned to support the delivery of specific parts of this project.

Leeds University provided expertise in vehicle motion dynamics and specialized software coding. The University specifically supported the fine tuning of the sled dynamics model (SDM) software in order to assess the Whistler track geometry.

PES Ltd is an engineering design consultancy with an expertise in reverse engineering and CAD and has a pedigree in F1 motorsport. PES Ltd provided expertise in track scanned data manipulation in CAD and general project management support to the project.

6.3 Project Deliverables

The deliverables of this project are:

Digitally model the Whistler Bobsleigh track from scanned ice surface data provided by project partner Dialog.

Theoretically analyze the trajectories of sled / athlete systems along the Whistler track model for Luge, Double Luge, 2 man and 4 man Bobsleigh and Skeleton.

Validate theoretical trajectory modeling with in-field data measurements of speed and centripetal accelerations.

Highlight areas of concern with respect to safety with recommendations.

Use the Trajectory model to recreate the fatal accident involving Georgian Athlete Mr. Nodar Kumaritashvili. The accident was reconstructed utilizing track video footage provided by WSL.
6.4 Digital Modelling of the Whistler Track Geometry

6.4.1 Introduction

The ice profile data captured by the scanning equipment at the track is output as a point cloud or polygon mesh (STL file). These data formats cannot be read directly into the trajectory software and therefore the raw data has to be ‘translated’ into a suitable format.

The trajectory software simulates the track geometry by creating ‘panels’ between locations down the track. These locations are defined by points positioned on the ice profile geometry at specific intervals. In order to position these points on the ice profile geometry the scan data has to be sectioned. The number of sections ‘cut’ and the number of points distributed over these individual sections ultimately defines the resolution of the geometry recreated by the trajectory software. The number of points on each section has to be equal and the points are equi-spaced over the length of each section curve. A benefit of this process is that the scan data does not have to be surfaced before the sections can be extracted as the STL file can be cut directly and the curves exported.

The trajectory software reads in the X, Y and Z coordinates of every point on the ice section curves, building a mathematical model of the complete track. This data is exported from the geometry created in the CAD package (Computer Aided Design) as an individual text file for every section cut through the scanned ice.

6.4.2 Methodology of geometry preparation and importation into the trajectory software

The initial plan was to cut the ice geometry at 1m intervals down the track. However, as the IBG vertical design sections were made available it was decided to use these to define the cut positions. This removed the need to create the sectioning planes and, as they are spaced every 0.5m, it increased the resolution of the mathematical model, although it also doubled the data to be processed. Added to this it allowed the ‘as designed’ concrete structure, ‘as constructed’ concrete structure and ice to be viewed and compared together.

Once the IBG design sections and ice scan data were aligned the cross section curves could be created and then imported into CAD for the application of the points. In total 3034 individual ice section curves were created covering 1516.5m of the track.

Before the points could be applied to the section curves some ‘clean-up’ operations and geometry modifications were required. Certain features and characteristics of the sectional data were identified as areas that could cause issues in the trajectory software. These modifications comprised of the follow actions:

- Spreading sharp/rapid changes in geometry between adjacent cross sections over a number of sections to create smooth transitions.
• Removing any abrupt geometry changes in a section curve, this included filling any holes or gaps present in a curve.
• Joining the segments of any broken section curves to form a single entity on every section station.

Over 100 points were then added, evenly distributed over every cross section curve. This gives a maximum point spacing of 60mm on the longest cross sectional curves, with the point separation distance reducing where the track cross sections are shorter in length.

The first (point #1) and last (point #101) points were positioned at the beginning and end of the section curve respectively, with the remaining 99 points equi-spaced in between. It was important that the positioning of point 1 and point 101 was consistent between adjacent sections.

Figure 6.1: Illustration of the application of points to the ice profile cross section curves.
Figure 6.1 Illustration of the application of points to the ice profile cross section curves shows the basic principle of the point application process to the cross section curves. The points are added to the section geometry using a ‘point set’ command in the CAD package. The start and finish points (1 and 101) are always at either end of the sectional curve, but which end depends on where the section curve is ‘physically’ selected in the ‘point set’ command, with point 1 being positioned at the curve end nearest to the selection position. If the start point on the adjacent section is on the opposite end of the ice profile curve then the panels becomes twisted in the trajectory software, as shown in the Figure 6-5.

This results in a total of 306,434 points being applied to the 3034 cross sections defining 1516.5m of track.

The coordinates of the 101 points for each section were then exported from the CAD model and saved to a text file. This file contained the X, Y and Z coordinates for the points relative to a common datum, which would define that section in the trajectory software. Each file of 101 points was named with a sequential number (file 0001 being the start of the track) and the SX value (in 0.5m increments) relating to the station defined by the IBG design sections. This gives a total of 919302 coordinates (X, Y & Z) defining the track!

Figure 6.2: Illustration of the trajectory software recreating the track geometry by forming panels defined by the point sets created from the scanned ice data.
After the point files are imported into the trajectory software the boundaries of the panels are formed by joining point 1 on a section with point 1 on the adjacent ‘downhill’ section, then point 2 to point 2, point 3 to point 3 all the way to point 101 to point 101, as shown in Figure 6.2 above. This requires that point 1 starts at the same end of the section curve to point 1 on the adjacent section, as highlighted earlier. The points are then connected to the next section and the geometry is progressively created between all the sections down the track.

6.4.3 Geometry Debugging:

The initial importation of the cross section points’ coordinate files into the trajectory software highlighted some issues with the geometry data that had to be addressed before simulations could be run. The issues encountered and their remedies are described below:

6.4.4 Overlaid/Duplicate files.

Due to some of the ice profile section data files being named incorrectly and duplicated where the track was separated into groups of corners to speed the processing, certain sets of points occurred twice. This was remedied by renaming the offending files or removing the duplicated data.

![Figure 6.3: Illustration of a duplicated point set data file. The image is the geometry created by the trajectory software.](image-url)
6.4.5 ‘Reversed’ Section files.

The ‘reversed’ section files result in a twist in the geometry generated by the trajectory software. The twisted geometry occurred where point 1 and point 101 were at the incorrect ends of the sectional curve, due to the selection point happening to be made too close to the wrong end of the section curve. These issues were resolved by deleting and recreating the ‘point set’ and re-exporting the point data files. These data files were checked against the originals they were replacing to ensure the points had been swapped.
6.4.6 ‘No Walls’.

There were a small number of sections where the internal wall of the track was missing when the geometry was generated in the trajectory software. The reason for this was that the ice profile curves at these section stations were not continuous. The ‘point set’ command positions the 101 points over whatever length of continuous curve is selected. In these areas there were some breaks in the geometry and therefore the points were not distributed over the extent of the entire section of track. This issue was remedied by joining the curves on each section to form a single continuous entity over which the 101 points were then redistributed. The data point files were then re-exported.
6.4.7 **Missing Section files.**

There were some point data files missing due to that section not having been exported or the file being incorrectly named. The trajectory software geometry constructor did not have an issue with these, however the ‘panels’ created were not as uniform and lost fidelity to the original track geometry. The problem was resolved by simply ensuring the missing point data files were available for the trajectory software to import.
Once all the ice geometry point data files had been ‘debugged’ from an importing perspective and the trajectory software was constructing the desired geometry the validation of the code commenced. This provided a final challenge to be resolved relating to the geometry. The sending of the virtual sled down the track for validating the code highlighted an issue with some sudden changes in the ice profile geometry that had not been addressed in the initial geometry ‘clean-up’ operations.

There were certain large and sudden changes in the ice profile geometry which were causing the trajectory software to ‘crash’ during a run. The solution to this issue was to remove the offending geometry and replace the deleted section with a smooth connecting curve. This was achieved in the CAD package by ‘breaking’ the existing section curve, deleting the offending portion and then filling the gap using a ‘bridge’ curve command. The shape of this ‘bridge’ curve was manipulated to maintain as close fidelity as possible to the original ice profile data whilst smoothing out the geometry that was causing the issues in the trajectory software. The section curve was then connected to form a single continuous entity, the 101 points applied and the point data file exported. Appendix figures 1.1 - 1.70 show examples of how the geometry was repaired.
Figure 6.11: Illustration showing a distortion in the ice profile geometry that had to be removed.

The geometry was exported from the CAD as a text file with the X, Y and Z coordinates of all 101 points that had been evenly distributed over that individual section curve. These text files were individually named with a sequential and unique identifier (file 0001 being the beginning of the track at Bob Start) and the IBG design section track position reference.

The file identification format is as follows:

AAAA – plus or minus – XXXX.X

AAAA is the sequential number of the file and determines the order in which the trajectory software reads the file into the geometry constructor. These range from 0001 to 3034.

XXXX.X is the position along the track relating to the IBG design section plane which was used to create the cross section curve through the ice geometry at this position.

Appendix D.1 shows examples of point data files used by the trajectory software to create the geometry.
Figure 6.12: Illustration showing the IBG design section (red), the ice geometry section curve (white) and the 101 points (blue) applied to the ice geometry at IBG station SX = 435.5 (ref. Upper Section)

The trajectory model has the capability to import sequential files in one action providing that all section files are present. Video file ‘TrackBuildDemo’ shows an example of the creation of 416 individual sections starting from the start of the track.

The next step for the Trajectory model is to create a continuous surface through all the recreated sections. Figure 6.13 shows over 200 individual sections recreated and surfaced within the trajectory model. Once the track has been recreated and surfaced, the dynamic trajectory model can be applied.
Figure 6.13: Curve showing over 200 individual sections
6.5 Sled Dynamics Model

6.5.1 Overview

Bromley Technologies has been continuously developing a sled dynamics model (SDM) since 1994. It started as a basic physics model and has evolved into a comprehensive software tool that can simulate sled descents down bob tracks. The model has evolved from 17 years of research & development with three British Universities and strategic partners.

The Bromley Technologies SDM is the central tool used to deliver the trajectory part of this project.

6.5.2 SDM Objective

For the purpose of this project, the main objective is to provide trajectory data at predefined locations along the Whistler track for specific sled types and sets of initial conditions.

The SDM outputs trajectory data in several formats:

Simulation of the ‘ride path’ undertaken. Presented in both i) dynamic format (video of the sled travelling its path down the track) and ii) static format (image displaying the path as a colored line through the section)

Data such as speed at specific points on the trajectory

G-MAP (timeline of ‘g- forces’ or Centripetal accelerations) through a section

6.5.3 SDM Input Data

The SDM input data is split into two categories:

- Physical data parameters
- Track surface data points

Physical data parameters include all data that drives the ‘physics’ behind the SDM. This data is entered into the model in numerical form. This includes the following parameters:

- Ice friction coefficient
- Aerodynamic drag coefficient
- Sled Weight
- Section entry speed & angle

Section 6.6.2 presents the parameters used in the study.

Track surface data is in essence a digital geometric form of the surface of the track in 3D space. The model can either generate its own complex 3D surface data or it can ‘accept’ it in a specific format generated from external geometry design packages such as CAD.

The surface geometry used in this study is a reverse engineered form of the track’s ice surface as presented in 6.4.
It must be noted that the track’s concrete structure is not an accurate representation of the surface travelled on by a sled. The concrete track is a support structure that essentially creates an initial form on which to create the ice on. The ice surface is ‘formed’ on top of this underlying concrete structure via careful layering/freezing by a track work team. The ice surface can vary in thickness (cm’s), smoothness/roughness and surface quality along the track length and through track sections.

For reference, reverse engineered geometry is ‘real world’ geometry and is not a perfectly smooth geometric form. It requires careful and complex manipulation to prepare it into a data set to be entered into the SDM. Irregularities in the ice surface arising from hand shaping, expansion joints, track transitions, wear etc. are also measured. It is important for this study that these irregularities were captured as they present real ‘entities’ on the track surface that are experienced by the sleds/athletes as they ride over them.

6.5.4 SDM Design

The SDM treats the vehicle system (sled and athlete(s)) as a particle. This means that all the mass is concentrated at a point and that all the forces acting on the real vehicle act through the same point, being the centre of gravity. Although this feature limits the functionality of the model, for example, steering cannot be simulated; the combined system (track model and particle model) is a highly effective and accurate tool with which to predict the trajectory of a free running sled. In this work, the particle model is used to replicate several different sled systems (skeleton, luge and bob) to good effect.

The trajectory model is unable to replicate athlete steering whether it is induced through head, shoulders, knees or toes.

The ‘Skeleton’ aerodynamic data used within the model corresponds to Team Bromley Athlete’s and sleds. Therefore validation of the trajectory model was done using practical data measured using another athlete (with their own set of Aerodynamic data).

The particle is given a theoretical width representative to that of a specific sled, so that contact with walls and roofs can be modeled accurately. The particle is not given a length.

Simulation of trajectory ends if the particle leaves the ice. Trajectory model cannot predict where an athlete / sled will go once it leaves the track.

Model cannot simulate if slider and sled become separated.

A side wall impact model is used to simulate the impact of the particle with the side wall of the track. This model can distinguish between ‘vertical’ wall, found along the straight track sections and those sections of wall that comprise the banked sections within a curve (including the transitions at the start and end of a curved track section). The same model is also able to predict if the vehicle impacts with the roof structure. However, there is currently no accurate data specific to the sleds/athletes used in testing to provide a coefficient of restitution. The coefficient of restitution determines how much energy and hence speed is lost due to contact with walls etc. The coefficient of restitution would also affect how a sled/athlete would rebound from a side wall impact etc.
The vehicle model can begin its journey down the track from any location along the length of the track. Its lateral position and orientation is also specified along with the initial sled speed. This allows a concentration of effort to be made on specific track sections. Parametric sensitivity studies can be performed around these ‘ideal’ initial conditions to quantify the sensitivity of the vehicle trajectory to small changes in, for example, speed, orientation and lateral position across the track.
6.6 Trajectory Study

6.6.1 Run Test Matrix

Each discipline was subject to a curve by curve analysis, starting at the designated start section. In excess of 270 curve analyses were run and the composition of the run matrix is presented in Table 6.1.

Analyses of three variations of entry trajectory were performed. Visual images are outputted from chosen entry trajectories:

**Early**: An early entry trajectory is the path given to the sled so that it enters the track section in close proximity to the outer track wall section without impacts. (Red line on the trajectory images)

**Middle**: A middle entry trajectory is the path given to the sled so that it enters the track section in the middle position in relation to the track sides. (Green line on the trajectory images)

**Late**: A late entry trajectory is the path given to the sled so that it enters the track section in close proximity to the inner track wall section without impact. (Blue line on the trajectory images)

Notes: C8 was not included in any of the studies due to the curve being considered a dogleg straight section and not a ‘g’ inducing curve.

Early and late lines vary slightly in relative position between Luge, Skeleton and Bobsleighs due to variation in the width of the sled designs.
<table>
<thead>
<tr>
<th>Sport</th>
<th>Curve Analysis</th>
<th>Curve entry position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Luge</td>
<td>New Men’s Start (C3) to Outrun</td>
<td>Early, Middle, Late</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Early + 10% Speed</td>
</tr>
<tr>
<td>4 Man Bobsleigh</td>
<td>Start to Outrun</td>
<td>Early, Middle, Late</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Early + 10% Speed</td>
</tr>
<tr>
<td>2 Man Bobsleigh</td>
<td>Start to Outrun</td>
<td>Early, Middle, Late</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Early + 10% Speed</td>
</tr>
<tr>
<td>Skeleton</td>
<td>Start to Outrun</td>
<td>Early, Middle, Late</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Early + 10% Speed</td>
</tr>
<tr>
<td>Double Luge</td>
<td>New Women’s/ Doubles Luge Start (C6) to Outrun</td>
<td>Early, Middle, Late</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Early + 10% Speed</td>
</tr>
</tbody>
</table>

Table 6.1: Trajectory Run Matrix for the Sled Disciplines
6.6.2  SDM Parameter Review

There is limited ice friction and aerodynamic data openly published. Data that is published is often ‘generic’ in nature and not specific across sled design types or athlete characteristics.

Sled designs, athlete forms and apparel designs are constantly changing as teams seek competitive advantage through design innovation across athlete, sled and apparel. This continual innovation activity is therefore continually creating new ice and aerodynamics conditions.

A review of published ice friction and aerodynamics drag coefficient value has been made with particular emphasis on data that represents the bob sport disciplines.

Air density values were implemented into the model comparative to the values at the time of the Olympic games.

This study aimed at using the most up to date and reliable data where possible. Where published data was not available, data from private research studies was obtained with owner permission.

6.6.2.1  Ice Friction

A value coefficient of friction data of 0.01 is used for the trajectory model analysis.

This coefficient value is representative of a steel sled runner sliding on ice and is a value presented by numerous leading research institutions for practical measurements and studies made over a range of sled runner types on ice.

Data published by the University of Innsbruck, Austria suggests a coefficient of friction value for a single luge runner on ice of 0.01 and a double luge runner on ice of 0.012. ([http://sport1.uibk.ac.at/mm/publ/226--Moessner--An_Approximate_Simulation_Model_for_Initial_Luge_Track_Design--Poster.pdf](http://sport1.uibk.ac.at/mm/publ/226--Moessner--An_Approximate_Simulation_Model_for_Initial_Luge_Track_Design--Poster.pdf))

In the Appraisal of the Track Speed Calculation Method by Ingenieurburo Gurgel (IBG) The Swiss Federal Institute of Technology, Zurich suggests a generic coefficient of friction for a bobsled runner on ice of 0.01. (Previous studies in 2006 suggests a coefficient value in the range of 0.0125)

Delft University, Holland through their studies of two man bobsled runners sliding on ice suggests a coefficient of friction of 0.014. This friction value was referenced to Zhang, BOBSLEIGH AERODYNAMICS 9, 1995.

IBG track designers present friction coefficient of 0.010 ([WSC_Luge_Speed_Calculation_Feb_2011_Existing_Conditions].)

Notes: Published data does not account for variation in friction coefficient due to ice and or air temperature and air humidity variation. Furthermore published data does not account for a range of specific runner geometries interacting with the ice surface.

Published data does not account for the variation in preparation methods used by track to ready ice for sliding. Tracks use a variety of techniques for cutting, shaping and smoothing the ice surface. These techniques are fine-tuned with local weather conditions.
conditions in mind. Ice for training days and race days receive different levels of preparation. It is well known within the sliding sports that ice that is ‘unprepared’ and left exposed to the weather where the ice surface can frost up (due to air moisture / dew point) can result in considerably slower descent time than ice that has been specifically prepared for racing. These variations can change performance by as much as 5 to 10 seconds over a 60 second descent.

The range of published values for ice friction and aerodynamic drag is limited, constantly developing and changing.

6.6.2.2 Aerodynamic Drag

Aerodynamic drag coefficient and frontal area data for Skeleton was supplied by Bromley Technologies Ltd. This data obtained from research performed of the sled / athlete system in a leading Formula One Wind Tunnel in 2009. This wind tunnel research was cross referenced to within 2% of two company run CFD projects of the same geometries. This data can be made available on request only.

Aerodynamic drag coefficient and frontal area data for Luge and Bobsleigh was supplied by Bobsleigh Skeleton Canada. This data can be made available on request only.

Notes: Sled aerodynamic drag coefficients vary due to variation in geometric shape and surface friction conditions surrounding the sleds, athletes and race apparel. For example, the drag coefficient for a 100kg male Luge athlete on a sled design ‘A’ will be different to a 55kg female Luge athlete on sled design ‘B’.

Each athlete sled system has its own unique set of aerodynamic conditions which is made even more specific due to the weather conditions and altitude of a particular venue and event time.

Published aerodynamic values consider static cases (i.e. they do not account for variations in athlete movement or rotational angles (yaw, pitch, and roll) of sleds.)

6.6.2.3 Steering Dynamics

Although the SDM does not consider steering mechanisms, the model can take into account different forward and side friction coefficients.

Published data by Ulman & Cross, Hubbard suggests that side friction for a bobsled runner sliding sideways in the direction of motion is approximately 7x that of the runner sliding forward in the direction of motions. The ratio was taken into account in the SDM model in order to create a degree of side grip.

6.6.2.4 Start Conditions

For two man bobsleigh, four man bobsleigh and Skeleton analysis the full start ramp geometry was used. The fastest start speed from the Olympic Winter Games event was chosen as the initial start speed condition.
For Luge, the trajectory model did not use luge start ramp geometry. Luge start ramps enter the main track section from the side. This need to create a sharp change in direction meant that the SDM particle would travel directly into the wall as the SDM has no steering. Instead the particle was started where the luge ramps entered the track and was given a start velocity at this point that matched that provided by Whistler track’s split time / speed data sheets. These split time sheets capture every athlete’s times and speeds during training and race events.

6.6.3 SDM Filtering Conditions

SDM raw data requires filtering. Noise is created from the free particle traversing over surface irregularities within the scanned track either resulting from an uneven bumpy ice surface or from the geometry conversion process from the scanned track data into the digital model used in the SDM.

6.6.3.1 Filter Rates

A review of the acceleration data acquired during the March 2011 testing trip was undertaken to determine the correct data filtering rate. Filtering raw data is needed to remove unwanted ‘noise’ from acquired signals which can affect the extraction of accurate data. However, to set the correct cut off frequency, we must understand which frequencies are of importance.

FFT (Fast Fourier Transformation) data capture performed by the Centre for Advanced Product Evaluation (CAPE) showed that the power spectrum of the acquired data is contained within the 0-1 Hz band. Beyond 1Hz, the acceleration power spectrum is contained in the noise floor. Thus the Low pass cut of filter level was set at 2Hz for;

- Analysing measured test data
- Acceleration outputs of the Sled dynamics model (SDM)

It must also be noted that the University of Innsbruck (Austria) also implement the same cut off frequency within their simulation models.

http://sport1uibk.ac.at/mm/publ/226--Moessner--
An_Approximate_Simulation_Model_for_Initial_Luge_Track_Design--Poster.pdf

Figure 6.14 Plot of raw unfiltered data as outputted from the SDM shows an example of a channel of raw data acquired during the March testing trip on board a skeleton sled. Figure 6.15 Plot of a 10 Hz filter shows how a 10Hz low pass filter cleans the signal, and further still Figure 6.16: Plot of a 2 Hz filter shows the difference the 2Hz low pass filter makes when applied.
Figure 6.14: Plot of raw unfiltered data as outputted from the SDM
Figure 6.15: Plot of a 10 Hz filter
Figure 6.16: Plot of a 2 Hz filter
6.6.4 SDM Results Format

The SDM outputs both quantitative data sets and visual representation of each trajectory or path travelled by the particle through the curve section. Quantitative data sets include information such as entry and exit speeds through the curve section, the maximum ‘g’ accelerations experienced through the section, the time (seconds) for ‘g’ accelerations experienced above 4g, and the time taken to complete the analyzed section.

The visual format includes:
- Static images of the particle’s trajectory path represented by coloured lines along the curve’s surface.
- Animated particle trajectories are presented as video files.

6.6.5 On Track Study (March 2011) - SDM Model validation

6.6.5.1 Introduction

The individual vehicle models were validated against measured run times taken at Whistler during the same period over which the track was surveyed. This validation including comparison to actual split times of descents down the track, measured by the track’s timing system (accurate to 1/100th’s) and overlays of simulated and actual ride paths as recorded by curve by curve track video). The SDM is a ‘tool’ that creates a simulated run of a sled down a track. Its accuracy depends entirely on the accuracy of the input data.

The validation of the trajectory model is an important part of the study. Knowing that the model can theoretically replicate trajectories, speeds and ‘g’ forces allows for the accurate analysis of specific sections of track. Certain assumptions are made within the validation process, which were discussed in Section 6.6.2.

Multiple techniques were used to validate the trajectory model including split time analysis, speed analysis ‘g’ force analysis of practical data acquired and Video analysis of track descents.

6.6.5.2 Validation Methodology

The validation process started during the testing week held in March 2011 at the Whistler track. Athlete’s sleds from each discipline were fitted with portable data acquisition systems allowing the capture of multi-axial forces and rotational data. In total data was successfully acquired for 28 track descents between Bromley Technologies and CAPE. (Fig 6.19)

To discuss the methodology of the practical data acquisition we will use Charles Wlodarczak Run1 - Skeleton as the example. An unobtrusive multi-channel portable data acquisition system was fitted into the Skeleton sled of Canadian National slider Charles Wlodarczak.
Forces were measured in X,Y,Z axis together with angular rotation in each axis as the sled and athlete descended the track. The measured data was filtered with a low pass 2 Hz filter (4th order Butterworth). This removes unwanted high frequency noise from the measured data. Video footage from the Whistler track was captured through every available fixed camera together with every possible split (interval time) possible from the track timing system. Speeds were also measured at four locations on the track. Using the video footage, the particle was given the same curve entry points as those achieved by the athlete. This combined data was used to validate the trajectory model by comparing the descent split times – Table 6.4 and Fig 6.17.

The trajectory model consists of a geometrical track and a free body particle (FBP) that represents the athletes and sled system. The FBP models the sled system by assigning it multi-mathematical equations which rule its motion. Inherent within these mathematical equations are forces which act on the sled system:

- Total athlete and sled weight (acting vertically)
- Normal force that acts perpendicular to the surface at the contact point
- Aerodynamic lift in the normal direction
- Ice friction
- Aerodynamic drag

Other parameters which are constants within the model are atmospheric air density and gravity.

Data is entered into the trajectory model for the sled system being analyzed. For example, drag coefficients, mass of slider + vehicle, lift coefficient, frontal area and friction coefficients all differ for each discipline.

The skeleton sled (FBP) was assigned parameters to replicate the test athlete and his sled. The FBP was started at the top of the geometric track with the same start speed as was measured from the track system. A major factor with the trajectory model is that it cannot replicate athlete steering. In essence the free body particle will take a natural line around every track corner dependent on the entry conditions presented. If the FBP is left to navigate the entire track without intervention there would be wall impacts out of certain curves. These impacts would affect the model validation process as the athlete test runs did not experience impacts as athlete induced steering and control changes sled direction and to avoid impacts. Therefore the FBP was aimed / guided towards specific entry points into each curve section as the it progressed down the track. Positional references gained from the video captured data obtained through the track’s camera systems for the Skeleton test athlete’s runs was used to positional and guide the FBP model.

The trajectory model outputs interval split times at the exact points where timing eyes are located on the physical track. Table 6.2 details the timing intervals and speed traps utilized for this project. The model was validated by a direct comparison of these 12 split times. Table 6.3 shows the training split times and speeds provided by the Whistler Track and Table 6.4 shows the tabulated comparison between measured split times and those outputted by the model. Figure 6.17 shows a graphical comparison of the compared split times.
<table>
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<th>Timer Channel #</th>
<th>Location</th>
<th>Timing Port Number</th>
<th>Track Port Designation</th>
<th>Distance (Meters)</th>
<th>Function</th>
<th>Patch Panel Port</th>
</tr>
</thead>
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<tr>
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<td>Bob/Skel Start</td>
<td>1</td>
<td>MB-1</td>
<td>0.00</td>
<td>Bob Start</td>
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<td>2</td>
<td>50M</td>
<td>3</td>
<td>TI-1</td>
<td>49.00</td>
<td>Bob/Skel Start Time</td>
<td>1</td>
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<td>32</td>
<td>Outrun</td>
<td>42</td>
<td>BF-1</td>
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<td>Bob/Skel Finish</td>
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</tr>
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</table>

Table 6.2: Timing interval / speed trap location points
## TRAINING RESULTS

**START:** 19:30 - 15 March 2011

<table>
<thead>
<tr>
<th>Rank</th>
<th>Name</th>
<th>Start</th>
<th>Init 1</th>
<th>Init 2</th>
<th>Init 3</th>
<th>Init 4</th>
<th>Init 5</th>
<th>Init 6</th>
<th>Init 7</th>
<th>Init 8</th>
<th>Init 9</th>
<th>Init 10</th>
<th>Init 11</th>
<th>Finish</th>
<th>Sk. Spd</th>
<th>Event</th>
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<td>5:23(4)</td>
<td>14:11(4)</td>
<td>17:35(4)</td>
<td>21:30(4)</td>
<td>23:77(3)</td>
<td>27:16(3)</td>
<td>31:74(2)</td>
<td>37:84(1)</td>
<td>41:06(1)</td>
<td>45:38(1)</td>
<td>49:23(1)</td>
<td>55:07(1)</td>
<td>43.6</td>
<td>62.5</td>
<td>128.8</td>
</tr>
<tr>
<td>4</td>
<td>CAN FAIRBERG Paul</td>
<td>5:04(1)</td>
<td>13:03(1)</td>
<td>17:24(3)</td>
<td>21:20(3)</td>
<td>23:77(3)</td>
<td>27:22(4)</td>
<td>31:84(4)</td>
<td>38:14(5)</td>
<td>41:43(5)</td>
<td>45:89(5)</td>
<td>49:85(5)</td>
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<tr>
<td>5</td>
<td>CAN GOOD Ryan</td>
<td>5:22(4)</td>
<td>14:12(3)</td>
<td>17:40(3)</td>
<td>21:42(3)</td>
<td>23:89(5)</td>
<td>27:31(5)</td>
<td>31:92(5)</td>
<td>38:09(4)</td>
<td>41:33(4)</td>
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<td>44.1</td>
<td>62.2</td>
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<tr>
<td>6</td>
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<td>5:30(9)</td>
<td>14:56(10)</td>
<td>17:84(10)</td>
<td>21:88(10)</td>
<td>24:34(9)</td>
<td>27:77(7)</td>
<td>32:37(7)</td>
<td>38:48(7)</td>
<td>41:67(8)</td>
<td>45:98(8)</td>
<td>49:81(5)</td>
<td>55:57(5)</td>
<td>42.2</td>
<td>61.3</td>
<td>126.0</td>
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<tr>
<td>7</td>
<td>CAN KELLY Michelle</td>
<td>5:50(9)</td>
<td>14:52(9)</td>
<td>17:79(9)</td>
<td>21:87(9)</td>
<td>24:40(10)</td>
<td>27:91(9)</td>
<td>32:63(9)</td>
<td>38:55(9)</td>
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<td>50:45(9)</td>
<td>56:34(8)</td>
<td>42.8</td>
<td>61.6</td>
<td>125.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5:47(9)</td>
<td>14:38(8)</td>
<td>17:85(7)</td>
<td>21:72(8)</td>
<td>24:25(8)</td>
<td>27:81(8)</td>
<td>32:64(8)</td>
<td>38:59(9)</td>
<td>42:12(9)</td>
<td>45:78(9)</td>
<td>50:75(9)</td>
<td>56:77(8)</td>
<td>43.5</td>
<td>62.2</td>
<td>123.2</td>
</tr>
</tbody>
</table>

**Whistler Sliding Centre, B.C., Canada**

379 BCS Skol
Table 6.3: Training split times and speeds provided by the Whistler Track

<table>
<thead>
<tr>
<th>Split time Interval</th>
<th>Distance from Bob Start (m)</th>
<th>Charles Wlodarczak (sec)</th>
<th>Trajectory Model (sec)</th>
<th>Difference (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start</td>
<td>49</td>
<td>5.29</td>
<td>5.29</td>
<td>0</td>
</tr>
<tr>
<td>Exit C2</td>
<td>199</td>
<td>14.23</td>
<td>14.203</td>
<td>-0.027</td>
</tr>
<tr>
<td>Exit C3</td>
<td>275.1</td>
<td>17.46</td>
<td>17.44</td>
<td>-0.04</td>
</tr>
<tr>
<td>Exit C4</td>
<td>372</td>
<td>21.48</td>
<td>21.464</td>
<td>-0.016</td>
</tr>
<tr>
<td>Entry C5</td>
<td>436</td>
<td>23.92</td>
<td>23.96</td>
<td>0.03</td>
</tr>
<tr>
<td>Exit C6</td>
<td>529</td>
<td>27.32</td>
<td>27.4</td>
<td>0.08</td>
</tr>
<tr>
<td>Exit C7</td>
<td>663.5</td>
<td>31.94</td>
<td>32.06</td>
<td>0.12</td>
</tr>
<tr>
<td>Exit C10</td>
<td>849.1</td>
<td>38.06</td>
<td>38.17</td>
<td>0.12</td>
</tr>
<tr>
<td>Exit C11</td>
<td>958</td>
<td>41.26</td>
<td>41.37</td>
<td>0.11</td>
</tr>
<tr>
<td>Exit C13</td>
<td>1103</td>
<td>45.56</td>
<td>45.65</td>
<td>0.1</td>
</tr>
<tr>
<td>Exit C15</td>
<td>1251.4</td>
<td>49.37</td>
<td>49.45</td>
<td>0.08</td>
</tr>
<tr>
<td>Finish</td>
<td>1460.4</td>
<td>65.13</td>
<td>65.18</td>
<td>0.05</td>
</tr>
<tr>
<td>Start Speed</td>
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<td>43.2 km/h</td>
<td>43.9 km/h</td>
<td>0.7 km/h</td>
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<tr>
<td>Speed C1 - C2</td>
<td>125.6</td>
<td>62.1 km/h</td>
<td>62.1 km/h</td>
<td>0 km/h</td>
</tr>
<tr>
<td>Speed C11-C12</td>
<td>568.1</td>
<td>127.4 km/h</td>
<td>125.7 km/h</td>
<td>-1.7 km/h</td>
</tr>
<tr>
<td>Speed C15-C16</td>
<td>1261.5</td>
<td>140 km/h</td>
<td>138.9 km/h</td>
<td>-1.1 km/h</td>
</tr>
</tbody>
</table>

Table 6.4: Tabulated comparison between measured split times and model prediction
Figure 6.17: Graphical comparison between measured split times and model prediction
Figure 6.18 shows the measured data acquired ('normal' / 'g' direction) for Charles Wlodarczak – test run 1. ‘G’ force comparisons were made between the measured data and the predicted model data. The trajectory run matrix (Table 6.1) developed from the findings of the ‘Crash injury frequency study’ identified that all trajectory studies were to be concentrated on the middle, lower and finish sections of the track. Comparative analysis on 'g' force was conducted on individual curves 8-16 through these sections 9 – 16. Table 6.5 shows the comparison of the measured 'g' force data vs. model prediction for Charles Wlodarczak Test Run 1.
Table 6.5: comparison of measured ‘g’ force data vs. model prediction middle, lower and finish sections

<table>
<thead>
<tr>
<th>Curve</th>
<th>(g)</th>
<th>Trajectory Model (g)</th>
<th>Difference (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C8</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>C9</td>
<td>3.8</td>
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<td>-0.2</td>
</tr>
<tr>
<td>C10</td>
<td>3.5</td>
<td>3.7</td>
<td>+0.2</td>
</tr>
<tr>
<td>C11</td>
<td>4.1</td>
<td>3.9</td>
<td>-0.2</td>
</tr>
<tr>
<td>C12</td>
<td>3</td>
<td>2.7</td>
<td>-0.3</td>
</tr>
<tr>
<td>C13</td>
<td>1.75</td>
<td>2</td>
<td>+0.25</td>
</tr>
<tr>
<td>C14</td>
<td>4</td>
<td>3.75</td>
<td>-0.25</td>
</tr>
<tr>
<td>C15</td>
<td>3.75</td>
<td>3.9</td>
<td>+0.15</td>
</tr>
<tr>
<td>C16</td>
<td>4.4</td>
<td>4.25</td>
<td>-0.15</td>
</tr>
</tbody>
</table>

The analyzed curves predict within 0.3g of the measured value. Predicted values will vary dependent on how much steering the athlete employs within the curve. The model predicts the ‘g’ force due to a trajectory line with no steering.

This validation process was carried out for the sliding disciplines of Single Luge, Double Luge, 2-man Bobsleigh and 4-man Bobsleigh relative to their specific section analyses.
6.6.5.3 Testing Week Considerations

Data acquired for Luge and Bobsleigh during the testing week was not for replicated start location and race speeds. For example 4-man Bobsleigh started the descent at Damen (Ladies) start which is positioned between curve 2 and curve 3. The single Luge men’s start was not in effect, although a descent was undertaken from the Bobsleigh and skeleton start.

The track was comparatively slow compared to track surfaces prepared for World Cup / Olympic events.

Exact aerodynamic data was not known for the sled/athlete systems used during the validation test week in March 2011. The values as supplied and used in the SDM are for an athlete of the same sex, similar size and weight.

Test data was captured using ‘home’ nation athletes with considerable experience of driving the track. This led to data being captured for clean lines with no impacts. This was critical in creating runs that could be used to validate the model.

Athletes during the test week were calm and composed. During high pressure events such as World Cups and Olympic Games, varying athlete emotional states and levels of adrenaline may well affect driving accuracy.

Figure 6.19: Photograph of CAPE Portable Data Acquisition System Installed on Singles Luge Sled
6.7 Results

The complete results of the trajectory modeling are presented in Appendix D. The trajectory paths, predicted velocities and “g” forces are analyzed for each discipline by corner/segment of the Track. In this section of the report a sample of the analysis of corner (C1 for 4 man bobsleigh) is presented. The results for each discipline, down the entire length of the track, are summarized and analyzed with recommendations and considerations for each discipline.

6.7.1 Descriptive Terms

In the analysis, the following terms are used and defined as:

- Peaks – used to describe the g acceleration profile associated to the waves.
- Waves - used to describe the shape of the trajectory around a curve as it rises and drops due to the mix of g accelerations and track geometry change.
- Drop – used to describe the descent from a high point on the curve. For example; between waves or at the end of a curve.
- Rise - used to describe the ascent from a low point on the curve. For example; between waves or at the entry of a curve.
- High line – used to describe the position of the sled with respect to the roof of the track or in relation to the other trajectories being analyzed.
- Left wall or Left side of the track – The wall designated on the left hand side of the track when facing the direction of motion
- Right wall or Right side of the track – The wall designated on the right hand side of the track when facing the direction of motion

6.7.2 Sample Analysis

The analysis for a particular discipline is presented in terms of the Sled Dynamics Model (SDM) parameters and an analysis of the trajectory for a specific area of the Track. The entire analysis is presented in Appendices D.2 to D.6.

For each discipline and section of the Track the trajectory analysis is comprised of:

- defined initial velocity,
- a graphical presentation of the SDM output trajectory paths,
- plots of the SDM centripetal acceleration and velocities,
- a summary table of SDM results in terms of velocities, maximum predicted “g” forces and duration of “g” forces exceeding 4 g’s,
- trajectory observations,
- considerations for track improvements.

The following is a sample of the trajectory analysis presentation using the results from the trajectory modeling of a four man bobsleigh travelling through corner 1.
6.7.2.1 Sample Trajectory Analysis of Four Man Bobsleigh

6.7.2.1.1 SDM Input Parameters for Four Man Bobsleigh

<table>
<thead>
<tr>
<th>Initial Particle Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Discipline</strong></td>
</tr>
<tr>
<td><strong>Combine Sled + Athlete weight</strong></td>
</tr>
<tr>
<td><strong>Aero Drag coefficient</strong></td>
</tr>
<tr>
<td><strong>Aero Lift coefficient</strong></td>
</tr>
<tr>
<td><strong>Frontal area (m^2)</strong></td>
</tr>
<tr>
<td><strong>Ice – Runner friction coefficient</strong></td>
</tr>
<tr>
<td><strong>Air density</strong></td>
</tr>
</tbody>
</table>

Table 6.6: Sled Dynamics Model (SDM) parameters

6.7.2.1.2 Curve 1 Analysis

6.7.2.1.2.1 Entry Speed

The sled / athlete particle is set to enter the curve section at a predefined speed determined from the exit speed of previous section analysis:

Sled speed in direction of travel at t=0 46 km/h
(Fastest speed recorded from Olympics for this section)

6.7.2.1.2.2 SDM Output Trajectories

Figure 6.20 and Figure 6.21 present the sled trajectories predicted by the Sled Dynamics Model (SDM).

The trajectories associated with the four entry lines as determined by the Run matrix in Table 6.1 are represented by different colors.

6.7.2.1.2.3 SDM Centripetal Acceleration Plots & Velocity Plots

Figure 6.22, Figure 6.23, Figure 6.24 and Figure 6.25 present the centripetal accelerations (measured in ‘g’) and velocity profile (km/hr) predicted by the Sled Dynamics Model (SDM).
Figure 6.20: Overlay of the SDM trajectories - C1 Entry 4 Man Bobsleigh
Figure 6.21: Overlay of the SDM trajectories - C1 Exit Reverse 4 Man Bobsleigh
Figure 6.22: 'g' Force & Velocity Speed Plot – Early entry line C1 4 Man Bobsleigh
Figure 6.23: 'g' Force and Velocity Plot – Middle entry line C1 4 Man Bobsleigh
Figure 6.24: 'g' Force and Velocity Plot – Late entry line C1 4 Man Bobsleigh
Figure 6.25: ‘g’ Force and Velocity Plot – Early entry line +10% entry speed C1 4 Man Bobsleigh
6.7.2.1.2.4 **SDM Results Summary**

Table 6.7 presents speed, time and g-force data for the curve analysis.

<table>
<thead>
<tr>
<th>SDM trajectory data – Four Man Bobsleigh</th>
<th>Early Entry</th>
<th>Middle Entry</th>
<th>Late Entry</th>
<th>Early Entry + 10% speed</th>
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<tr>
<td>Exit Speed (km/hr)</td>
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<td>66.1</td>
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<td>69.3</td>
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<td>Max 'g' force predicted (g)</td>
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<td>3.3</td>
<td>3.2</td>
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<tr>
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<td>0</td>
<td>0</td>
<td>0</td>
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</tbody>
</table>

Table 6.7: SDM Trajectory Data for C1 4 Man Bobsleigh

6.7.2.1.2.5 **Trajectory Observations**

Early Entry Line 'g' profile reaches a maximum of 2.7g

Middle Entry Line 'g' profile reaches a maximum of 2.8 g.

Late Entry Line 'g' profile reaches a maximum of 3.3 g

The late entry line creates a considerably higher line through the curve. This creates a 'high' position at the end of the curve. This high position creates a steep exit trajectory which creates an impact into right (inner) wall.

Early Entry Line + 10% speed ‘g’ profile reaching maximum of 3.2g

6.7.2.1.2.6 **Considerations**

Consideration should be given to barriers at the exit of C1 on the right side wall at the site of impact of the particle.
### 6.7.3 Summary of 4 Man Bobsleigh Trajectory Findings

#### 6.7.3.1 Speed & ‘g’ Force Acceleration Results for 4 Man Bobsleigh

In Table 6.8 a summary of the predicted ‘g’ accelerations down the Whistler track broken down into sections from the Bob start to the finish curve 16. is presented where ‘g’s’ predicted over 5 are highlighted in red.

<table>
<thead>
<tr>
<th>Curve 1</th>
<th>Entry</th>
<th>Early</th>
<th>Middle</th>
<th>Late</th>
<th>Early + 10% speed</th>
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<tbody>
<tr>
<td></td>
<td>Entry Speed (km/hr)</td>
<td>46</td>
<td>46</td>
<td>46</td>
<td>50.6</td>
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<td></td>
<td>Exit Speed (km/hr)</td>
<td>66.1</td>
<td>66.1</td>
<td>65.5</td>
<td>69.3</td>
</tr>
<tr>
<td></td>
<td>Max 'g' force predicted (g)</td>
<td>2.7</td>
<td>2.8</td>
<td>3.3</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>time 'g' value exceeds 4g (sec)</td>
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</table>

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<th>Late</th>
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<tr>
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<td>66.1</td>
<td>66.1</td>
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<td>Exit Speed (km/hr)</td>
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</tr>
<tr>
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<td>Max 'g' force predicted (g)</td>
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<td>4.0</td>
<td>4.6</td>
<td>4.3</td>
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<table>
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<th>Late</th>
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<tr>
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<td>84.0</td>
<td>84.0</td>
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<td>Exit Speed (km/hr)</td>
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<td>90.8</td>
<td>89.0</td>
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</tr>
<tr>
<td></td>
<td>Max 'g' force predicted (g)</td>
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<td>2.40</td>
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<th>Entry</th>
<th>Early</th>
<th>Middle</th>
<th>Late</th>
<th>Early + 10% speed</th>
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<tbody>
<tr>
<td></td>
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<td>91.5</td>
<td>91.5</td>
<td>100.7</td>
</tr>
<tr>
<td></td>
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<td>96</td>
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<td></td>
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<td>3.8</td>
<td>4.4</td>
<td>5.8</td>
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<td></td>
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<td>0</td>
<td>0.36</td>
<td>0.84</td>
<td>1.14</td>
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Table 6.8: Summary of SDM predicted Speed and ‘g’ accelerations
<table>
<thead>
<tr>
<th>Curve 5</th>
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<tbody>
<tr>
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<td>Early</td>
<td>Middle</td>
<td>Late</td>
<td>Early + 10% speed</td>
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<td>Exit Speed (km/hr)</td>
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<td>Late</td>
<td>Early + 10% speed</td>
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<td>Exit Speed (km/hr)</td>
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<tbody>
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<td>Middle</td>
<td>Late</td>
<td>Early + 10% speed</td>
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<tr>
<td>Entry Speed (km/hr)</td>
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<td>Exit Speed (km/hr)</td>
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<td>129</td>
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<td>5.4</td>
<td>6.3</td>
<td>5.8</td>
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<table>
<thead>
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<td>Entry Speed (km/hr)</td>
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<table>
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<td>Entry Speed (km/hr)</td>
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<td>130.5</td>
<td>130.5</td>
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<tr>
<td>Exit Speed (km/hr)</td>
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Table 6.8: Summary of SDM predicted Speed and ‘g’ accelerations (cont.)
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<td>135.5</td>
<td>135.5</td>
<td>149</td>
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<tr>
<td>Exit</td>
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<td>141.7</td>
<td>143</td>
<td>158</td>
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<tr>
<td>Entry</td>
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<td>137</td>
<td>137</td>
<td>150.7</td>
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<td>Exit</td>
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<tr>
<td>Entry</td>
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<td>137.5</td>
<td>137.5</td>
<td>151.25</td>
</tr>
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<td>142</td>
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<table>
<thead>
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<th>Early + 10% speed</th>
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<tr>
<td>Entry</td>
<td>143</td>
<td>143</td>
<td>143</td>
<td>157.3</td>
</tr>
<tr>
<td>Exit</td>
<td>143</td>
<td>146</td>
<td>144</td>
<td>162</td>
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<table>
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<td>Entry</td>
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<td>Exit</td>
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Table 6.8: Summary of SDM predicted Speed and ‘g’ accelerations (cont.)
Table 6.8: Summary of SDM predicted Speed and ‘g’ accelerations (cont.)

![Velocity plot and g-force map for 4 man bobsleigh](image)

The SDM model has an error bar of +/- 0.3g when compared to a real run of similar run parameters. The velocity plot and g-force map in Figure 6.26 is a composite of the plots.
and maps modeled for each section and is generated using the early and middle curve entries.

This study presents trajectories and predicted ‘g’ for a theoretical free flowing sled particle. Bobsleighs in reality can steer and thus can adjust the lines and waves to create considerable variation from the natural free flowing paths. An athlete is able to affect change on the bob through steering inputs and therefore change the trajectory. By creating longer, lower waves, lower g forces will be experienced. Likewise an athlete can create shorter higher waves through a curve by steering against natural tendencies of the track and by choosing to enter a curve with an extreme angle. Thus higher g’s than those predicted could be attained.

This study used the fastest four man bob speed recorded off the start from the 2010 Vancouver Olympic Winter Games. This set the initial condition from which the rest of the run followed.

This trajectory study simulated the path of a particle on a real scanned track surface. This surface is not perfectly smooth and shows considerable undulations in the surface. These undulations can arise from a variety of sources. For example, from the man-made ice preparation techniques, expansion and contraction of ice and the concrete track structure as temperature rises and falls, degradation due to runner wear or weather effects or undulating concrete structures beneath the ice. These ice surface variations create small direction changes that can result in increased g’s experienced through a section. The degree and size of the undulation will influence the g measured. The variation in g and velocity due to surface irregularities are highlighted and measured by the SDM and illustrated in the g and velocity plots. Original track design studies will use smooth CAD generated curves from original design intent. These curves will give back smooth g profiles and potentially lower g values than an irregular real ice surface. It is recommended that further studies are performed to understand the variation in g from a perfectly smooth curvature to that of a real undulating ice surface that has been hand shaped and prepared by ice workers and has experienced the changing environmental conditions. This would help track designers to set an error bar or working tolerance that would enable track designers to predict real g forces from a smooth perfect model surface.

6.7.3.2 Injury and Incident Frequency Study Analysis 4 Man Bobsleigh

6.7.3.2.1 Crash Frequency Study for 4 Man Bobsleigh

The injury and incident frequency study highlighted that curves 13 and 14 were the areas of highest incident. The most common incident for any Bobsleigh through this section is to be turned onto its side.

Curves 9 and 16 were other areas where incidents occurred with higher frequency.
6.7.3.2.2 Potential Reasons for Crash Frequency Statistics for 4 Man Bobsleigh

Based on the trajectory modeling for the 4 man bobsleigh, the following is a perspective on the contributions to incidents on the track.

The injury and incident frequency study highlighted that curves 13 and 14 were the areas of highest incident for the 4 man bobsleigh.

A sequence of trajectory studies with varying entry lines into C13 highlights key curve characteristics that could cause the highest crash incidence rate through C13 to C14.

Even though the ‘g’ accelerations recorded through C13 are not high, the curve appears to be a challenge due to two reasons:

The high exit line out of C12 naturally creates an impact on the left wall very close to the entry point of C13. The rebound effect of this impact creates a ‘push’ off the left wall which results in the sled cutting across C13 as opposed to travelling around it. The result of this is that the sled rides back up the end of C13 and the sharp direction change can flip the bob onto its right side.

On close inspection of the scanned geometry the entry to C13 appears to have a hump in the ice on the entry to the curve, with the highest part of this hump being on the left side into the curve. If the bobsleigh manages to negotiate C12 and exit without a left wall impact into C13, the left runner of the bob rides over a hump in the ice. The earlier the line into C13 the more extreme the effects of riding this hump. The hump will create a sudden push upwards on the left runner of the bob and could in effect ‘pop’ the left side of the bob up off the ice. This pop could either flip the bob onto its right side or at least destabilize the bob. If the bob manages to ride this hump, it has the added effect of pushing the sled off the curve, which results in the sled cutting across curve 13 as opposed to travelling around it. The result of this is that the sled rides back up the end of C13 and the sharp direction change can flip the bob onto its right side.

The reality is that C13 is very difficult to negotiate through without the bob flipping on its right side at worst or at best becoming unstable. An unstable bob out of C13 will create an unstable bob through C14.

6.7.3.3 SDM Model Results vs Actual Run Data for 4 Man Bobsleigh

In Figure 6.27 a comparison of the time SDM model run time versus the base line USA – 1 run time is presented in terms of the difference between the model run time and actual run time. This plot shows that the model is in relatively good agreement with the actual run time of a 4 – man bobsleigh.
Figure 6.27: Distance against Time plots of the SDM model performance vs the Gold medal performance from the 2010 Vancouver Olympic Games

6.7.3.4 Considerations & Recommendations – 4 Man Bobsleigh

The SDM analyzes the sled trajectory as a free particle model. In other words it considers the path of a particle flowing naturally down the track without the external influence of any athlete steering inputs and skill level or variations in control authority of the sled.

It must be noted that sleds across the sport have a broad spectrum of designs and control authority of which there is very little or no published data. Combined with almost limitless variation in runner design (even within a tightly controlled technical rule book) it becomes impossible to account for the steering mechanisms and variation in design for all bobsleighs across the nations and teams.

The free particle model however is a powerful tool that predicts the trajectory of a generic sled along the course without steering inputs (i.e. left to run freely). For the purpose of this project this in essence allows the SDM to predict trajectories and highlight areas of concern that are generated purely from the track & sled physics, the track/ice geometry, ice properties associated with sleds sliding on ice and aerodynamic properties of generic sled designs within the sled category.
6.7.3.4.1 G Force & Velocity Limitations for 4 Man Bobsleigh

Table 6.8 highlights predicted ‘g’ forces over 5 g. The options to reduce the ‘g’ accelerations in a curve are:

- Increasing curve radius with particular emphasis on the section of the curve which shows high g.
- Slowing the track by slowing the ice i.e. increasing the ice friction coefficient. Individual track sections could be targeted which could then act as ‘speed limiters’.
- Slowing the sled. e.g. by slowing the runner i.e. increasing the ice friction coefficient by employing a roughness and surface finish control.
- Modify track sections to create uphill sections that act as speed limiters.

Since ‘g’ force acceleration is proportional to velocity squared, it could be argued that the most effective way to reduce ‘g’ accelerations through a section is to slow the track speed.

6.7.3.4.2 Safety Boards / Barriers /Roof Integrity for 4 Man Bobsleigh

This study highlights potential impact sites on the track from a free flowing sled particle. In all areas where track impacts are seen from free flowing lines, it is recommended that the current roll over barriers and safety boards are reviewed in the zones of impact or zones of concern taking into account the following observations.

From the trajectory analysis it is evident that the trajectories through some curves are more sensitive to speed and entry line variation than others. These curves create the potential for a wider range of lines and thus a wider range of possible events. These curves need careful consideration.

Curves 4, 6, 7, 11, and 16 are in particular sensitive to entry line and speed variation.

Consideration with respect to safety barrier construction should be given to all impact sites or areas where the sled approaches the limit of the track geometry. Each impact site is explained in more detail in each curve analysis section.

In summary these sites are:

- Curve 1: Right wall on exit
- Curve 2: Roof to right wall area on curve exit
- Curve 3: Left wall on exit
- Curve 4: Right wall on exit; Roof area on the left extending onto and along the left wall on exit; Roof integrity at the end of C4.
- Curve 5: Left wall on curve exit
- Curve 6: Roof area at the end of the curve and the transition from roof section to the left track wall: Integrity of the roof construction at the very end of curve in the event of a roof impact; Left wall on exit.
- Curve 7: Roof area at the end of the curve and the transition from roof section onto the right track wall: Integrity of the roof construction at the very end of curve in the event of a roof impact; Right wall on exit.
• Curve 9: Left wall on exit (between C9 and C10)
• Curve 10: Left wall on exit
• Curve 11: Right wall on exit; Roof area / end of the curve transition onto the left wall.
• Curve 12: Left and right walls on exit (between C12 and entry C13).
• Curve 14: Left wall on exit (between C14 and C15)
• Curve 15: Right wall on exit; Area of the roof at the end of C15 and the left wall
• Curve 16: Right wall and left wall on exit. The natural line creates multiple rebound impact potential; Integrity of the curve roof for wave 1 and 2 peak locations in the event of roof impacts.

Note that this study does not recommend specific barrier size or exact location for considering safety barriers. This study presents areas for concern for the lines identified in the test run matrix. This study does not present the range of all possible impacts arising from a comprehensive range of entry speeds and lines or trajectories created from human driver error or decision making. It is highly recommended that further work is undertaken to assess a wider cross section of entry lines and speeds in order to gain a better understanding of the size of the impact zone areas.

6.7.3.4.3 Ice Profile Considerations for 4 Man Bobsleigh

Based on the observations of the trajectory lines, the following are recommendations for monitoring the ice profiles

In C6 consideration must be given to the ice profile between the track ‘floor’ and the left wall on the exit of C16. Oversized rounded fillets between the floor and the left wall could in effect create a ramp upon which the left runner of the bob could ride up.

In C9 consideration should be given to the ice profile through C9 in order to reduce the natural push off the curve into the left wall on exit. This would give the driver more range and choice of entry lines into C10.

In C12 the trajectory study highlighted the difficulty for a sled to ride up early onto C12 due to the lead in geometry of the track making this possibility very difficult.

Consideration should be given to adjusting this entry portion of the curve profile to make it easier to create height earlier in C12 when on an early entry line, which is the natural line form the exit of C11. The extreme height gained in curve 12 is a factor in the left wall impact out of C12 which destabilizes the bob before negotiation of C13.

Information attained from MAIN DOCUMENT Var03a WSCPART-A (October 232004, page 11) suggests that the entrance to C12 was intentionally designed into the track to create an additional level of difficulty through C12:

'As an additional difficulty the vertical radius are formed so that the vertical centrifugal force shows one easy answering. That is N = 0,40 at the end of the "bended straight line" ( C8 ) with N ( Sx = 714,5 m ) and in the straight line in front of curve C12 with N = 0,67.'

Note: This is an English translation where “one easy answering” could be interpreted as “one driving line”.
For curves 12 to 13 it is recommended that the ice profile in C12 is shaped where possible to create a longer exit radius, more progressive ‘g’ and less extreme exit trajectory out of C12 into C13. This will create more choice for driving line selection into curve 13 as opposed to a forced path due to extreme C12 exit height and exit line.

At the entry to C13 the trajectory study highlighted the existence of a ‘hump’ in the ice on entry to C13 and highlighted the effect this hump has on ‘pushing’ the sleds off the early entry line and onto a line that cuts across the curve. This entry hump in essence increases the crash potential through C13.

It is highly recommended that the ‘hump’ on the left side of the track on the entry to C13 is modified. When combined with the modifications to the C12 ice profile this will remove the potential for the left runner to ride up the hump and thus reduce the chance of the sled flipping over on its right side. Reducing the significance of this hump will also prevent the sled from being pushed back off the curve and will enable the sled to follow a line into the ‘belly’ of the curve. This will in turn allow lessen the extreme direction change at the end of the curve and therefore reduce the second potential area for the sled flipping over onto its rights side.

For curves 15 to 16 it is recommended that the ice profile through C15 is modified so that drivers are given more range to choose their entry line into C16.

The model predictions show that the natural tendency of C15 is to ‘force’ a free flowing path down the right side of the track sometimes creating a right wall impact and thus creating a ‘late’ or right side entry trajectory into C16.

The late line into C16 creates more g through the first wave of curve 16 than an entry or middle entry line would create.

In C16 careful consideration must be given to the ice profile between the track ‘floor’ and the right wall on the exit of C16. Oversized rounded fillets between the floor and the right wall could in effect create a ramp upon which the right runner of the bob could ride up.
6.7.3.5 Final General Considerations for 4 Man Bobsleigh

There are four key factors of the track’s characteristics that need to be carefully considered together during track design phase.

These factors are:

- Fast speeds (usually the bottom part of tracks)
- High ‘g’ forces (curves that combine small radii or sharp change in direction with speed)
- Technical sections requiring high skill levels to negotiate through without incidence.
- Curve profiles that force natural paths and therefore limit the range of lines achievable by the athlete through steering.

It is when three or four of these factors combine that the potential for crashes and wall impacts rise.

It is recommended that future track designs avoid the combination of three or four of these factors. It is recognized that the sports rely on creating tracks that are challenging in order to differentiate between the skill abilities of the best athletes in the world. However it is recommended that technical sections are combined with slower speed sections and possible lower ‘g’ forces as opposed to technical sections are combined with high g loading, fast speeds and curve profiles that tend to force a particular trajectory or path. It is the combination of all four factors that heightens the probability of incidence.

It must be noted that athletes if so wished, could possibly ‘tip’ or crash a sled or create a wall impact in the slower curves of a track if they steered against the curves in an extreme manner. Thus when considering what is ‘safe’ and ‘what is not safe’ with respect to track design it must be understood that poor steering decisions by the athlete will always result in lines that are considered unsafe or dangerous. This is inherent within the sport.

It is recommended that all new tracks are independently analyzed during the design stages to offer a second or third opinion on design and trajectory simulations.
6.7.4 Summary of Results for Singles Luge

6.7.4.1 SDM Input Parameters for Singles Luge

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<td>Aero Drag coefficient</td>
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<td>Aero Lift coefficient</td>
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<td>Frontal area (m^2)</td>
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<td>Ice – Runner friction coeff</td>
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</tbody>
</table>

Table 6.9: Sled Dynamics Model (SDM) parameters for Singles Luge

6.7.4.2 Speed & ‘g’ Force Acceleration Results for Singles Luge

In Table 6.10 a summary of the predicted ‘g’ accelerations down the Whistler track broken down into sections from the Ladies start to the finish curve 16 is presented. The g-forces predicted over 5 g are highlighted in red.

Table 6.10: Summary of SDM predicted ‘g’ and velocities for singles luge from the ‘Ladies start’
<table>
<thead>
<tr>
<th>Curve 5</th>
<th>Entry</th>
<th>Early</th>
<th>Middle</th>
<th>Late</th>
<th>Early + 10% speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry Speed (km/hr)</td>
<td>62.5</td>
<td>62.5</td>
<td>62.5</td>
<td>68.8</td>
<td></td>
</tr>
<tr>
<td>Exit Speed (km/hr)</td>
<td>72.8</td>
<td>72.7</td>
<td>72.4</td>
<td>78</td>
<td></td>
</tr>
<tr>
<td>Max 'g' force predicted (g)</td>
<td>1.7</td>
<td>1.58</td>
<td>1.8</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td>time 'g' value exceeds 4g (sec)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Curve 6</th>
<th>Entry</th>
<th>Early</th>
<th>Middle</th>
<th>Late</th>
<th>Early + 10% speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry Speed (km/hr)</td>
<td>72.8</td>
<td>72.8</td>
<td>72.8</td>
<td>80.1</td>
<td></td>
</tr>
<tr>
<td>Exit Speed (km/hr)</td>
<td>83.0</td>
<td>81.6</td>
<td>80.9</td>
<td>88.3</td>
<td></td>
</tr>
<tr>
<td>Max 'g' force predicted (g)</td>
<td>2.45</td>
<td>2.72</td>
<td>4.6</td>
<td>3.2</td>
<td></td>
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<tr>
<td>time 'g' value exceeds 4g (sec)</td>
<td>0</td>
<td>0</td>
<td>0.39</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Note the relatively high late entry line max g may be due to an impact</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Curve 7</th>
<th>Entry</th>
<th>Early</th>
<th>Middle</th>
<th>Late</th>
<th>Early + 10% speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry Speed (km/hr)</td>
<td>83.0</td>
<td>83.0</td>
<td>83.0</td>
<td>91.3</td>
<td></td>
</tr>
<tr>
<td>Exit Speed (km/hr)</td>
<td>95.5</td>
<td>94.9</td>
<td>96.1</td>
<td>100.7</td>
<td></td>
</tr>
<tr>
<td>Max 'g' force predicted (g)</td>
<td>2.9</td>
<td>3.1</td>
<td>4.9</td>
<td>3.8</td>
<td></td>
</tr>
<tr>
<td>time 'g' value exceeds 4g (sec)</td>
<td>0</td>
<td>0</td>
<td>0.3</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Curve 9</th>
<th>Entry</th>
<th>Early</th>
<th>Middle</th>
<th>Late</th>
<th>Early + 10% speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry Speed (km/hr)</td>
<td>96.0</td>
<td>96.0</td>
<td>96.0</td>
<td>105.6</td>
<td></td>
</tr>
<tr>
<td>Exit Speed (km/hr)</td>
<td>105.5</td>
<td>102.7</td>
<td>101.1</td>
<td>112.3</td>
<td></td>
</tr>
<tr>
<td>Max 'g' force predicted (g)</td>
<td>2.9</td>
<td>3.2</td>
<td>3.9</td>
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<tr>
<td>time 'g' value exceeds 4g (sec)</td>
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<td>0</td>
<td>0</td>
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<table>
<thead>
<tr>
<th>Curve 10</th>
<th>Entry</th>
<th>Early</th>
<th>Middle</th>
<th>Late</th>
<th>Early + 10% speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry Speed (km/hr)</td>
<td>105.5</td>
<td>105.5</td>
<td>105.5</td>
<td>116.1</td>
<td></td>
</tr>
<tr>
<td>Exit Speed (km/hr)</td>
<td>114.5</td>
<td>114.0</td>
<td>113.7</td>
<td>123.6</td>
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</tr>
<tr>
<td>Max 'g' force predicted (g)</td>
<td>3.4</td>
<td>3.3</td>
<td>3.65</td>
<td>3.6</td>
<td></td>
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<tr>
<td>time 'g' value exceeds 4g (sec)</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td></td>
</tr>
</tbody>
</table>

Table 6.10: Summary of SDM predicted ‘g’ and velocities for singles luge (cont.)
Table 6.10: Summary of SDM predicted ‘g’ and velocities for singles luge (cont.)
### Curve 16

<table>
<thead>
<tr>
<th>Entry</th>
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<th>Late</th>
<th>Early + 10% speed</th>
</tr>
</thead>
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<td>Entry Speed (km/hr)</td>
<td>140</td>
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<td>140</td>
<td>154</td>
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<tr>
<td>Exit Speed (km/hr)</td>
<td>107</td>
<td>107</td>
<td>107</td>
<td>118.5</td>
</tr>
<tr>
<td>Max 'g' force predicted (g)</td>
<td>4.7</td>
<td>5.0</td>
<td>6.3</td>
<td>5.7</td>
</tr>
<tr>
<td>time 'g' value exceeds 4g (sec)</td>
<td>0.78</td>
<td>1.36</td>
<td>0.88</td>
<td>1.87</td>
</tr>
</tbody>
</table>

Note: the maximum g recorded though the curve for a late entry = 6.3g. This is not considered a true curve g reading.

Table 6.10: Summary of SDM predicted ‘g’ and velocities for singles luge starting from the ‘Ladies start’ (cont.)

This study used the potential new Luge start point (Ladies start before curve 3).

The SDM model has an error bar of +/- 0.3g when compared to a real run of similar run parameters. The velocity plot and g-force map in Figure 6.28 is a composite of the plots and maps modeled for each section and is generated using the early and middle curve entries.

![Figure 6.28: Velocity plot and g-force map for singles luge](image)

Figure 6.28: Velocity plot and g-force map for singles luge
This study presents trajectories and predicted ‘g’ for a theoretical free flowing sled particle. Luge sleds in reality can steer and thus athletes can adjust the lines and waves to create considerable variation from the natural free flowing paths. An athlete is able to affect change on the luge through steering inputs and therefore change the trajectory. By creating longer, lower waves, lower g forces will be experienced. Likewise an athlete can create shorter higher waves though curve by steering with as opposed to against natural tendencies of the track and by choosing to enter a curve with an extreme angle. Thus higher g’s than those predicted could be attained.

This trajectory study simulated the path of a particle on a real scanned track surface. This surface is not perfectly smooth and shows considerable undulations in the surface. These undulations can arise from a variety of sources. For example, from the man made ice preparation techniques, expansion and contraction of ice and the concrete track structure as temperature rises and falls, degradation due to runner wear or weather effects or undulating concrete structures beneath the ice. These ice surface variations create small direction changes that can result in increased g’s experienced through a section. The degree and size of the undulation will influence the g measured. The variation in g and velocity due to surface irregularities are highlighted and measured by the SDM and illustrated in the g and velocity plots. Original track design studies will use smooth CAD generated curves from original design intent. These curves will give back smooth g profiles and potentially lower g values than an irregular real ice surface. It is recommended that further studies are performed to understand the variation in g from a perfectly smooth curvature to that of a real undulating ice surface that has been hand shaped and prepared by ice workers and has experienced the changing environmental conditions. This would help track designers to set an error bar or working tolerance that would enable track designers to predict real g forces from a smooth perfect model surface.

6.7.4.3 Injury and Incident Frequency Study Analysis for Singles Luge

6.7.4.3.1 Crash Frequency Study for Singles Luge

The injury and incident frequency study for singles luge highlighted four main curves of incidence; C13, C14, C15, and C16. It must be remembered that this incidence report includes luge starting from the luge tower at the top of the track where 20% of crashes in C13 were for single luge and 50%+ of crashes in C14, C15, C16 were single luge. Specifically:

- Curve 13
  - Total crashes = 170 (single Luge = 33)
  - Injured = 63 (single Luge = 12)
  - Taken to clinic = 16 (single Luge = 4)

- Curve 14
  - Total crashes = 44 (single Luge = 23)
  - Injured = 11 (single Luge = 7)
  - Taken to clinic = 4 (single Luge = 2)
• Curve 15
  Total crashes = 60 (single Luge = 33)
  Injured = 17 (single Luge = 13)
  Taken to clinic = 7 (single Luge = 6)

• Curve 16
  Total crashes = 43  (single Luge = 24)
  Injured = 27  (single Luge = 17)
  Taken to clinic = 10 (single Luge = 7)

6.7.4.3.2 Potential Reasons for Crash Frequency Statistics for Singles Luge

The trajectory studies through curves 12, 13 and 14 highlight key curve characteristics and linked effects that may account for the high crash rates observed in curves 13, 14 and potentially curve 15. These are as follows:

It appears C12 was intentionally designed to create a technically difficult section to negotiate. The entrance to C12 has a 'lead in geometry that makes it difficult to obtain height early in the curve. This 'lead in' feature into C12 is seen on the scanned track geometry. The effect of this lead in feature is to push the height of the wave in C12 to the end of the curve. The steep transition off C12 creates a left wall impact before C13. This trajectory was demonstrated by the SDM. The result of this extreme left wall impact may either create a crash or create a rebound off the left wall that destabilizes the sled with a late entry line into C13. If an athlete manages to negotiate C12 without an impact in the left wall on exit, the height in C12 will still result in a 'push over' from C12 towards an early entrance into C13. The dynamics of C12 mean that it is very difficult to achieve a middle line into C13.

Analysis of C13 has shown that an early entry line into the curve means the sled has to ride over the identified entrance hump on the left side of C13 entry. The effect of riding over this hump can either flip the sled and cause a crash or push the sled off the curve resulting in the sled cutting across the curve and riding back up the curve wall at the end of the curve. This high line either flips the sled causing a crash or destabilizes the sled on exit so that it enters C14 with minimal control.

Entering C14 with minimal control can create excessive height and a left wall impact before C15 which appears to create crash potential.

It appears that the high technical difficulty of C12 and C13 creates potential multiple crash sites through these curves. If crashes do not occur within these curves the technical difficulty of them creates a higher probability of destabilization and loss of control entering into C14 which could significantly increase the probability of crash incidence out of C14.

It is the opinion of this study, reducing the technical difficulty of C12, and improving the entrance geometry of C13 (i.e. modifying the entrance hump), the crash potential through curves 13, 14 and 15 will be significantly reduced.

Technical difficulty can be achieved through geometry change or potentially through a reduction in speed. In both cases trajectory studies would be needed to assess these changes.
The trajectory studies through C16 highlights key curve characteristics that account for the high crash rates observed.

The C16 geometry creates a sled trajectory with two waves. Each wave experiences high g. The entry line into the curve creates a very high first wave and wave that then drops to the base of the curve before climbing to a very high point at the end of the curve.

All entry lines into C16, if left to run freely, appear to result in an impact on the right side of the track on exit.

The extreme height and abrupt direction change of the final part of curve 16 creates a steep line out with a harsh impact with the right wall.

It is ultimately the extreme height of this second wave that causes right wall impact and crash potential on exit of C16. The high g and high speed of both waves through C16 add complexity and difficulty for the athlete to control a line through this curve.

Reducing the speed through C16 will reduce the g's experienced and may lower the wave height through the curve. However, as seen with curves 6 and 7 trajectories for a luge with lower speed (due to a ladies start position), lowering the speed may not solve the height problem at the end of C16.

### 6.7.4.4 SDM Model Results vs Actual Runs for Singles Luge

In Figure 6.29 a comparison of the time SDM model run time versus the base line singles luge run time of Felix Loch is presented in terms of the difference between the model run time and actual run time. This plot shows that the model is in relatively good agreement with the actual run time of Felix Loch.
6.7.4.5 Considerations and Recommendations for Singles Luge

The SDM analyzes the sled trajectory as a free particle model. In other words it considers the path of a particle flowing naturally down the track without the external influence of any athlete steering inputs and skill level or variations in control authority of the sled.

It must be noted that sleds across the sport have a range of designs and control authority of which there is very little or no published data. Combined with almost limitless variation in runner design (even within a tightly controlled technical rule book) it becomes impossible to account for the steering mechanisms and variation in design for all Luge design variations across the nations and teams.

The free particle model is a powerful tool that predicts the trajectory of a generic sled along the course without steering inputs i.e. left to run freely. For the purpose of this project this in essence allows the SDM to predict trajectories and highlight areas of concern that are generated purely from the track and sled physics, the track/ice geometry, ice properties associated with sleds sliding on ice and aerodynamic properties of generic sled designs within the sled category.

Figure 6.29: Distance against Time plots of the SDM model performance vs the Gold medal performance from the 2010 Vancouver Olympic Games
6.7.4.5.1  **G Force & Velocity Limitation for Singles Luge**

Table 6.10 highlights predicted the 'g' forces that are over 5 g.

Only curve 15 and curve 16 for late entry line trajectory predict g readings over 5 g for unadjusted speed. Only curve 15 and curve 16 for the entry line +10% speed adjustment trajectory predicts g readings over 5 g.

This low incidence of predicted 'g' over 5 (compared to four man bobsleigh) is attributed to the lower speed of the luge due to starting the run at the 'Ladies start' as opposed to from the luge ramp at the top of the track.

The possible options to further reduce the 'g' accelerations in these lower curves include:

- Increasing curve radius with particular emphasis on the section of the curve which shows high g.
- Slowing the track by slowing the ice i.e. increasing the ice friction coefficient. Individual track sections could be targeted which could then act as 'speed limiters'.
- Slowing the sled. e.g. by slowing the runner i.e. increasing the ice friction coefficient by employing a roughness and surface finish control.
- Modify track sections to create uphill sections that act as speed limiters.

The 'g' force acceleration is proportional to velocity squared. It could be argued that the most effective way to reduce 'g' force accelerations through a section is to slow the track speed.

It should be noted that variation in the initial luge start speed due to athlete arm strength needs consideration when determining the maximum start speed possible from the ladies start.

6.7.4.5.2  **Safety Boards / Barriers /Roof Integrity for Single Luge**

This study highlights potential impact sites on the track from a free flowing sled particle.

In all areas where track impacts are seen from free flowing lines, it is recommended that the current roll over barriers and safety boards are reviewed in the zones of impact or zones of concern, taking into account the following observations.

From the trajectory analysis it is evident that the trajectories through some curves are more sensitive to speed and entry line variation than others. These curves create the potential for a wider range of lines and thus a wider range of possible events. These curves need careful consideration.

Curves 4, 6, 7, 11, and 16 are in particular sensitive to entry line and speed variation. Specifically, C6 and C7 require careful consideration as they show a large range of trajectories possible for the luge through this section. This large spread of lines seems to stem from the fact that the luge speed is not high enough to maintain a steady wave. The C3 run start position highlight areas of particular concern at the exit points as the trajectories approach the limits of the track geometry.
Consideration with respect to safety barrier construction should be given to all impact sites or area where the sled approaches the limit of the track geometry. Each impact site is explained in more detail in each curve analysis section.

In summary these sites are:

- Curve 4: Right wall on exit
- Curve 6: This is an important area of concern as there is great variation in the trajectories observed through C6 based on the entry line taken and speed of entry.
  
  Curve 6 presents a considerable challenge for the athlete due to the wide range of lines possible.
  
  Consideration should be given to extension of the existing boarding at the end of the curve on the right wall.
  
  Consideration should be given to extending the roof at the end of the curve to prevent the sled running out of track to travel on due to an extreme line from exiting the curve.
  
  Consideration should be given to the integrity of the roof construction at the very end of curve in the event of a roof impact.
  
  Consideration should be given to placement of barriers on the left and right walls from exit of the curve extending part way down the straight. The height of the barriers should be sufficient to prevent a sled leaving the track.

- Curve 7: This is also an important area of concern as there is great variation in the trajectories observed through C7 based on the entry line taken and speed of entry variation.
  
  The exit of C7 presents a challenge for the athlete due to the wide range of lines possible.
  
  Consideration should be given to extension of the existing boarding at the end of the curve on the left wall to prevent the sled from running out of curve and onto the wall side.
  
  Consideration should be given to placement of barriers on the right wall from exit of the curve extending part way down the straight.

- Curve 9: Left wall on exit (between C9 and C10)
- Curve 10: Left wall on exit
- Curve 11: Right wall on exit; Roof area and existing boarding needs consideration at the end of the curve transition onto the left wall
- Curve 12: Left and right walls on exit (between C12 and entry C13).
- Curve 14: Left wall on exit (between C14 and C15)
- Curve 15: Right wall on exit; Area of the roof at the end of curve 15 and the left wall
- Curve 16: Right wall and left wall on exit. The natural line creates multiple rebound impact potential; Integrity of the curve roof for wave 1 and 2 peak locations in the event of roof impacts.
Note: This study does not recommend specific barrier size or exact location for considering safety barriers. This study presents areas for concern for the lines identified in the test run matrix. This study does not present the range of all possible impacts arising from a comprehensive range of entry speeds and lines or trajectories created form human driver error or decision making. It is highly recommended that further work is undertaken to assess a wider cross section of entry lines and speeds in order to gain a better understanding of the size of the impact zone areas.

6.7.4.5.3  Ice Profile for Singles Luge

Based on the observations of the trajectory lines, the following are recommendations for monitoring the ice profiles:

- Consideration should be given to the ice profile through C5 so as to avoid a late entry line into C6. Curve 5 has a natural tendency to push the sled off the curve and direct the sled down the left side and late into C6.
- In C6 consideration should be given to ensure that the ice fillet between the left track wall and track floor at the potential site of impact does not create a potential ramp that could project the sled up off the ice if a sled rides into the wall.
- In C7 consideration should be given to ensure that the ice fillet between the right track wall and track floor on exit of the curve does not create a potential ramp that could project the sled off the ice if a sled rides into the wall.
- In C9 consideration should be given to shaping the ice through the middle to end of C9 to create a longer less extreme exit and thus minimize the left wall impact potential.
- For C12 the trajectory study highlighted the difficulty for a sled to ride up early onto C12 due to the lead in geometry feature of the track making this possibility very difficult.

Consideration should be given to adjusting this entry portion of the curve profile to make it easier to create height earlier in C12 when on an early entry line, which is the natural line form the exit of C11. The extreme height gained in C12 is a factor in the left wall impact out of C12 which destabilizes the bob before negotiation of C13.

Information attained from MAIN DOCUMENT Var03a WSC_PART-A (October 232004, page 11) suggests that the entrance to C12 was intentionally designed into the track to create an additional level of difficulty through C12:

‘As an additional difficulty the vertical radius are formed so that the vertical centrifugal force shows one easy answering. That is once ≈ 0.40 at the end of the "bended straight line" ( C8 ) with N ( Sx = 714.5 m ) and in the straight line in front of curve C12 with N = 0.67.’

Note: This is an English translation where “one easy answering” could be interpreted as “one driving line”.

- For C12 to C 13 it is recommended that the ice profile in C12 is shaped where possible to create a longer exit radius, more progressive ‘g’ and less extreme exit trajectory out of C12 into C13. This will create more choice for driving line
selection into C13 as opposed to a forced path due to extreme C12 exit height and exit line.

- At the entry to C13 it is recommended that the ‘hump’ on the left side of the track on the entry to C13 is modified or removed.

  When combined with the modifications to the C12 ice profile this will remove the potential for the left runner to ride up the hump and thus reduce the chance of the sled flipping over on its right side. Removing this hump will also prevent the sled from being pushed back off the curve and will enable the sled to follow a line into the ‘belly’ of the curve. This will in turn allow a less extreme direction change at the end of curve and therefore reduce the second potential area for the sled flipping over onto its rights side.

- From C15 to C16 it is recommended that the ice profile through C15 is modified so that drivers are given more range to choose their entry line into C16.

  The model predictions show that the natural tendency of C15 is to ‘force’ a free flowing path down the right side of the track sometimes creating a right wall impact and thus creating a ‘late’ or right side entry trajectory into C16.

  A late line into C16 creates more g through the first wave of C16 than an entry or middle entry line would create.

- In C16 careful consideration must be given to the ice profile between the track ‘floor’ and the right wall on the exit of C16. Oversized rounded fillets between the floor and the right wall could in effect create a ramp upon which the right runner of the luge could ride up.

Note: Ice features on the entry and exits of curve (e.g. humps and wall-floor fillets) needs extra care when considering Luge sleds. Luge sleds sit higher off the ice surface than Bobsleds or Skeleton sleds. This creates a higher centre of gravity of the sled and athlete and potentially more instability when faced with impacts. The design of the Luge runner is rounder and projects out in front of the sled and athlete (unlike Skeleton sleds and Bobsleds). This makes the luge runner more susceptible to riding up ice features.
6.7.4.6 Final General Considerations for Singles Luge

There are four key factors of the track’s characteristics that need to be carefully considered together during track design phase.

These four factors are:

- Fast speeds (usually the bottom part of tracks)
- High ‘g’ forces (curves that combine small radii or sharp change in direction with speed)
- Technical sections requiring high skill levels to negotiate through without incidence.
- Curve profiles that force natural paths and therefore limit the range of lines achievable by the athlete through steering.

It is when three or four of these factors combine that the potential for crashes and wall impacts rise.

It is recommended that future track designs avoid the combination of three or four of these factors. It is recognized that the sports rely on creating tracks that are challenging in order to differentiate between the skill abilities of the best athletes in the world. However, it is recommended that technical sections are combined with slower speed sections and possible lower ‘g’ forces as opposed to technical sections combined with high g loading, fast speeds and curve profiles that tend to force a particular trajectory or path. It is the combination of all four factors that heightens the probability of incidence.

Is must be noted that athletes if so wished, could possibly ‘tip’ or crash a sled or create a wall impact in the slower curves of a track if they steered against the curves in an extreme manor. Thus when considering what is ‘safe’ and ‘what is not safe’ with respect to track design it must be understood that poor steering decisions by the athlete will always result in lines that are considered unsafe or dangerous. This is inherent within the sport.

It is recommended that all new tracks are independently analyzed during the design stages to offer a second or third opinion on design and trajectory simulations.
6.7.5 Summary of Two Man Bobsleigh Trajectory Findings

6.7.5.1 SDM Input Parameters for Two Man Bobsleigh

<table>
<thead>
<tr>
<th>Initial Particle Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discipline</td>
</tr>
<tr>
<td>Combine Sled + Athlete weight</td>
</tr>
<tr>
<td>Aero Drag coefficient</td>
</tr>
<tr>
<td>Aero Lift coefficient</td>
</tr>
<tr>
<td>Frontal area (m^2)</td>
</tr>
<tr>
<td>Ice – Runner friction coefficient</td>
</tr>
<tr>
<td>Air density</td>
</tr>
</tbody>
</table>

Table 6.11: Sled Dynamics Model (SDM) parameters

6.7.5.2 Speed & ‘g’ Force Acceleration Results for 2 Man Bobsleigh

Table 6.12 presents a summary of the predicted ‘g’ accelerations down the Whistler track broken down into sections from the Bob start to the finish C16.

The ‘g’s’ predicted over 5 are highlighted in red.

<table>
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<tr>
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<tr>
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<td>Entry Speed (km/hr)</td>
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<tr>
<td>Exit Speed (km/hr)</td>
</tr>
<tr>
<td>Max ‘g’ force predicted (g)</td>
</tr>
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<table>
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</thead>
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<tr>
<td>Entry Speed (km/hr)</td>
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<tr>
<td>Exit Speed (km/hr)</td>
</tr>
<tr>
<td>Max ‘g’ force predicted (g)</td>
</tr>
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<td>time ‘g’ value exceeds 4g (sec)</td>
</tr>
</tbody>
</table>

<table>
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</thead>
<tbody>
<tr>
<td>Entry</td>
</tr>
<tr>
<td>Entry Speed (km/hr)</td>
</tr>
<tr>
<td>Exit Speed (km/hr)</td>
</tr>
<tr>
<td>Max ‘g’ force predicted (g)</td>
</tr>
<tr>
<td>time ‘g’ value exceeds 4g (sec)</td>
</tr>
</tbody>
</table>

Table 6.12: Summary of SDM predicted Speed and ‘g’ accelerations for Two Man Bobsleigh
### Curve 4

<table>
<thead>
<tr>
<th>Entry</th>
<th>Early</th>
<th>Middle</th>
<th>Late</th>
<th>Early + 10% speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry Speed (km/hr)</td>
<td>88.0</td>
<td>88.0</td>
<td>88.0</td>
<td>96.8</td>
</tr>
<tr>
<td>Exit Speed (km/hr)</td>
<td>90.1</td>
<td>94.7</td>
<td>92.0</td>
<td>99.8</td>
</tr>
<tr>
<td>Max 'g' force predicted (g)</td>
<td>3.6</td>
<td>3.8</td>
<td>5.5</td>
<td>4.5</td>
</tr>
<tr>
<td>time 'g' value exceeds 4g (sec)</td>
<td>0</td>
<td>0</td>
<td>N.A.</td>
<td>0.46</td>
</tr>
</tbody>
</table>

Note: the g force for the late entry includes the effect of a roof impact. These g readings are not considered a true centrifugal g measurement.

### Curve 5

<table>
<thead>
<tr>
<th>Entry</th>
<th>Early</th>
<th>Middle</th>
<th>Late</th>
<th>Early + 10% speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry Speed (km/hr)</td>
<td>94.7</td>
<td>94.7</td>
<td>94.7</td>
<td>104.2</td>
</tr>
<tr>
<td>Exit Speed (km/hr)</td>
<td>100.2</td>
<td>99.7</td>
<td>100.9</td>
<td>108.7</td>
</tr>
<tr>
<td>Max 'g' force predicted (g)</td>
<td>1.4</td>
<td>1.6</td>
<td>1.7</td>
<td>2.4</td>
</tr>
<tr>
<td>time 'g' value exceeds 4g (sec)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

### Curve 6

<table>
<thead>
<tr>
<th>Entry</th>
<th>Early</th>
<th>Middle</th>
<th>Late</th>
<th>Early + 10% speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry Speed (km/hr)</td>
<td>101.0</td>
<td>101.0</td>
<td>101.0</td>
<td>111.1</td>
</tr>
<tr>
<td>Exit Speed (km/hr)</td>
<td>104.3</td>
<td>102.8</td>
<td>105.0</td>
<td>112.6</td>
</tr>
<tr>
<td>Max 'g' force predicted (g) wave 1</td>
<td>3.7</td>
<td>3.8</td>
<td>4.3</td>
<td>4.6</td>
</tr>
<tr>
<td>Max 'g' force predicted (g) wave 2</td>
<td>4.8</td>
<td>4.5</td>
<td>5.1</td>
<td>5.8</td>
</tr>
<tr>
<td>time 'g' value exceeds 4g (sec) wave 1</td>
<td>0</td>
<td>0</td>
<td>1.52</td>
<td>0.83</td>
</tr>
<tr>
<td>time 'g' value exceeds 4g (sec) wave 2</td>
<td>0.97</td>
<td>1.07</td>
<td>N.A.</td>
<td>1.45</td>
</tr>
</tbody>
</table>

Note: the g force for wave 2 for the late entry and early entry +10% speed lines includes the effect of a roof impact. These g readings are not considered a true centrifugal g measurement.

### Curve 7

<table>
<thead>
<tr>
<th>Entry</th>
<th>Early</th>
<th>Middle</th>
<th>Late</th>
<th>Early + 10% speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry Speed (km/hr)</td>
<td>105.0</td>
<td>105.0</td>
<td>105.0</td>
<td>115.5</td>
</tr>
<tr>
<td>Exit Speed (km/hr)</td>
<td>110.2</td>
<td>109.6</td>
<td>114.9</td>
<td>117.4</td>
</tr>
<tr>
<td>Max 'g' force predicted (g)</td>
<td>3.7</td>
<td>3.85</td>
<td>4.6</td>
<td>4.3</td>
</tr>
<tr>
<td>time 'g' value exceeds 4g (sec)</td>
<td>0</td>
<td>0</td>
<td>0.41</td>
<td>0.57</td>
</tr>
</tbody>
</table>

Table 6.12: Summary of SDM predicted Speed and 'g' accelerations for Two Man Bobsleigh (cont.)
<table>
<thead>
<tr>
<th>Curve 9</th>
<th>Entry Speed (km/hr)</th>
<th>Early</th>
<th>Middle</th>
<th>Late</th>
<th>Early + 10% speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry Speed</td>
<td>115.0</td>
<td>115.0</td>
<td>115.0</td>
<td>126.5</td>
<td></td>
</tr>
<tr>
<td>Exit Speed</td>
<td>120.3</td>
<td>118.8</td>
<td>118.6</td>
<td>129.6</td>
<td></td>
</tr>
<tr>
<td>Max 'g' force</td>
<td>3.3</td>
<td>4.2</td>
<td>5.0</td>
<td>4.3</td>
<td></td>
</tr>
<tr>
<td>time 'g' value exceeds 4g (sec)</td>
<td>0</td>
<td>0.16</td>
<td>0.36</td>
<td>0.34</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Curve 10</th>
<th>Entry Speed (km/hr)</th>
<th>Early</th>
<th>Middle</th>
<th>Late</th>
<th>Early + 10% speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry Speed</td>
<td>121.0</td>
<td>121.0</td>
<td>121.0</td>
<td>133.1</td>
<td></td>
</tr>
<tr>
<td>Exit Speed</td>
<td>127.2</td>
<td>126.0</td>
<td>126.0</td>
<td>137.6</td>
<td></td>
</tr>
<tr>
<td>Max 'g' force</td>
<td>4.1</td>
<td>4.6</td>
<td>6.3</td>
<td>4.3</td>
<td></td>
</tr>
<tr>
<td>time 'g' value exceeds 4g (sec)</td>
<td>0.29</td>
<td>0.9</td>
<td>1.03</td>
<td>0.91</td>
<td></td>
</tr>
</tbody>
</table>

Note: The g measured for the late line includes the effects of a roof impact therefore is not considered a true centrifugal g force.

<table>
<thead>
<tr>
<th>Curve 11</th>
<th>Entry Speed (km/hr)</th>
<th>Early</th>
<th>Middle</th>
<th>Late</th>
<th>Early + 10% speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry Speed</td>
<td>127.2</td>
<td>127.2</td>
<td>127.2</td>
<td>139.9</td>
<td></td>
</tr>
<tr>
<td>Exit Speed</td>
<td>133.0</td>
<td>132.6</td>
<td>135.0</td>
<td>141.5</td>
<td></td>
</tr>
<tr>
<td>Max 'g' force</td>
<td>3.7</td>
<td>4.2</td>
<td>4.6</td>
<td>4.7</td>
<td></td>
</tr>
<tr>
<td>time 'g' value exceeds 4g (sec)</td>
<td>0</td>
<td>0.24</td>
<td>0.3</td>
<td>0.5</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Curve 12</th>
<th>Entry Speed (km/hr)</th>
<th>Early</th>
<th>Middle</th>
<th>Late</th>
<th>Early + 10% speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry Speed</td>
<td>135.0</td>
<td>135.0</td>
<td>135.0</td>
<td>148.5</td>
<td></td>
</tr>
<tr>
<td>Exit Speed</td>
<td>138.5</td>
<td>137.0</td>
<td>133.1</td>
<td>147.0</td>
<td></td>
</tr>
<tr>
<td>Max 'g' force</td>
<td>3.6</td>
<td>3.7</td>
<td>4.3</td>
<td>4.2</td>
<td></td>
</tr>
<tr>
<td>time 'g' value exceeds 4g (sec)</td>
<td>0</td>
<td>0</td>
<td>0.33</td>
<td>0.37</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Curve 13</th>
<th>Entry Speed (km/hr)</th>
<th>Early</th>
<th>Middle</th>
<th>Late</th>
<th>Early + 10% speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry Speed</td>
<td>138.5</td>
<td>138.5</td>
<td>138.5</td>
<td>152.4</td>
<td></td>
</tr>
<tr>
<td>Exit Speed</td>
<td>144.0</td>
<td>144.5</td>
<td>138.8</td>
<td>158.0</td>
<td></td>
</tr>
<tr>
<td>Max 'g' force</td>
<td>2.5</td>
<td>2.3</td>
<td>3.2</td>
<td>2.8</td>
<td></td>
</tr>
<tr>
<td>time 'g' value exceeds 4g (sec)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.12: Summary of SDM predicted Speed and ‘g’ accelerations for Two Man Bobsleigh (cont.)
### Curve 14

<table>
<thead>
<tr>
<th>Entry</th>
<th>Early</th>
<th>Middle</th>
<th>Late</th>
<th>Early + 10% speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry Speed (km/hr)</td>
<td>144.0</td>
<td>144.0</td>
<td>144.0</td>
<td>157.3</td>
</tr>
<tr>
<td>Exit Speed (km/hr)</td>
<td>144.0</td>
<td>144.2</td>
<td>149.6</td>
<td>154.1</td>
</tr>
<tr>
<td>Max ‘g’ force predicted (g)</td>
<td>3.8</td>
<td>4.1</td>
<td>5.3</td>
<td>4.3</td>
</tr>
<tr>
<td>time ‘g’ value exceeds 4g (sec)</td>
<td>0</td>
<td>0.56</td>
<td>0.87</td>
<td>0.71</td>
</tr>
</tbody>
</table>

### Curve 15

<table>
<thead>
<tr>
<th>Entry</th>
<th>Early</th>
<th>Middle</th>
<th>Late</th>
<th>Early + 10% speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry Speed (km/hr)</td>
<td>149.0</td>
<td>149.0</td>
<td>149.0</td>
<td>164.0</td>
</tr>
<tr>
<td>Exit Speed (km/hr)</td>
<td>149.4</td>
<td>150.5</td>
<td>154.0</td>
<td>172.2</td>
</tr>
<tr>
<td>Max ‘g’ force predicted (g)</td>
<td>4.2</td>
<td>5.0</td>
<td>5.6</td>
<td>5.2</td>
</tr>
<tr>
<td>time ‘g’ value exceeds 4g (sec)</td>
<td>0.39</td>
<td>0.74</td>
<td>1.1</td>
<td>0.77</td>
</tr>
</tbody>
</table>

### Curve 16

<table>
<thead>
<tr>
<th>Entry</th>
<th>Early</th>
<th>Middle</th>
<th>Late</th>
<th>Early + 10% speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry Speed (km/hr)</td>
<td>150.5</td>
<td>150.5</td>
<td>150.5</td>
<td>165.6</td>
</tr>
<tr>
<td>Exit Speed (km/hr)</td>
<td>115.3</td>
<td>124.8</td>
<td>119.8</td>
<td>131.5</td>
</tr>
<tr>
<td>Max ‘g’ force predicted (g) wave 1</td>
<td>4.6</td>
<td>4.7</td>
<td>5.2</td>
<td>4.9</td>
</tr>
<tr>
<td>Max ‘g’ force predicted (g) wave 2</td>
<td>5.0</td>
<td>4.9</td>
<td>4.8</td>
<td>5.0</td>
</tr>
<tr>
<td>time ‘g’ value exceeds 4g (sec) wave 1</td>
<td>2.02</td>
<td>1.86</td>
<td>2.01</td>
<td>2.03</td>
</tr>
<tr>
<td>time ‘g’ value exceeds 4g (sec) wave 2</td>
<td>2.49</td>
<td>2.31</td>
<td>2.25</td>
<td>2.41</td>
</tr>
</tbody>
</table>

**Notes:**
The g in curve 16 does not fall below 4 g through the two waves. Therefore the time through waves one and two combined = the time ‘g’ values exceeds 4g.
The speed variation through the exit point, i.e. where measured is greatly influenced by the degree of right wall impact on exit.
The g measured for the late line includes the effects of a roof impact therefore is not considered a true centrifugal g force.

Table 6.12: Summary of SDM predicted Speed and ‘g’ accelerations for Two Man Bobsleigh (cont.)
The SDM model has an error bar of +/- 0.3g when compared to a real run of similar run parameters.

This study presents trajectories and predicted ‘g’ for a theoretical free flowing sled particle. Bobsleighs in reality can steer and thus can adjust the lines and waves to create considerable variation from the natural free flowing paths. An athlete is able to affect change on the bob through steering inputs and therefore change the trajectory. By creating longer, lower waves, lower g forces will be experienced. Likewise an athlete can create shorter higher waves though curve by steering with as opposed to against natural tendencies of the track and by choosing to enter a curve with an extreme angle. Thus higher g’s than those predicted could be attained.

This study used the two man bob speed recorded off the start associated with the fastest finish time from the 2010 Vancouver Olympic Winter Games. This set the initial condition from which the rest of the run followed.

This trajectory study simulated the path of a particle on a real scanned track surface. This surface is not perfectly smooth and shows considerable undulations in the surface. These undulations can arise from a variety of sources. For example, from the man-made ice preparation techniques, expansion and contraction of ice and the concrete track structure as temperature rises and falls, degradation due to runner wear or weather effects or undulating concrete structures beneath the ice. These ice surface variations create small direction changes that can result in increased g’s experienced through a section. The degree and size of the undulation will influence the g measured. The variation in g and velocity due to surface irregularities are highlighted and measured by the SDM and illustrated in the g and velocity plots. Original track design studies will use smooth CAD generated curves from original design intent. These curves will give back smooth g profiles and potentially lower g values than an irregular real ice surface. It is recommended that further studies are performed to understand the variation in g from a perfectly smooth curvature to that of a real undulating ice surface that has been hand shaped and prepared by ice workers and has experienced the changing environmental conditions. This would help track designers to set an error bar or working tolerance that would enable track designers to predict real g forces from a smooth perfect model surface.

The velocity plot and g-force map in Figure 6.30 is a composite of the plots and maps modeled for each section and is generated using the early and middle curve entries.
6.7.5.3 Injury and Incident Frequency Study Analysis 2 Man Bobsleigh

6.7.5.3.1 Crash Frequency Study for 2 Man Bobsleigh

The injury and incident frequency study highlighted that C13 and C14 were the areas of highest incident. The most common incident for any Bobsleigh through this section is to be turned onto its side.

Other areas of high incidence were C16 exit.

6.7.5.3.2 Potential Reasons for Crash Frequency Statistics for 2 Man Bobsleigh

The injury and incident frequency study highlighted that C13 was the area of highest incident.

A sequence of trajectory studies with varying entry lines into C13 highlights key curve characteristics that could cause the highest crash incidence rate through C13.
Even though the ‘g’ accelerations recorded through C13 are not high, the curve appears to be a challenge due to two reasons:

- The high exit line out of C12 naturally creates an impact on the left wall very close to the entry point of C13. The rebound effect of this impact creates a ‘push’ off the left wall which results in the sled cutting across C13 as opposed to travelling around it. The result of this is that the sled rides back up the end of C13 and the sharp direction change can flip the bob onto its right side.

- On close inspection of the scanned geometry the entry to C13 appears to have a hump in the ice on the entry to the curve, with the highest part of this hump being on the left side into the curve. If the bobsleigh manages to negotiate C12 and exit without a left wall impact into C13, the left runner of the bob rides over a hump in the ice. The earlier the line into C13 the more extreme the effects of riding this hump. The hump will create a sudden push upwards on the left runner of the bob and could in effect ‘pop’ the left side of the bob up off the ice. This ‘pop’ could either flip the bob onto its right side or at least destabilize the bob. If the bob manages to ride this hump, the bump has the added effect of pushing the sled off the curve, which can result in the sled cutting across C13 as opposed to travelling around it. The result of this is that the sled rides back up the end of C13 and the sharp direction change can flip the bob onto its right side.

The reality is that C13 is very difficult to negotiate through without the bob flipping on its right side at worst or at best becoming unstable. An unstable bob out of C13 will create an unstable bob through C14.

6.7.5.4 SDM Model Results vs Actual Runs for 2 Man Bobsleigh

In Figure 6.31 a comparison of the time SDM model run time versus the base line 2 Man bobsleigh run time of Andre Lange is presented in terms of the difference between the model run time and actual run time. This plot shows that the model is in relatively good agreement with the actual run time of Lange.
6.7.5.5 Considerations and Recommendations for 2 Man Bobsleigh

The SDM analyzes the sled trajectory as a free particle model. In other words it considers the path of a particle flowing naturally down the track without the external influence of any athlete steering inputs and skill level or variations in control authority of the sled.

It must be noted that sleds across the sport have a broad spectrum of designs and control authority of which there is very little or no published data. Combined with almost limitless variation in runner design (even within a tightly controlled technical rule book) it becomes impossible to account for the steering mechanisms and variation in design for all bobsleighs across the nations and teams.

The free particle model however is a powerful tool that predicts the trajectory of a generic sled along the course without steering inputs i.e. left to run freely. For the purpose of this project this in essence allows the SDM to predict trajectories and highlight areas of concern that are generated purely from the track & sled physics, the track/ice geometry, ice properties associated with sleds sliding on ice and aerodynamic properties of generic sled designs within the sled category.
6.7.5.5.1  **G Force & Velocity Limitation for 2 Man Bobsleigh**

Table 6.12 highlights predicted ‘g’ over 5 g.

The options to reduce the ‘g’ accelerations in a curve are:

- Increasing curve radius with particular emphasis on the section of the curve which shows high g.
- Slowing the track by slowing the ice i.e. increasing the ice friction coefficient. Individual track sections could be targeted which could then act as ‘speed limiters’.
- Slowing the sled. e.g. by slowing the runner i.e. increasing the ice friction coefficient by employing a roughness and surface finish control.
- Modify track sections to create uphill sections that act as speed limiters

The ‘g’ acceleration is proportional to velocity squared. It could be argued that the most effective way to reduce ‘g’ accelerations through a section is to slow the track speed.

6.7.5.5.2  **Safety Boards / Barriers /Roof Integrity for 2 Man Bobsleigh**

This study highlights potential impact sites on the track from a free flowing sled particle. In all areas where track impacts are seen from free flowing lines, it is recommended that suitable safety boards are constructed in the zones of impact or zones of concern.

From the trajectory analysis it is evident that the trajectories through some curves are more sensitive to speed and entry line variation than others. These curves create the potential for a wider range of lines and thus a wider range of possible events. These curves need careful consideration.

Curves 4, 6, 7, 11, and 16 are in particular sensitive to entry line and speed variation.

Consideration with respect to safety barrier construction should be given to all impact sites or area where the sled approaches the limit of the track geometry. Each impact site is explained in more detail in each curve analysis section.

In summary these sites are:

- Curve 1: Right wall on exit.
- Curve 2: Roof to right wall area on curve exit.
- Curve 3: Left wall on exit.
- Curve 4: Right wall on exit; Roof area on the left extending onto and along the left wall on exit; Roof integrity at the end of curve 4.
- Curve 5: Left wall on curve exit.
- Curve 6: Roof area at the end of the curve and the transition from roof section to the left track wall: Integrity of the roof construction at the very end of curve in the event of a roof impact; Left wall on exit.
- Curve 7: Roof area at the end of the curve and the transition from roof section onto the right track wall: Integrity of the roof construction at the very end of curve in the event of a roof impact; Right wall on exit.
• Curve 9: Left wall on exit (between C9 and C10).
• Curve 10: Left wall on exit.
• Curve 11: Right wall on exit; Roof area / end of the curve transition onto the left wall.
• Curve 12: Left and right walls on exit (between C12 and entry C13).
• Curve 14: Left wall on exit (between C14 and C15).
• Curve 15: Right wall on exit; Area of the roof at the end of C15 and the left wall.
• Curve 16: Right wall and left wall on exit. The natural line creates multiple rebound impact potential; Integrity of the curve roof for wave 1 and 2 peak locations in the event of roof impacts.

Note: This study does not recommend specific barrier size or exact location for considering safety barriers. This study presents areas for concern for the lines identified in the test run matrix. This study does not present the range of all possible impacts arising from a comprehensive range of entry speeds and lines or trajectories created from human driver error or decision making. It is highly recommended that further work is undertaken to assess a wider cross section of entry lines and speeds in order to gain a better understanding of the size of the impact zone areas.

6.7.5.5.3 Ice Profile for 2 Man Bobsleigh

From the results of the study, attention should be given to the ice profiles in the following areas:

• Curve 6: Consideration must be given to the ice profile between the track ‘floor’ and the left wall on the exit of C6. Oversized rounded fillets between the floor and the left wall could in effect create a ramp upon which the left runner of the bob could ride up.
• Curve 9: Consideration should be given to the ice profile through curve 9 in order to reduce the natural push off the curve into the left wall on exit. This would give the driver more range and choice of entry lines into C10.
• Curve 12: The trajectory study highlighted the difficulty for a sled to ride up early onto C12 due to the lead in geometry of the track making this possibility very difficult.
• Consideration should be given to adjusting this entry portion of the curve profile to make it easier to create height earlier in C12 when on an early entry line, which is the natural line from the exit of C11. The extreme height gained at the end of C12 is a factor in the left wall impact out of C12 which destabilizes the bob before negotiation of C13.

Information attained from MAIN DOCUMENT Var03a WSC_PART-A (October 232004, page 11) suggests that the entrance to C12 was intentionally designed into the track to create an additional level of difficulty through C12:

‘As an additional difficulty the vertical radius are formed so that the vertical centrifugal force shows one easy answering. That is once = 0,40 at the end of the “bended straight line” ( C8 ) with N ( Sx = 714,5 m ) and in the straight line in front of curve C12 with N = 0,67.’

Whistler Sliding Centre Sled Trajectory Study
Note: This is an English translation where “one easy answering” could be interpreted as “one driving line”.

- Curve 12 to Curve 13: It is recommended that the ice profile in C12 is shaped where possible to create a longer exit radius, more progressive ‘g’ and less extreme exit trajectory out of C12 into C13. This will give drivers more range to choose their line/path into and through C13 as opposed to a forced path due to the extreme C12 exit height and exit line.

- Curve 13 Entry: The trajectory study highlighted the existence of a ‘hump’ in the ice on entry to C13 and highlighted the effect this hump has on ‘pushing’ the bob off the early entry line and onto a line that cuts across the curve. This entry hump in essence increases the crash potential through C13.

It is recommended that the ‘hump’ on the left side of the track on the entry to C13 is modified or removed. When combined with the modifications to the C12 ice profile this will remove the potential for the left runner to ride up the hump and thus reduce the chance of the sled flipping over on its right side. Removing this hump will also prevent the sled from being pushed back off the curve and will enable the sled to follow a line into the ‘belly’ of the curve. This will in turn allow a less extreme direction change at the end of curve and therefore reduce the second potential area for the sled flipping over onto its rights side.

- Curve 15 to Curve 16: It is recommended that the ice profile through C15 is modified so that drivers are given more range to choose their entry line into C16.

The model predictions show that the natural tendency of C15 is to ‘force’ a free flowing path down the right side of the track sometimes creating a right wall impact and thus creating a ‘late’ or right side entry trajectory into C16.

The late line into C16 creates more g through the first wave of C16 than an entry or middle entry line would create.

- Curve 16: Careful consideration must be given to the ice profile between the track ‘floor’ and the right wall on the exit of C16. Oversized rounded fillets between the floor and the right wall could when combined with the extremity of the exit trajectory in effect create a ramp upon which the right runner of the bob could ride up.

The height and location of the two waves through C16 creates extreme height very late in the curve which in turn creates the extreme exit trajectory that leads to a severe right wall impact. The height and location of wave two is greatly influenced by the height and location of wave one and the entry line into the curve. It is highly recommended that consideration is given to remodeling of C16 to create a longer and lower exit trajectory that removes the wall impact. This may be possible through ice profiling but this will ultimately depend on the limitations imposed by the underlying concrete structure.

Reducing the speed through C16 will reduce the g’s experienced and may change the wave height and position through the curve. However as seen with C6 and C7 trajectories for a single luge (with lower speed due to a ladies start position), lowering the speed alone may not create a less extreme exit of curve.
16. The important consideration is the combined effect of wave height and location at the end of curve 16. Both waves are interconnected and thus must be considered together.

6.7.5.6 Final General Considerations for 2 Man Bobsleigh

There are four key factors of the track’s characteristics that need to be carefully considered together during track design phase.

These four factors are:
- Fast speeds (usually the bottom part of tracks)
- High ‘g’ forces (curves that combine small radii or sharp change in direction with speed)
- Technical sections requiring high skill levels to negotiate through without incidence.
- Curve profiles that force natural paths and therefore limit the range of lines achievable by the athlete through steering.

It is when three or four of these factors combine that the potential for crashes and wall impacts rise.

It is recommended that future track designs avoid the combination of three or four of these factors. It is recognized that the sports rely on creating tracks that are challenging in order to differentiate between the skill abilities of the best athletes in the world. However, it is recommended that technical sections are combined with slower speed sections and possible lower ‘g’ forces as opposed to technical sections are combined with high g loading, fast speeds and curve profiles that tend to force a particular trajectory or path. It is the combination of all four factors that heightens the probability of incidence.

It must be noted that athletes if so wished, could possibly ‘tip’ or crash a sled or create a wall impact in the slower curves of a track if they steered against the curves in an extreme manor. Thus when considering what is ‘safe’ and ‘what is not safe’ with respect to track design it must be understood that poor steering decisions by the athlete will always result in lines that are considered unsafe or dangerous. This is inherent within the sport.

It is recommended that all new tracks are independently analyzed during the design stages to offer a second or third opinion on design and trajectory simulations.
6.7.6 Summary of Skeleton Trajectory Findings

6.7.6.1 SDM Input Parameters for Skeleton

<table>
<thead>
<tr>
<th>Initial Particle Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discipline</td>
</tr>
<tr>
<td>Combine Sled + Athlete weight</td>
</tr>
<tr>
<td>Aero Drag coefficient</td>
</tr>
<tr>
<td>Aero Lift coefficient</td>
</tr>
<tr>
<td>Frontal area (m^2)</td>
</tr>
<tr>
<td>Ice – Runner friction coefficient</td>
</tr>
<tr>
<td>Air density</td>
</tr>
</tbody>
</table>

Table 6.13: Sled Dynamics Model (SDM) parameters for Skeleton

6.7.6.2 Speed & ‘g’ Force Acceleration Results for Skeleton

In Table 6.14 a summary of the predicted ‘g’ accelerations down the Whistler track broken down into sections from the Skeleton start to the finish at C16 is presented.

The ‘g’s’ predicted over 5 are highlighted in red.

<table>
<thead>
<tr>
<th>Curve 1</th>
<th>Early</th>
<th>Middle</th>
<th>Late</th>
<th>Early + 10% speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry Speed (km/hr)</td>
<td>46</td>
<td>46</td>
<td>46</td>
<td>50.6</td>
</tr>
<tr>
<td>Exit Speed (km/hr)</td>
<td>65.9</td>
<td>66.2</td>
<td>66.2</td>
<td>69.0</td>
</tr>
<tr>
<td>Max ‘g’ force predicted (g)</td>
<td>2.5</td>
<td>2.7</td>
<td>2.9</td>
<td>2.8</td>
</tr>
<tr>
<td>time ‘g’ value exceeds 4g (sec)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Curve 2</th>
<th>Early</th>
<th>Middle</th>
<th>Late</th>
<th>Early + 10% speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry Speed (km/hr)</td>
<td>66.0</td>
<td>66.0</td>
<td>66.0</td>
<td>72.6</td>
</tr>
<tr>
<td>Exit Speed (km/hr)</td>
<td>86.4</td>
<td>86.0</td>
<td>85.3</td>
<td>92.6</td>
</tr>
<tr>
<td>Max ‘g’ force predicted (g)</td>
<td>4.1</td>
<td>4.1</td>
<td>4.3</td>
<td>4.2</td>
</tr>
<tr>
<td>time ‘g’ value exceeds 4g (sec)</td>
<td>0.14</td>
<td>0.13</td>
<td>0.3</td>
<td>0.37</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Curve 3</th>
<th>Early</th>
<th>Middle</th>
<th>Late</th>
<th>Early + 10% speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry Speed (km/hr)</td>
<td>85.0</td>
<td>85.0</td>
<td>85.0</td>
<td>93.5</td>
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<tr>
<td>Exit Speed (km/hr)</td>
<td>87.6</td>
<td>89.5</td>
<td>88.9</td>
<td>95.1</td>
</tr>
<tr>
<td>Max ‘g’ force predicted (g)</td>
<td>2.8</td>
<td>2.9</td>
<td>2.7</td>
<td>3.3</td>
</tr>
<tr>
<td>time ‘g’ value exceeds 4g (sec)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 6.14: Summary of SDM predicted Speed and ‘g’ accelerations for Skeleton
<table>
<thead>
<tr>
<th>Curve 4</th>
<th>Entry</th>
<th>Early</th>
<th>Middle</th>
<th>Late</th>
<th>Early + 10% speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry Speed (km/hr)</td>
<td>89.5</td>
<td>89.5</td>
<td>89.5</td>
<td>98.5</td>
<td></td>
</tr>
<tr>
<td>Exit Speed (km/hr)</td>
<td>95.4</td>
<td>92.9</td>
<td>96.3</td>
<td>104.9</td>
<td></td>
</tr>
<tr>
<td>Max 'g' force predicted (g)</td>
<td>4.0</td>
<td>4.2</td>
<td>6.0</td>
<td>4.7</td>
<td></td>
</tr>
<tr>
<td>time 'g' value exceeds 4g (sec)</td>
<td>0</td>
<td>0.89</td>
<td>0.70</td>
<td>0.39</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Curve 5</th>
<th>Entry</th>
<th>Early</th>
<th>Middle</th>
<th>Late</th>
<th>Early + 10% speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry Speed (km/hr)</td>
<td>97.0</td>
<td>97.0</td>
<td>97.0</td>
<td>106.7</td>
<td></td>
</tr>
<tr>
<td>Exit Speed (km/hr)</td>
<td>102.6</td>
<td>102.3</td>
<td>103.3</td>
<td>111.0</td>
<td></td>
</tr>
<tr>
<td>Max 'g' force predicted (g)</td>
<td>1.57</td>
<td>1.39</td>
<td>1.68</td>
<td>1.85</td>
<td></td>
</tr>
<tr>
<td>time 'g' value exceeds 4g (sec)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
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</tbody>
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<table>
<thead>
<tr>
<th>Curve 6</th>
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<th>Early</th>
<th>Middle</th>
<th>Late</th>
<th>Early + 10% speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry Speed (km/hr)</td>
<td>102.6</td>
<td>102.6</td>
<td>102.6</td>
<td>112.8</td>
<td></td>
</tr>
<tr>
<td>Exit Speed (km/hr)</td>
<td>103.2</td>
<td>105.6</td>
<td>102.7</td>
<td>110.0</td>
<td></td>
</tr>
<tr>
<td>Max predicted g force wave 1</td>
<td>4.3</td>
<td>3.7</td>
<td>4.6</td>
<td>5.6</td>
<td></td>
</tr>
<tr>
<td>Max predicted g force wave 2</td>
<td>4.7</td>
<td>4.8</td>
<td>5.0</td>
<td>5.1</td>
<td></td>
</tr>
<tr>
<td>time 'g' value exceeds 4g (sec) wave 1</td>
<td>0.38</td>
<td>0</td>
<td>0.58</td>
<td></td>
<td></td>
</tr>
<tr>
<td>time 'g' value exceeds 4g (sec) wave 2</td>
<td>1.09</td>
<td>0.68</td>
<td>1.39</td>
<td>2.49</td>
<td></td>
</tr>
<tr>
<td>Note: the time over 4g for the early entry +10% speed line is combined time through both waves as the g did not drop below 4g between waves.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Curve 7</th>
<th>Entry</th>
<th>Early</th>
<th>Middle</th>
<th>Late</th>
<th>Early + 10% speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry Speed (km/hr)</td>
<td>106.0</td>
<td>106.0</td>
<td>106.0</td>
<td>116.6</td>
<td></td>
</tr>
<tr>
<td>Exit Speed (km/hr)</td>
<td>110.1</td>
<td>112.0</td>
<td>111.8</td>
<td>119.6</td>
<td></td>
</tr>
<tr>
<td>Max 'g' force predicted (g)</td>
<td>3.75</td>
<td>4.0</td>
<td>5.3</td>
<td>4.8</td>
<td></td>
</tr>
<tr>
<td>time 'g' value exceeds 4g (sec)</td>
<td>0</td>
<td>0</td>
<td>0.62</td>
<td>0.51</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Curve 9</th>
<th>Entry</th>
<th>Early</th>
<th>Middle</th>
<th>Late</th>
<th>Early + 10% speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry Speed (km/hr)</td>
<td>112.0</td>
<td>112.0</td>
<td>112.0</td>
<td>123.2</td>
<td></td>
</tr>
<tr>
<td>Exit Speed (km/hr)</td>
<td>117.6</td>
<td>120.5</td>
<td>118.0</td>
<td>127.6</td>
<td></td>
</tr>
<tr>
<td>Max 'g' force predicted (g)</td>
<td>3.65</td>
<td>4.1</td>
<td>5.1</td>
<td>4.0</td>
<td></td>
</tr>
<tr>
<td>time 'g' value exceeds 4g (sec)</td>
<td>0</td>
<td>0.14</td>
<td>0.37</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.14: Summary of SDM predicted Speed and 'g' accelerations for Skeleton (cont.)
Table 6.14: Summary of SDM predicted Speed and ‘g’ accelerations for Skeleton (cont.)
### Curve 14

<table>
<thead>
<tr>
<th>Entry</th>
<th>Early</th>
<th>Middle</th>
<th>Late</th>
<th>Early + 10% speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry Speed (km/hr)</td>
<td>141.0</td>
<td>141.0</td>
<td>141.0</td>
<td>155.1</td>
</tr>
<tr>
<td>Exit Speed (km/hr)</td>
<td>144.8</td>
<td>141.9</td>
<td>143.6</td>
<td>158.0</td>
</tr>
<tr>
<td>Max predicted g main wave 1</td>
<td>4.5</td>
<td>4.3</td>
<td>6.0</td>
<td>4.3</td>
</tr>
<tr>
<td>Max predicted g end of curve wave 2</td>
<td>4.8</td>
<td>3.6</td>
<td>4.2</td>
<td>5.8</td>
</tr>
<tr>
<td>time 'g' value exceeds 4g (sec) main wave 1</td>
<td>0.85</td>
<td>0.40</td>
<td>0.76</td>
<td>0.73</td>
</tr>
<tr>
<td>time 'g' value exceeds 4g (sec) end wave 2 (note: no time available for this g)</td>
<td>N.A.</td>
<td>N.A.</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
</tbody>
</table>

### Curve 15

<table>
<thead>
<tr>
<th>Entry</th>
<th>Early</th>
<th>Middle</th>
<th>Late</th>
<th>Early + 10% speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry Speed (km/hr)</td>
<td>144.0</td>
<td>144.0</td>
<td>144.0</td>
<td>158.4</td>
</tr>
<tr>
<td>Exit Speed (km/hr)</td>
<td>143.6</td>
<td>146.7</td>
<td>123.8</td>
<td>159.0</td>
</tr>
<tr>
<td>Max 'g' force predicted (g)</td>
<td>4.0</td>
<td>4.7</td>
<td>5.3</td>
<td>4.7</td>
</tr>
<tr>
<td>time 'g' value exceeds 4g (sec)</td>
<td>0.42</td>
<td>0.55</td>
<td>0.55</td>
<td>0.45</td>
</tr>
</tbody>
</table>

Note: An impact for the late entry line affected the exit speed.

### Curve 16

<table>
<thead>
<tr>
<th>Entry</th>
<th>Early</th>
<th>Middle</th>
<th>Late</th>
<th>Early + 10% speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry Speed (km/hr)</td>
<td>147.0</td>
<td>147.0</td>
<td>147.0</td>
<td>161.7</td>
</tr>
<tr>
<td>Exit Speed (km/hr)</td>
<td>116.9</td>
<td>108.1</td>
<td>115.8</td>
<td>133.0</td>
</tr>
<tr>
<td>Max predicted g wave 1</td>
<td>3.9</td>
<td>4.9</td>
<td>5.8</td>
<td>4.9</td>
</tr>
<tr>
<td>Max predicted g wave 2</td>
<td>3.8</td>
<td>4.9</td>
<td>4.7</td>
<td>4.3</td>
</tr>
<tr>
<td>time 'g' value exceeds 4g (sec) wave 1</td>
<td>0</td>
<td>0.51</td>
<td></td>
<td></td>
</tr>
<tr>
<td>time 'g' value exceeds 4g (sec) wave 2</td>
<td>0.86</td>
<td>2.0</td>
<td>1.72</td>
<td></td>
</tr>
</tbody>
</table>

Notes:
The g in curve 16 does not fall below 4 g through the two waves for the late and early +10% speed lines. Therefore the time above 4g through these two waves is combined = the time 'g' values exceeds 4g.
The speed variation through the exit point, i.e. where measured is greatly influenced by the degree of right wall and rebound impacts on exit.

Table 6.14: Summary of SDM predicted Speed and ‘g’ accelerations for Skeleton (cont.)
The SDM model has an error bar of +/- 0.3g when compared to a real run of similar run parameters.
This study presents trajectories and predicted ‘g’ for a theoretical free flowing sled particle. Skeletons do not have active steer control. They cannot induce large steering
effects. Thus Skeleton sleds are more prone than any of the bobsleigh disciplines to follow a natural free flowing path. An athlete is only able to affect a small amount of steering effect via steering inputs.

This study used the Skeleton speed recorded off the start associated with the fastest finish time from the 2010 Vancouver Olympic Winter Games. This set the initial condition from which the rest of the run followed.

This trajectory study simulated the path of a particle on a real scanned track surface. This surface is not perfectly smooth and shows considerable undulations in the surface. These undulations can arise from a variety of sources. For example, from the man made ice preparation techniques, expansion and contraction of ice and the concrete track structure as temperature rises and falls, degradation due to runner wear or weather effects or undulating concrete structures beneath the ice. These ice surface variations create small direction changes that can result in increased g’s experienced through a section. The degree and size of the undulation will influence the g measured. The variation in g and velocity due to surface irregularities are highlighted and measured by the SDM and illustrated in the g and velocity plots. Original track design studies will use smooth CAD generated curves from original design intent. These curves will give back smooth g profiles and potentially lower g values than an irregular real ice surface. It is recommended that further studies are performed to understand the variation in g from a perfectly smooth curvature to that of a real undulating ice surface that has been hand shaped and prepared by ice workers and has experienced the changing environmental conditions. This would help track designers to set an error bar or working tolerance that would enable track designers to predict real g forces from a smooth perfect model surface.

The velocity plot and g-force map in Figure 6.14 is a composite of the plots and maps modeled for each section and is generated using the early and middle curve entries.
6.7.6.3 Injury and Incident Frequency Study Analysis Skeleton

6.7.6.3.1 Crash Frequency Study for Skeleton

The injury and incident frequency study highlighted that C16 exit had the highest incident rate. The most common incident for any Skeleton through this section was a severe right wall impact.

Other areas of incidence, in order of incidence rate were curves 15, 13, 6, 12 & 4.

6.7.6.3.2 Potential Reasons for Crash Frequency Statistics for Skeleton

Curve 16: The C16 geometry creates a sled trajectory with two waves. Each wave experiences relatively high levels of g for longer periods of time than other curves on the track. The entry line into C16 creates a high first wave. The trajectory then drops to the base of the curve before climbing to a very high point at the end of the curve.

All entry lines into curve 16 will result in an impact on the right side of the track on exit.
The extreme height and abrupt direction change of the final part of C16 creates a steep exit line which results in an extreme impact with the right wall.

It is ultimately the extreme height and the location of the high point of this second wave at the end of the curve that causes the severe right wall impact and crash potential on exit of C16. The combination of high g and high speed through both waves through curve 16 adds complexity and difficulty for the athlete to control a line through this curve.

Reducing the speed through C16 will reduce the g’s experienced and may change the wave height and position through the curve. However as seen with C6 and C7 trajectories for a single luge (with lower speed due to a ladies start position), lowering the speed alone may not create a less extreme exit of C16. The important consideration is the combined effect of wave height and location at the end of C13. Both waves are interconnected and thus must be considered together.

The SDM trajectory studies through C12, C13 and C14 highlights key curve characteristics and linked effects that may account for the crash rates observed in C14 and C15. The following describes the linked relationship through these corners.

It appears C12 was intentionally designed to create a technically difficult section to negotiate. The entrance to C12 has a ‘lead in geometry that makes it difficult to obtain height early in the curve. This ‘lead in’ feature into C12 is seen on the scanned track geometry. This lead in feature makes it difficult for the sled to achieve the height of the wave early in the curve and the height is pushed instead to the end of the curve. The steep transition off C12 creates an extreme left wall impact before C13. This trajectory was demonstrated by the SDM. The result of this extreme left wall impact may either create a crash through C13 or create a rebound off the left wall that destabilises the sled through C13 with subsequent difficulties being experiences at the end of the curve. The dynamics of C12 mean that it is very difficult to achieve a middle line into and through C13.

Analysis of C13 has shown that an early entry line into the curve means the sled has to ride over the identified entrance hump on the left side of C13 entry. The effect of riding over this hump can potentially lead to either the sled being flipped and thus cause a crash or alternatively push the sled back away from the curve on entry resulting in the sled cutting across the curve and riding back up the curve wall at the end of the curve. This high exit line potentially can cause the sled to ‘run out’ of curve and thus fall off the end of the curve or flip onto its side. If no crash is experienced from this line, the high exit will potentially destabilize the sled before entering C14.

Entering C14 with minimal control can create excessive height which results in a left wall impact before C15.

It appears that the high technical difficultly of C12 and C13 entry creates crash sites through the entry and exit of C13. If crashes do not occur within these curves the technical difficult of them creates high probability of sled destabilization and loss of control entering into C14 which could significantly increase the probability of crash incidence out of C14 and into C15.
It is of the opinion of this study that by reducing the technical difficulty of C12, and improving the entrance geometry of C13 (i.e. remove the entrance hump) then the crash potential through curves 13, 14 and 15 will be significantly reduced.

Technical difficulty can be achieved through geometry change or potentially through a reduction in speed through ice surface manipulation. In both cases further trajectory studies would be needed to assess the effects of any changes.

6.7.6.4 SDM Model Results vs Actual Runs for Skeleton

In Figure 6.33 a comparison of the time SDM model run time versus the base line run time of John Montgomery Olympic third run is presented in terms of the difference between the model run time and actual run time. This plot shows that the model is in relatively good agreement with the actual run time.

![Figure 6.33: Distance against Time plots of the SDM model performance vs the Gold medal performance from the 2010 Vancouver Olympic Games](image)

6.7.6.5 Considerations and Recommendations for Skeleton

The SDM analyzes the sled trajectory as a free particle model. In other words it considers the path of a particle flowing naturally down the track without the external influence of any athlete steering inputs and skill level or variations in control authority of the sled.
It must be noted that sleds across the sport have a broad spectrum of designs and control authority of which there is very little or no published data. Combined with almost limitless variation in runner design (even within a tightly controlled technical rule book) it becomes impossible to account for the steering mechanisms and variation in design for all sleds across the nations and teams.

The free particle model however is a powerful tool that predicts the trajectory of a generic sled along the course without steering inputs i.e. left to run freely. For the purpose of this project this in essence allows the SDM to predict trajectories and highlight areas of concern that are generated purely from the track & sled physics, the track/ice geometry, ice properties associated with sleds sliding on ice and aerodynamic properties of generic sled designs within the sled category.

6.7.6.5.1 G Force & Velocity Limitation for Skeleton

Table 6.14 highlights predicted ‘g’ over 5 g.

The options to reduce the ‘g’ accelerations in a curve are:

- Increasing curve radius with particular emphasis on the section of the curve which shows high g.
- Slowing the track by slowing the ice i.e. increasing the ice friction coefficient. Individual track sections could be targeted which could then act as ‘speed limiters’.
- Slowing the sled. e.g. by slowing the runner i.e. increasing the ice friction coefficient by employing a roughness and surface finish control.
- Modify track sections to create uphill sections that act as speed limiters.

The ‘g’ acceleration is proportional to velocity squared. It could be argued that the most effective way to reduce ‘g’ accelerations through a section is to slow the track speed.

6.7.6.5.2 Safety Boards / Barriers /Roof Integrity for Skeleton

This study highlights potential impact sites on the track from a free flowing sled particle. In all areas where track impacts are seen from free flowing lines, it is recommended that suitable safety boards are constructed in the zones of impact or zones of concern.

From the trajectory analysis it is evident that the trajectories through some curves are more sensitive to speed and entry line variation than others. These curves create the potential for a wider range of lines and thus a wider range of possible events. These curves need careful consideration.

Curves 4, 6, 7, 11, and 16 are in particular sensitive to entry line and speed variation.

Consideration with respect to safety barrier construction should be given to all impact sites or area where the sled approaches the limit of the track geometry. Each impact site is explained in more detail in each curve analysis section.

In summary these sites are:
- Curve 1: Right wall on exit.
- Curve 2: Roof to right wall area on curve exit.
- Curve 3: Left wall on exit.
- Curve 4: Right wall on exit; Roof area on the left extending onto and along the left wall on exit; Roof integrity at the end of C4.
- Curve 5: Left wall on curve exit.
- Curve 6: Roof area at the end of the curve and the transition from roof section to the left track wall: Integrity of the roof construction at the very end of curve in the event of a roof impact; Left wall on exit.
- Curve 7: Roof area at the end of the curve and the transition from roof section onto the right track wall: Integrity of the roof construction at the very end of curve in the event of a roof impact; Right wall on exit.
- Curve 9: Left wall on exit (between C9 and C10).
- Curve 10: Left wall on exit.
- Curve 11: Right wall on exit; Roof area / end of the curve transition onto the left wall.
- Curve 12: Left and right walls on exit (between C12 and entry C13).
- Curve 14: Left wall on exit (between C14 and C15).
- Curve 15: Right wall on exit; Area of the roof at the end of C15 and the left wall.
- Curve 16: Right wall and left wall on exit. The natural line creates multiple rebound impact potential; Integrity of the curve roof for wave 1 and 2 peak locations in the event of roof impacts.

This study does not recommend specific barrier size or exact location for considering safety barriers. This study presents areas for concern for the lines identified in the test run matrix. This study does not present the range of all possible impacts arising from a comprehensive range of entry speeds and lines or trajectories created from human driver error or decision making. It is highly recommended that further work is undertaken to assess a wider cross section of entry lines and speeds in order to gain a better understanding of the size of the impact zone areas.

### 6.7.6.5.3 Ice Profile for Skeleton

From the results of the study, attention should be given to the ice profiles in the following areas:

- Curve 4 – Curve 5: The height created at the end of C4 creates a steep transition off the curve which can result in an impact on the right wall before C5. Consideration should be given to the ice profile and fillet profile between the track floor and the wall on the right side of the track between the exit of C4 and entry to C5 to reduce the potential for the sled to ride up the wall.
- Curve 6: Consideration must be given to the ice profile between the track ‘floor’ and the left wall on the exit of C6. Oversized rounded fillets between the floor and the left wall could in effect create a ramp upon which the left runner of the bob could ride up.
- Curve 9: Consideration should be given to the ice profile through C9 in order to reduce the natural push off the curve into the left wall on exit. This would give the driver more range and choice of entry lines into C10.

- Curve 12: The trajectory study highlighted the difficulty for a sled to attain early wave height in C12 due to the restrictions caused from the lead in geometry of the track into C12.

  Consideration should be given to adjusting this entry portion of the curve profile to make it easier to create height earlier in C12 and therefore reduce the extreme height gained at the end of C12. This late extreme height is a factor in the left wall impact out of C12 which destabilizes the sled.

  Information attained from MAIN DOCUMENT Var03a WSC_PART-A (October 23, 2004, page 11) suggests that the entrance to curve 12 was intentionally designed into the track to create an additional level of difficulty through C12:

  ‘As an additional difficulty the vertical radius are formed so that the vertical centrifugal force shows one easy answering. That is once = 0,40 at the end of the "bended straight line" (C8) with N (Sx = 714,5 m ) and in the straight line in front of curve C12 with N = 0,67.’

  Note: This is an English translation where “one easy answering” could be interpreted as “one driving line”.

- Curve 12 to Curve 13: It is recommended that the ice profile in C12 is shaped where possible to create a longer exit radius, more progressive ‘g’ and less extreme exit trajectory out of C12 into C13. This will give drivers more range to choose their line/path into and through C13 as opposed to a forced path due to the extreme C12 exit height and exit line.

- Curve 13 Entry: The trajectory study highlighted the existence of a ‘hump’ in the ice on entry to C13 and highlighted the effect this hump has on ‘pushing’ the bob off the early entry line and onto a line that cuts across the curve. This entry hump in essence increases the crash potential through C13.

  It is highly recommended that the ‘hump’ on the left side of the track on the entry to C13 is modified or removed. When combined with the modifications to the C12 ice profile this will remove the potential for the left runner to ride up the hump and thus reduce the chance of the sled flipping over on its right side. Removing this hump will also prevent the sled from being pushed back off the curve and will enable the sled to follow a line into the ‘belly’ of the curve. This will in turn allow a less extreme direction change at the end of curve and therefore reduce the second potential area for the sled flipping over onto its rights side.

- Curve 15 to Curve 16: It is recommended that the ice profile through C15 is modified so that athletes are given more range to choose their entry line into C16.

  The model predictions show that the natural tendency of C15 is to ‘force’ a free flowing path down the right side of the track sometimes creating a right wall impact and thus creating a ‘late’ or right side entry trajectory into C16.
The late line into C16 creates more g through the first wave of C16 than an entry or middle entry line would create.

- Curve 16: Careful consideration must be given to the ice profile between the track ‘floor’ and the right wall on the exit of C16. Oversized rounded fillets between the floor and the right wall could, when combined with the extremity of the exit trajectory, create a ramp upon which the right runner of the bob could ride up.

The height and location of the two waves through C16 creates extreme height very late in the curve which in turn creates the extreme exit trajectory that leads to a severe right wall impact. The height and location of wave two is greatly influenced by the height and location of wave one and the entry line into the curve. It is highly recommended that consideration is given to remodeling of C16 to create a longer and lower exit trajectory that removes the wall impact. This may be possible through ice profiling but this will ultimately depend on the limitations imposed by the underlying concrete structure.

6.7.6.6 Final General Considerations for Skeleton

There are four key factors of the track’s characteristics that need to be carefully considered together during track design phase.

These fours factors are:

- Fast speeds (usually the bottom part of tracks)
- High ‘g’ forces (curves that combine small radii or sharp change in direction with speed)
- Technical sections requiring high skill levels to negotiate through without incidence.
- Curve profiles that force natural paths and therefore limit the range of lines achievable by the athlete through steering.

It is when three or four of these factors combine that the potential for crashes and wall impacts rise.

It is recommended that future track designs avoid the combination of three or four of these factors. It is recognized that the sports rely on creating tracks that are challenging in order to differentiate between the skill abilities of the best athletes in the world. However, it is recommended that technical sections are combined with slower speed sections and possible lower ‘g’ forces as opposed to technical sections combined with high g loading, fast speeds and curve profiles that tend to force a particular trajectory or path. It is the combination of all four factors that heightens the probability of incidence.

It must be noted that athletes if so wished, could possibly ‘tip’ or crash a sled or create a wall impact in the slower curves of a track if they steered against the curves in an extreme manor. Thus when considering what is ‘safe’ and ‘what is not safe’ with respect
to track design it must be understood that poor steering decisions by the athlete will always result in lines that are considered unsafe or dangerous. This is inherent within the sport.

It is recommended that all new tracks are independently analyzed during the design stages to offer a second or third opinion on design and trajectory simulations.
6.7.7 Summary of Doubles Luge Trajectory Findings

6.7.7.1 SDM Input Parameters for Doubles Luge

<table>
<thead>
<tr>
<th>Initial Particle Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discipline</td>
</tr>
<tr>
<td>Combine Sled + Athlete weight x2</td>
</tr>
<tr>
<td>Aero Drag coefficient</td>
</tr>
<tr>
<td>Aero Lift coefficient</td>
</tr>
<tr>
<td>Frontal area (m^2)</td>
</tr>
<tr>
<td>Ice – Runner friction coefficient</td>
</tr>
<tr>
<td>Air density</td>
</tr>
</tbody>
</table>

Table 6.15: Sled Dynamics Model (SDM) parameters

6.7.7.2 Speed & ‘g’ Force Acceleration Results for Doubles Luge

Table 6.16 presents a summary of the predicted ‘g’ accelerations down the Whistler track broken down into sections from curve 7 start to the finish curve 16.

The g accelerations predicted over 5 are highlighted in red.

<table>
<thead>
<tr>
<th>Curve 7</th>
<th>Entry Speed (km/hr)</th>
<th>Early</th>
<th>Middle</th>
<th>Late</th>
<th>Early + 10% speed</th>
</tr>
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<tbody>
<tr>
<td>Entry Speed (km/hr)</td>
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<td>36.3</td>
<td>36.3</td>
<td>39.9</td>
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<tr>
<td>Exit Speed (km/hr)</td>
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<td>65.7</td>
<td>65.6</td>
<td>67.6</td>
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<tr>
<td>Max ‘g’ force predicted (g)</td>
<td>1.7</td>
<td>1.6</td>
<td>1.8</td>
<td>1.65</td>
<td></td>
</tr>
<tr>
<td>time ‘g’ value exceeds 4g (sec)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Curve 9</th>
<th>Entry Speed (km/hr)</th>
<th>Early</th>
<th>Middle</th>
<th>Late</th>
<th>Early + 10% speed</th>
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<tr>
<td>Entry Speed (km/hr)</td>
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<td>65.8</td>
<td>65.8</td>
<td>72.4</td>
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<tr>
<td>Exit Speed (km/hr)</td>
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<td>91.0</td>
<td>88.6</td>
<td>93.1</td>
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<tr>
<td>Max ‘g’ force predicted (g)</td>
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<td>2.25</td>
<td>2.3</td>
<td>2.0</td>
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<td>0</td>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Curve 10</th>
<th>Entry Speed (km/hr)</th>
<th>Early</th>
<th>Middle</th>
<th>Late</th>
<th>Early + 10% speed</th>
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<tbody>
<tr>
<td>Entry Speed (km/hr)</td>
<td>91.0</td>
<td>91.0</td>
<td>91.0</td>
<td>101.0</td>
<td></td>
</tr>
<tr>
<td>Exit Speed (km/hr)</td>
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<td>104.0</td>
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<td>time ‘g’ value exceeds 4g (sec)</td>
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<td>0</td>
<td>0</td>
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</table>

Table 6.16: Summary of SDM predicted Speed and ‘g’ accelerations for Doubles Luge
### Table 6.16: Summary of SDM predicted Speed and 'g' accelerations for Doubles Luge (cont.)

<table>
<thead>
<tr>
<th>Curve</th>
<th>Entry</th>
<th>Early</th>
<th>Middle</th>
<th>Late</th>
<th>Early + 10% speed</th>
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<td>Curve 11</td>
<td>Entry Speed (km/hr)</td>
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<tr>
<td></td>
<td>Exit Speed (km/hr)</td>
<td>113.0</td>
<td>111.0</td>
<td>107.0</td>
<td>123.0</td>
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<tr>
<td></td>
<td>Max predicted g force wave 1</td>
<td>2.2</td>
<td>2.7</td>
<td>4.3</td>
<td>2.6</td>
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<tr>
<td></td>
<td>Max predicted g force wave 2</td>
<td>2.75</td>
<td>N.A.</td>
<td>N.A.</td>
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<td>0.36</td>
<td>0.24</td>
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<tr>
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<td>time 'g' exceeds 4g (sec) wave 2</td>
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<td>N.A.</td>
<td>N.A.</td>
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<tr>
<td>Curve 12</td>
<td>Entry Speed (km/hr)</td>
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<td>113.0</td>
<td>113.0</td>
<td>124.3</td>
</tr>
<tr>
<td></td>
<td>Exit Speed (km/hr)</td>
<td>120.0</td>
<td>119.0</td>
<td>118.5</td>
<td>130.0</td>
</tr>
<tr>
<td></td>
<td>Max 'g' force predicted (g)</td>
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<td>3.5</td>
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<tr>
<td></td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Curve 13</td>
<td>Entry Speed (km/hr)</td>
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<td>120.0</td>
<td>120.0</td>
<td>132.0</td>
</tr>
<tr>
<td></td>
<td>Exit Speed (km/hr)</td>
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<td>126.0</td>
<td>125.0</td>
<td>138.5</td>
</tr>
<tr>
<td></td>
<td>Max 'g' force predicted (g)</td>
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<td>2.5</td>
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</tr>
<tr>
<td></td>
<td>time 'g' value exceeds 4g (sec)</td>
<td>0</td>
<td>0</td>
<td>0</td>
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</tr>
<tr>
<td>Curve 14</td>
<td>Entry Speed (km/hr)</td>
<td>127.0</td>
<td>127.0</td>
<td>127.0</td>
<td>139.7</td>
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<tr>
<td></td>
<td>Exit Speed (km/hr)</td>
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<td>130.0</td>
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</tr>
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<td>Max 'g' force predicted (g)</td>
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<td>4.1</td>
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<td>0.12</td>
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<td>Curve 15</td>
<td>Entry Speed (km/hr)</td>
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<td>128.0</td>
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<td>140.8</td>
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<td></td>
<td>Exit Speed (km/hr)</td>
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<td>132.0</td>
<td>131.5</td>
<td>142.0</td>
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</tr>
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<td>0</td>
<td>0.47</td>
<td>0.38</td>
</tr>
</tbody>
</table>

Whistler Sliding Centre Sled Trajectory Study
<table>
<thead>
<tr>
<th>Entry</th>
<th>Early</th>
<th>Middle</th>
<th>Late</th>
<th>Early + 10% speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry Speed (km/hr)</td>
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<td>132.0</td>
<td>132.0</td>
<td>145.0</td>
</tr>
<tr>
<td>Exit Speed (km/hr)</td>
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<tr>
<td>Max predicted g force wave 1</td>
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<td>4.1</td>
</tr>
<tr>
<td>Max predicted g force wave 2</td>
<td>3.8</td>
<td>3.7</td>
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<td>time 'g' exceeds 4g (sec) wave 1</td>
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<td>time 'g' exceeds 4g (sec) wave 2</td>
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</tr>
</tbody>
</table>

Notes:
The speed variation through the exit point, i.e. where measured is influenced by the degree of right wall and rebound impacts on exit.

Table 6.16: Summary of SDM predicted Speed and ‘g’ accelerations for Doubles Luge (cont.)

The SDM model has an error bar of +/- 0.3g when compared to a real run of similar run parameters.

This study presents trajectories and predicted ‘g’ for a theoretical free flowing sled particle. Double Luge sleds in reality can steer and thus can adjust the lines and waves to create considerable variation from the natural free flowing paths. An athlete is able to affect change on the sled through steering inputs and therefore change the trajectory. By creating longer, lower waves, lower g forces will be experienced. Likewise an athlete can create shorter higher waves though curve by steering with as opposed to against natural tendencies of the track and by choosing to enter a curve with an extreme angle. Thus higher g’s than those predicted could be attained.

This study used the luge speed from a theoretical curve 7 start point. This set the initial condition from which the rest of the run followed.

This trajectory study simulated the path of a particle on a real scanned track surface. This surface is not perfectly smooth and shows considerable undulations in the surface. These undulations can arise from a variety of sources. For example, from the man made ice preparation techniques, expansion and contraction of ice and the concrete track structure as temperature rises and falls, degradation due to runner wear or weather effects or undulating concrete structures beneath the ice. These ice surface variations create small direction changes that can result in increased g’s experienced through a section. The degree and size of the undulation will influence the g measured. The variation in g and velocity due to surface irregularities are highlighted and measured by the SDM and illustrated in the g and velocity plots. Original track design studies will use smooth CAD generated curves from original design intent. These curves will give back smooth g profiles and potentially lower g values than an irregular real ice surface. It is recommended that further studies are performed to understand the variation in g from a perfectly smooth curvature to that of a real undulating ice surface that has been hand shaped and prepared by ice workers and has experienced the changing environmental conditions. This would help track designers to set an error bar or working tolerance that would enable track designers to predict real g forces from a smooth perfect model surface.
The velocity plot and g-force map in Figure 6.34 is a composite of the plots and maps modeled for each section and is generated using the early and middle curve entries.

![Velocity plot and g-map for Double Luge](image)

**Figure 6.34**: G - Map of a full simulated run for Doubles Luge (average of the early entry and middle entry line trajectories)

### 6.7.7.3 Injury and Incident Frequency Study Analysis Doubles Luge

The injury and incident frequency study highlighted that C13 had the highest crash incident rate followed by curves 15, 14 and 16.

#### 6.7.7.3.1 Potential Reasons for Crash Frequency Statistics

The injury and incident frequency study highlighted that C13 was the area of highest incident.

A sequence of trajectory studies with varying entry lines into C13 highlights key curve characteristics that could cause the highest crash incidence rate through C13.
Even though the ‘g’ accelerations recorded through C13 are not high, the curve appears to be a challenge due to two reasons:

- The high exit line out of C12 naturally creates an impact on the left wall very close to the entry point of C13. The rebound effect of this impact creates a ‘push’ off the left wall which results in the sled cutting across C13 as opposed to travelling around it. The result of this is that the sled rides back up the end of C13 and the sharp direction change can flip the luge onto its right side.

- On close inspection of the scanned geometry the entry to C13 appears to have a hump in the ice on the entry to the curve, with the highest part of this hump being on the left side into the curve. If the luge manages to negotiate C12 and exit without a left wall impact into C13, the left runner of the luge rides over the hump in the ice. The earlier the line into C13 the more extreme the effects of riding this hump. The hump will create a sudden push upwards on the left runner of the luge and could in effect ‘pop’ the left side of the sled up off the ice. This ‘pop’ could either flip the sled onto its right side or at least destabilise the sled. If the sled manages to ride this hump, the bump has the added effect of pushing the sled off the curve, which can result in the sled cutting across C13 as opposed to travelling around it. The result of this is that the sled rides back up the end of C13 and the sharp direction change can flip the sled onto its right side.

The reality is that C13 is very difficult to negotiate through without the luge flipping on its right side at worst or at best becoming unstable. An unstable sled out of C13 will create an unstable sled through C14.

Note: Doubles luge has a higher centre of gravity when compared to single luge or skeleton. This higher centre of gravity makes it more sensitive and vulnerable to changes in stability.

In curve 15, the exit of C14 creates in the case of the middle and late entry lines a left wall impact before C15. This impact will destabilize the sled and in some cases (dependent on the angel of impact and location of impact with respect to the entry into C15) could potentially induce a crash. The rebound effect of this left wall impact could also in addition results in a late entry line into C15. This late entry line will in effect create more height at the end of the curve and thus a steeper exit off the curve and a more severe right wall impact on exit.

The trajectory studies through C16 highlights key curve characteristics that account for the crash rates observed.

The C16 geometry creates a sled trajectory with two waves. Each wave experiences relatively high levels of g for longer periods of time than other curves on the track. The entry line into C16 creates a high first wave. The trajectory then drops to the base of the curve before climbing to a very high point at the end of the curve.

All entry lines into C16 will result in an impact on the right side of the track on exit.
The extreme height and abrupt direction change of the final part of C16 creates a steep exit line which results in an extreme impact with the right wall. The lower speeds of double luge result in an earlier exit point out of C16 than the singles luge for example. This earlier exit point creates a more acute impact angle due to the hitting a portion of curve wall as opposed to a portion of straight wall.

It is ultimately the height and the location of the high point of the second wave at the end of the curve that causes the severe right wall impact and crash potential on exit of C16. The combination of high g and high speed through both waves through C16 adds complexity and difficulty for the athlete to control a line through this curve.

6.7.7.4 SDM Model Results vs Actual Runs for Doubles Luge

This graphic is not available due to the Double Luge SDM analysis being of a theoretical start point with no actual run data to compare against.

6.7.7.5 Considerations and Recommendations for Doubles Luge

The SDM analyzes the sled trajectory as a free particle model. In other words it considers the path of a particle flowing naturally down the track without the external influence of any athlete steering inputs and skill level or variations in control authority of the sled.

It must be noted that sleds across the sport have a range of designs and control authority of which there is very little or no published data. Combined with almost limitless variation in runner design (even within a tightly controlled technical rule book) it becomes impossible to account for the exact steering mechanisms and variation in design for all sleds across the nations and teams.

The free particle model however is a powerful tool that predicts the trajectory of a generic sled along the course without steering inputs i.e. left to run freely. For the purpose of this project this in essence allows the SDM to predict trajectories and highlight areas of concern that are generated purely from the track & sled physics, the track/ice geometry, ice properties associated with sleds sliding on ice and aerodynamic properties of generic sled designs within the sled category.

6.7.7.5.1 G Force & Velocity Limitation for Doubles Luge

Table 6.16 highlights only two points with predicted ‘g’ over 5 g. Curve 14 (6.1) and C16 (5.0 in wave 1). These g’s are associated with the late entry line into the curve. The high g in C14 is associated with combined centrifugal and impact ‘g’ as the sled impacts with the roof. This is not considered a true centrifugal g.

The reduced speed through the lower portions of the track (due to a start location at C7) is the reason for only two instances of g recorded by the SDM over ‘5g’. The double luge still builds to a max speed of 132 km/hr into C16.

If further g reductions are required, the options available to reduce the ‘g’ accelerations in a curve are:
• Increasing curve radius with particular emphasis on the section of the curve which shows high g.
• Slowing the track by slowing the ice i.e. increasing the ice friction coefficient. Individual track sections could be targeted which could then act as ‘speed limiters’.
• Slowing the sled. e.g. by slowing the runner i.e. increasing the ice friction coefficient by employing a roughness and surface finish control.
• Modify track sections to create uphill sections that act as speed limiters.

The ‘g’ acceleration is proportional to velocity squared. It could be argued that the most effective way to reduce ‘g’ accelerations through a section is to slow the track speed.

6.7.7.5.2 Safety Boards / Barriers /Roof Integrity for Doubles Luge

This study highlights potential impact sites on the track from a free flowing sled particle. In all areas where track impacts are seen from free flowing lines, it is recommended that suitable safety boards are constructed in the zones of impact or zones of concern.

From the trajectory analysis it is evident that the trajectories through some curves are more sensitive to speed and entry line variation than others. These curves create the potential for a wider range of lines and thus a wider range of possible events.

Initiating the start of double luge at the C7 point on the track eradicates the challenges seen for the other sled disciplines in negotiating curves 4, 6 and 7.

However, curves 11, 13 and 16 in particular still need careful consideration.

Consideration with respect to safety barrier construction should be given to all impact sites or area where the sled approaches the limit of the track geometry. Each impact site is explained in more detail in each curve analysis section.

In summary these sites are:

• Curve 9: Left wall on exit (between C9 and C10).
• Curve 10: Left wall on exit.
• Curve 11: Right wall on exit; Roof area / end of the curve transition onto the left wall.
• Curve 12: Left and right walls on exit (between C12 and entry C13).
• Curve 13: The late line creates exit lines that approach the end of the track and onto the wall / side boarding. The extent of this boarding must be considered.
• Curve 14: Left wall on exit (between C14 and C15).
• Curve 15: Right wall on exit.
• Curve 16: Right wall and left wall on exit. The natural line creates multiple rebound impact potential; Integrity of the curve roof for wave 2 peak locations in the event of roof impacts.

This study does not recommend specific barrier size or exact location for considering safety barriers. This study presents areas for concern for the lines identified in the test run matrix. This study does not present the range of all possible impacts arising from a
comprehensive range of entry speeds and lines or trajectories created from human driver error or decision making. It is highly recommended that further work is undertaken to assess a wider cross section of entry lines and speeds in order to gain a better understanding of the size of the impact zone areas.

6.7.7.5.3 Ice Profile for Doubles Luge

From the results of the study, attention should be given to the ice profiles in the following areas:

- **Curve 12:** The trajectory study highlighted the difficulty for a sled to ride up early onto C12 due to the lead in geometry of the track making this possibility very difficult.

  Consideration should be given to adjusting this entry portion of the curve profile to make it easier to create height earlier in C12 when on an early entry line, which is the natural line from the exit of C11. The extreme height gained at the end of C12 is a factor in the left wall impact out of C12 which destabilizes the luge before negotiation of C13.

  Information attained from MAIN DOCUMENT Var03a WSC_PART-A (October 2004, page 11) suggests that the entrance to C12 was intentionally designed into the track to create an additional level of difficulty through C12:

  'As an additional difficulty the vertical radius are formed so that the vertical centrifugal force shows one easy answering. That is once = 0.40 at the end of the "bended straight line" (C8) with N (Sx = 714.5 m) and in the straight line in front of curve C12 with N = 0.67.'

  Note: This is an English translation where “one easy answering” could be interpreted as “one driving line”.

- **Curve 12 to Curve 13:** It is recommended that the ice profile in C12 is shaped where possible to create a longer exit radius, more progressive ‘g’ and less extreme exit trajectory out of C12 into C13. This will give drivers more range to choose their line/path into and through C13 as opposed to a forced path due to the extreme C12 exit height and exit line.

- **Curve 13 Entry:** The trajectory study highlighted the existence of a ‘hump’ in the ice on entry to C13 and highlighted the effect this hump has on ‘pushing’ the bob off the early entry line and onto a line that cuts across the curve. This entry hump in essence increases the crash potential through C13.

  It is highly recommended that the ‘hump’ on the left side of the track on the entry to C13 is modified or removed. When combined with the modifications to the C12 ice profile this will remove the potential for the left runner to ride up the hump and thus reduce the chance of the sled flipping over on its right side. Removing this hump will also prevent the sled from being pushed back off the curve and will enable the sled to follow a line into the ‘belly’ of the curve. This will in turn allow a less extreme direction change at the end of curve and therefore reduce the second potential area for the sled flipping over onto its rights side.
• Curve 15 to Curve 16: It is recommended that the ice profile through C15 is modified so that drivers are given more range to choose their entry line into C16. The model predictions show that the natural tendency of C15 is to ‘force’ a free flowing path down the right side of the track sometimes creating a right wall impact and thus creating a ‘late’ or right side entry trajectory into C16. The late line into C16 creates more g through the first wave of C16 than an entry or middle entry line would create.

• Curve 16: Careful consideration must be given to the ice profile between the track ‘floor’ and the right wall on the exit of C16, particularly in the early exit impact location. Oversized rounded fillets between the floor and the right wall could when combined with the extremity of the exit trajectory in effect create a ramp upon which the right runner of the bob could ride up.
6.7.7.6 Final General Considerations for Doubles Luge

There are four key factors of the track’s characteristics that need to be carefully considered together during track design phase.

These four factors are:

- Fast speeds (usually the bottom part of tracks)
- High ‘g’ forces (curves that combine small radii or sharp change in direction with speed)
- Technical sections requiring high skill levels to negotiate through without incidence.
- Curve profiles that force natural paths and therefore limit the range of lines achievable by the athlete through steering.

It is when three or four of these factors combine that the potential for crashes and wall impacts rise.

It is recommended that future track designs avoid the combination of three or four of these factors. It is recognized that the sports rely on creating tracks that are challenging in order to differentiate between the skill abilities of the best athletes in the world. However, it is recommended that technical sections are combined with slower speed sections and possible lower ‘g’ forces as opposed to technical sections are combined with high g loading, fast speeds and curve profiles that tend to force a particular trajectory or path. It is the combination of all four factors that heightens the probability of incidence.

It must be noted that athletes if so wished, could possibly ‘tip’ or crash a sled or create a wall impact in the slower curves of a track if they steered against the curves in an extreme manor. Thus when considering what is ‘safe’ and ‘what is not safe’ with respect to track design it must be understood that poor steering decisions by the athlete will always result in lines that are considered unsafe or dangerous. This is inherent within the sport.

It is recommended that all new tracks are independently analyzed during the design stages to offer a second or third opinion on design and trajectory simulations.
6.8 Fatal Accident Re-Creation

6.8.1 Overview

The final deliverable of the project was to recreate using the SDM the fatal accident involving Georgian Athlete Mr. Nodar Kumaritashvili.

The accident was reconstructed utilizing track video footage and information provided by WSL as guiding information.

Trajectory analysis was made of the athlete/sled sliding through the C14 to C15 to C16 sections using the parameters in Table 6.17.

6.8.2 SDM Input Parameters

<table>
<thead>
<tr>
<th>Initial Particle conditions: Single Luge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discipline</td>
</tr>
<tr>
<td>Track Reference Section</td>
</tr>
<tr>
<td>Specific curve analysis</td>
</tr>
<tr>
<td>Curve Entry Direction</td>
</tr>
<tr>
<td>Combine Sled + Athlete weight</td>
</tr>
<tr>
<td>Drag coefficient</td>
</tr>
<tr>
<td>Lift coefficient</td>
</tr>
<tr>
<td>Frontal area (m^2)</td>
</tr>
<tr>
<td>Friction coefficient</td>
</tr>
<tr>
<td>Air density</td>
</tr>
<tr>
<td>Sled speed in direction of travel at t=0</td>
</tr>
</tbody>
</table>

Table 6.17: Parameters used for re-creation of the fatal accident
6.8.3 Results

The SDM trajectory for the crash recreation is illustrated by the red line on the surface of the track.

Figure 6.35 shows the sled through curve 14 to curve 15.
Figure 6.36 shows the exit of curve 15 and the entry trajectory into curve 16.
Figure 6.37 shows an overview of curve 14, 15 & 16.
Figure 6.38 shows a zoomed in image of curve 16 from a reverse perspective.

Video animations of the sled trajectory through the curve sections are available in Appendix D.7

The SDM model was adjusted to recreate the same sled trajectory into C16 as shown on video footage. The sled trajectory out of curve 15 avoids contact with the right wall out of curve and as a consequence enter curve 16 on a late trajectory line.

The late entry into curve 16 results in a very high first wave through the early part of the curve which is very close to the roof. A very low drop in height then followed as can be seen in Figure 6.35. The sled then climbed to create a very high second wave towards the end of the curve. The line through the wave of curve 16 is very close to the roof. The sled then exits the curve with a very steep and angled transition which directed the luge at a steep angle towards the right inside wall. The extreme height and position of the second wave through curve 16 created an extreme wall impact that resulted in a rebound up and over to the opposite side of the track.

Table 6.18 is a summary of the predicted “g” force exposure from the modeling of the trajectory of the fatal accident.

<table>
<thead>
<tr>
<th>Particle trajectory results</th>
<th>Curve 15</th>
<th>Curve 16</th>
<th>Full section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time taken to complete section (sec)</td>
<td></td>
<td></td>
<td>6.1</td>
</tr>
<tr>
<td>Max ‘g’ force predicted (g)</td>
<td>4.1g (C15)</td>
<td>4.7 (C16)</td>
<td>-</td>
</tr>
<tr>
<td>time ’g’ value exceeds 4g (sec)</td>
<td>0.1</td>
<td>0.5</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 6.18: Predicted ‘g’ force exposure for the accident recreation
Figure 6.35: Trajectory of luge through section Curve 14 – C15

Figure 6.36: Trajectory of luge through section Curve 15 – C16
Figure 6.37: Trajectory of luge through section Curve 15 – C16
Figure 6.38: Zoomed in image of the exit trajectory from curve 16 and the following impact into the wall
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CHAPTER 7 - SAFETY AUDIT

Authors: Shelly MacKenzie, John Oullette
Organization: MacKenzie Safety Training and Consulting Ltd.
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TABLE OF CONTENTS

CHAPTER 7 - SAFETY AUDIT ................................................................. 299

7.1 Introduction .................................................................................. 303

7.2 Methodology .................................................................................. 304

7.2.1 Certificate of Recognition Benchmark Audit ................................ 305

7.3 Key Activities and Milestones ....................................................... 306

7.4 Deliverables .................................................................................. 306

7.5 Results/Findings ............................................................................. 307

7.5.1 Communication .......................................................................... 307

7.5.2 Hazard Identification and Control ............................................... 307

7.5.3 Emergency Response .................................................................. 309

7.5.4 Safe Work Practices and Procedures ........................................... 309

7.5.5 Training ...................................................................................... 310

7.5.6 Incident Investigation ................................................................... 311

7.5.7 Analysis of the Incidents .............................................................. 311

7.5.8 Interpretation of the Data ............................................................ 314

7.5.9 Visual Analysis of the Safety Features ........................................ 314

7.5.10 Controls for Access to the Track ............................................... 315

7.5.11 Internal Controls ....................................................................... 317

7.5.12 Effectiveness of Barriers ............................................................ 320

7.5.13 Coroner’s Report ....................................................................... 324

7.5.14 COR™ Benchmark Audit Summary ......................................... 324

7.6 Limitations/Dependencies/Variables .............................................. 332

7.7 Recommendations ......................................................................... 333
LIST OF TABLES
Table 7.5.1 Incident Summary .................................................................................... 312
Table 7.5.2: Whistler Sliding go2 Audit Scoring Summary ........................................ 325

LIST OF FIGURES
Figure 7.5.1: Plot of Incident Frequency................................................................. 313
Figure 7.5.2: Lower Start Area Viewed at Corner 2.................................................. 315
Figure 7.5.3: Corner 11 Underpass ........................................................................... 315
Figure 7.5.4: CCTV Camera near C6 ....................................................................... 316
Figure 7.5.5: CCTV Camera plus PA Horn at Finish line........................................... 316
Figure 7.5.6: Walls – Representative Image Near C9................................................. 318
Figure 7.5.7: Wall at Finish – March 2010............................................................... 319
Figure 7.5.8: Finish Line Wall – Anchor Points....................................................... 320
Figure 7.5.9: C11 Roof Markings .......................................................................... 321
Figure 7.5.10: Marks – C11 Rollover ..................................................................... 321
Figure 7.5.11: Transition – C13-C14 .................................................................... 322
Figure 7.5.12: Run-out Outer Barrier ..................................................................... 323
Figure 7.5.13: Run-out Inner Wall ........................................................................ 323
Figure 7.5.14: Extra Braces by Upper Overpass / Tunnel Near C11 ...................... 324
7.1 Introduction

The Whistler Sliding Centre was constructed prior to the 2010 Winter Olympics to host the bobsled, luge, and skeleton events for the 2010 Olympics. It was put into operation prior to that event, used for training, and testing to assure the Track met the standards for the Winter Olympic events.

During this evaluation and testing phase, some modifications were made to the Track and the barriers to enhance the safety of the Track. The summary of these items is generally included in the homologation documents of the Track records.

During the opening stage of the 2010 Olympics, a luge athlete lost control during training and was fatally injured in the incident. A complete investigation was conducted, modifications made to the Track, and the events continued for the 2010 Winter Olympics.

Following the Olympics, a BC Coroner conducted a fatality Inquiry and produced a report with some recommendations for the Track operators. Part of these recommendations included a complete audit of the Safety Management Systems of the operator, WSL.

The WSL commissioned an independent evaluation of the bobsleigh, luge and skeleton Track at Whistler BC in response to recommendations by the fatality inquiry. A team managed by SAIT was hired to effect this evaluation.

MacKenzie Safety Training and Consulting Ltd. was engaged by SAIT to conduct a safety audit of the Track Safety Management System. The objective of the safety audit is to determine if the Safety Management System in place meets international safety standards and recognized practices.

MacKenzie Safety is headed by Shelly Mackenzie (BS (OHS), CRSP, CHSC, Certified Safety Auditor (ENFORM)). Shelly founded the company in 1991, and has been active in the safety field as an educator and consultant since the company’s inception. She is currently a full time instructor in safety at SAIT and the CEO of the company bearing her name. Shelly is currently working on her master’s degree in safety.

Shelly started her career as an EMT for municipalities and through public education awareness campaigns and workplace fatalities recognized there was a need for preventing incidents and accidents. Through her career in safety, Shelly has developed health and safety management systems, developed and delivered company and industry specific safety training. Through her consulting, Shelly has represented her clients by conducting Prime Contractor fatality investigations, incident and accident investigations and emergency response evaluations.

John Ouellette (CFO, Consultant) has been with the company for six years, doing safety consulting work in the upstream oil and gas industry. His background is as an engineering manager for a manufacturer of heavy equipment, operations manager, service manager, and CEO, all in manufacturing. During his career in manufacturing he has worked in many areas of the world, supporting the companies he was employed by.

He moved to safety seven years ago to support Shelly in her company. His background in safety includes the University of Alberta OH&S Certificate, incident investigations
(including fatalities), and insurance investigations to determine root cause of mechanical failures. His prime role in Mackenzie Safety Training and Consulting Ltd. is safety program development, teaching safety at SAIT and training various groups in the programs Mackenzie Safety is contracted to develop. He is an ENFORM Certified Internal Auditor.

Basic safety management systems are developed to ensure the protection of workers, materials, equipment and the environment. These systems are also applied to volunteers and visitors as a measure of due diligence. Due diligence is a measure of doing everything that is reasonable and practicable in the situation to prevent injury or loss. Protecting workers from harm will also ensure the protection of athletes, visitors and participants.

Safety Management Systems focus on Communication, Hazard Identification and Control, Emergency Response, Safe Work Practices and Procedures, Training, and Incident Investigations. This report will address all of these elements with a focus on all elements being complete and effective.

7.2 Methodology

The audit process is a review of existing policies and procedures included in the current Safety Management System. The methodology used to carry out the safety audit of the Track included two parts. One part included an evaluation of the safety protective measures in place to assist in determining if there are any gaps and opportunities for improvement. The second part followed the Certificate of Recognition audit process to determine the current state of the Safety Management System and identify any opportunities for improvement of the System.

The scope of this audit is basically limited to the Track and facilities, as related to winter on-Track operations. During the review other additional hazards, such as wildlife or Track security, may have been identified but this review mainly concentrated on keeping in scope, and confining remarks to those items identified directly with the sliding Track operations.

Methodologies used in the Safety Protection Measures section of the Sled Trajectory Evaluation include:

- Reviewing documented policy and management practices as related to the activity on the Track.
- Identifying existing protective measures for their location and application.
- Creating an incident plot of the Track to determine the frequency and severity of incidents related to training or competition to date.
- Working with the trauma and trajectory lead investigators to correlate existing measures with predicted incidents.
- Working with trauma and trajectory lead investigators to identify gaps and opportunities for additional protective measures.
Data selected and used for the analysis was provided as raw, and was data entered by the trauma study team. Data included information retrieved from crash reports and tower logs, injury records, as well as Track use records.

Documents reviewed include those developed for workers, volunteers and visitors, and include policies and procedures as well as copies of completed documents to verify processes are occurring. Information from other sources such as those involved in this study is also utilized. These include the trauma study, RCMP report and the Coroner’s report. Documents provided by the Sliding Centre were reviewed, as well as those documents generated by the design and construction of the Track itself.

Other contributors to the safety audit deliverables are the Track drawings provided by WSL and others involved in the project.

Observations of the facility were conducted in the spring of 2011 while the Track was still in use and included observations of slides by elite athletes, the activities of workers in relation to clearing and preparing the Track, the Track structure and design, activities of the sliding center in relation to operations, and hazard control methods in use.

Another Track visit was conducted in June to observe the Track without the ice in, which allowed our team to take pictures of the Track and the safety barriers in place when the ice was out. Other activities completed included taking specific measurements of barriers on the Track, constructed to contain the slider and the sled in Track, which allowed for a comparison of barriers with any documentation. It also allowed our team to observe the emergency measures and activities of the workers during the season when the Track is not open.

The volume of the information was truly formidable. Over 44,000 sliding records and 700 plus incidents were reviewed. Evaluation of the safety measures in place included the review of over 400 drawings, the homologation documents, and the comparison of the installed Track safety systems with the design specifications. Over 300 photographs were taken and studies, along with measurements to confirm the safety barriers and other systems conformed to the design specifications.

There were over 2,500 documents related to the safety management system, including procedures, policies, and Emergency Response Plans that were reviewed.

7.2.1 Certificate of Recognition Benchmark Audit

The primary tool used to assess the current state of the safety program at the WSC Track was the Certificate of Recognition (COR™) Benchmark Audit. The COR™ program is an occupational health and safety accreditation program that verifies a fully implemented safety & health program which meets national standards.

The WSC Track is located in the Province of British Columbia and its operations are regulated by the various Ministries of the Government of British Columbia. In order to provide proper guidance to the WSC management team, consistent with the Provincial Government regulations, the COR™ guidelines provided by the Ministry of Tourism (http://www.go2hr.ca/IndustrybrHealthSafety/CertificateofRecognitionProgram/tabid/1915/Default.aspx ) were used for the benchmark audit.
Any past or future modifications to the track and the safe operation of the facility should be rooted in the safety policies and procedures. These policies should also take into account the various regulations that are provided by The Province and the sliding federations such as the FIBT and FIL. The COR™ benchmark audit determines the level of employee awareness of the policies and procedures that are in place but it doesn’t determine the adequacy of the policies or procedures for the facility. This is discussed elsewhere in this report.

7.3 Key Activities and Milestones

The following is a summary of the key activities:

- Visit to Whistler, collection of injury reports, photography, kick-off meeting
- Mapping of incidents on spreadsheets, request documents from Whistler (safety manual)
- Received and evaluated safety related documents from Whistler.
- Second visit to Whistler to take pictures with all blinds up and take measurements of Track, met with RCMP regarding investigation report. Obtained copies of tower records
- Mid Term Report
- Matching photos with corners and identified which areas of the track required further review,
- Conducted interviews for COR™ benchmark audit

7.4 Deliverables

The deliverables provided in this safety audit include:

- A detailed summary of observations,
- A map of protective measures,
- Incident plot,
- Detailed summary of gaps and opportunities for additional protective measures,
- Assessment of the implementation of the recommendations included in the Coroner’s Report,
- COR™ benchmark audit score and gap analysis,
- Opportunities and recommendations for improvements in the safety program based on observations and the COR™ benchmark audit.
7.5 Results/Findings

7.5.1 Communication

Communication is essential to ensure the safety of everyone at the Sliding Centre. Effective communication between the Olympic Committees, the Organizing Committee, regional managers, volunteers, staff, athletes, coaches, and the general public must be clear and convey a consistent message. The consistency of the messages avoids misunderstandings and will provide the greatest protection of all stakeholders.

Safety communication is used to ensure the management policies and procedures are understood and followed. The effectiveness of the internal responsibility system is based on everyone involved meeting their safety responsibilities set out by management and being held accountable to ensure they are being met. This can be done through the distribution of policies and procedures, safety meetings, the Joint Health and Safety Committees, posting of site rules, and safety orientations.

Documents reviewed for this audit were used to communicate processes, procedures and specifications including training materials for visitors and volunteers, meeting minutes from the safety committee, the site health and safety manual, and hazard identification records. The procedure for clearing the Track after workers had entered was reviewed as a part of the documentation review.

Overall, there appears to be effective communication that is consistent for all areas where documentation was available. Training programs, safety manuals and procedures are documented and appear to address all levels of workers and volunteers. There is also a map with information about what visitors should do if a bear is seen while the visitor is on a walking tour. This information is provided to visitors who go to the Sliding Centre as a part of their visit. Signs with rules are also posted for visitors notifying them to stay out of the Track and other specific site rules with pictograms.

To ensure accountability, there was a document reviewed that would be used to address non-compliance for the contractors used during the design and construction phase, but there was no evidence of an accountability program in place once the construction was completed. There were also no completed documents available to show if the process is applied to workers on the Track who fail to comply with the procedures established for clearing or maintaining the Track. Observations made at the site in the spring showed visitors were not complying with posted rules, indicating this type of communication was not effective.

7.5.2 Hazard Identification and Control

The basis and goals for all safety programs is the identification of hazards and the control of those hazards. A hazard is generally defined as any situation, condition or thing that has the capacity to cause loss or injury to people, materials, equipment and the environment. Hazards can be classified as physical, chemical, biological and psychological.

Identifying hazards requires the input from all levels of employees and management on a continuous basis. Hazards can be identified by observing the work environment,
evaluating employees’ tasks, conducting an exercise where hazards are identified by asking “what if,” and hiring consultants who are familiar with the tasks to provide guidance. This is a process that doesn’t stop because the facility is operating at what may be considered normal operations. Hazards can change on a day-to-day basis and since the Sliding Centre is open year round, the hazards associated with the different seasons also need to be identified.

Once hazards have been identified, they need to be assessed for risk. Some hazards present more of a risk than others, and those with the highest risk must be controlled first. Risk is a product of probability, severity and frequency.

The probability of a hazard causing a loss is determined in a number of ways. Has this hazard resulted in a previous loss, such as an injury to a worker, or damage to equipment, materials or the environment? Has this hazard resulted in a near miss, where slightly different conditions would have resulted in a loss? Has this hazard caused a loss at other facilities that have the same type of activities? Has this hazard caused a loss at other companies in the same industry? If there is a history of this hazard causing a loss, or it has been the cause of near misses, there is more impetus to control it sooner.

The severity component of risk relates to how much would not controlling this hazard cost the company if a loss were to occur? Is there a possibility of a loss of life, facility, equipment or materials? What is the total cost of that loss including soft expenses such as training and hiring replacement employees, investigation time by the supervisor and down time while the investigation is conducted? The more money it would cost to return to normal operations or the greater the severity of a potential injury, the higher the risk the hazard poses.

The final component of risk is the frequency an employee is exposed to the hazard. The uncontrolled hazards that are frequently exposed to employees present a higher risk.

All high-risk hazards need to be controlled completely or the risk reduced to an acceptable level before work can proceed or continue. This also applies to users of the Track and the general public.

The control of hazards is accomplished through four different methods: elimination of the hazard; engineered controls; administrative controls; and personal protective equipment. A combination of controls may also be used to eliminate or reduce the risk. One of the most significant parts of hazard control is to re-evaluate the hazard once it has been controlled, to ensure the control measure is effective.

The WSC documents reviewed included completed hazard assessments. These documents were created during the construction phase and operations phase of the Centre. Hazards identified include overexertion, cold exposure, wildlife encounters, and driving. Engineered controls in place that were observed by our team include guardrails where access to the Track is necessary, pole and hook to raise and lower sun shades, and road access to critical points at the facility. Administrative controls reviewed through the documentation included training on how to recognize cold injuries, procedures to follow when wildlife encounters occur, and procedures for clearing the Track when track workers are crossing or removing debris from the Track during
operations. Personal protective equipment observed in use includes cold weather work clothes and high visibility clothing.

From the review of the documents and the observations conducted at the site, it appears the hazards have been identified and controlled for the workers. Hazard controls for the public and the athletes will be addressed later in this report. However, anytime there is an incident, near miss or a loss, the existing hazard controls need to be reassessed and new controls instituted as required. This process was demonstrated by modifying the location and height of the containment walls on the Track after incidents occurred on the Track indicating an improperly controlled hazard.

There was no documentation of near misses or documented evidence that incident reports and medical records were used to take corrective action, such as the installation or modification of roll over walls. Without this documentation it was assumed the control measures in place are adequate.

7.5.3 Emergency Response

Emergency response planning is necessary because emergencies will occur and having an effective plan will reduce the amount of loss and help to ensure a return to normal operations. Plans need to be developed specific to the work environment and activities carried out. It also needs to represent all operations that occur in all seasons. The Sliding Centre has operations that vary on a wide range, from pre-Olympic activities, to the Olympic activities, to completion on a smaller scale, to summer operations where the Track activities are shut down but the site is still operational. The response plans also need to reflect the number of people on the site, the amount of risk the public and employees are exposed to, and the reasonableness of response teams.

Emergency response plans reviewed for this audit include ammonia leaks, injuries and wildlife encounters during the Olympics, when the Track is set up for training and public use and in the summer when the Track activities are shut down but the general public is still at the site.

One of the hazards identified for visitors in the summer is bear encounters, and visitors are instructed to “notify Guest Services immediately.” Observations made in the spring when the Track was not in service included bears in the breaking outrun area of the Track and by the finish building. Calls to the Sliding Centre to notify staff of the presence of the bears went unanswered during Guest Services open hours. This is an indication there needs to be an assessment completed on the current procedures and they may need to be modified so they are consistent with printed materials and instructions provided to the visitors. When there is an indication of a gap in a procedure, then it becomes prudent to test all related procedures. There are logistical challenges between plans that are followed in the ‘busy’ season when there are multiple resources available, and the ‘off’ season when activities on the Track are shut down.

7.5.4 Safe Work Practices and Procedures

Safe work practices and procedures are considered administrative hazard controls. These are developed by the employer, operator or owner of the site and are specific to
the hazards identified. They are generally developed with the input of those who will be complying with the procedures and may be used in conjunction with other hazard control methods.

Included in this section of a Safety Management System are the specific rules to be followed and an enforcement process for when they are not. This should include the public while they are on site. Specific rules that are posted need to have some enforcement behind them. Observations made when the Track was not operating in the spring identified two separate instances where the public entered the Track when posted rules indicated this activity was not allowed.

Documents evaluated included the procedure for clearing the Track after an incident, lock out procedures and operating machinery. In general, the procedures include the hazards, the controls and the steps to be followed which are standard for safe work procedures. This is based on the documentation and limited observations of activities in March 2011.

The procedure for clearing the Track appears to be adequate based on the document and the observations made while the Track was in operation. However, there were no documents available for review that provided information on worker near miss reports or incident reports on the Track. Without documents indicating if there were incidents that resulted in a worker injury or a close call, the assumption was made the procedure is adequate.

7.5.5 Training

Safety training can be conducted in many ways. Formal training such as certification courses including first aid may be regulated. Safety orientations are a common method of training workers, visitors and athletes to the facility and will usually include emergency procedures, hazards and their controls. This training can be done one-on-one, as a group or through an on-line system. Other safety training is site specific and usually includes the specific policies and procedures workers are required to perform as a part of their job tasks. The employer is responsible for ensuring workers are competent in their job tasks. Competency is a result of adequate training, the ability to perform the tasks safely and enough experience to perform the task with little to no supervision.

Documents reviewed from the Sliding Centre include the safety orientation programs for volunteers, workers and coaches. Other training records include training on-the-Track clearing procedures and the sign off workers were required to complete after they had received training in the procedure.

Assumptions are made that the training provided was adequate as there were no completed documents presented to the auditor or available to prove workers were tested for competence. (The VANOC Safety Competency assessment form is part of the OHS Documents, but we were not presented with any completed forms.)

Without completed forms proving competency testing, the employer cannot be diligent in proving the workers are capable of performing their job tasks safely. We recommend
that all workers be tested for competence in the tasks they are required to perform as a part of their job duties.

7.5.6 Incident Investigation

During the review of the OHS documentation, many of the forms and procedures were VANOC forms and procedures. As this organization is now past its usefulness for the Centre, the question can be posed if the procedures and policies used by VANOC are still the ones endorsed by the Centre. Both the incident investigation forms and the hazard reporting forms fall into this category.

During the major incident at the Track, the investigation was conducted for the most part by external bodies. The Track did not appear to have staff on site trained in incident investigation, or if they were there, the records do not show it.

7.5.7 Analysis of the Incidents

A key component of the Safety Audit involved working with the Trauma Study team to determine the adequacy of safety measures and safety reporting procedures. From the Trauma Study, Table 7.5.1 and Figure 7.5.1 summarize the incident frequency from the track logs over the period from the opening of the track to March, 2011.
<table>
<thead>
<tr>
<th></th>
<th>Total Number of Runs</th>
<th>Incidents</th>
<th>Frequency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bob - 2 man Athlete</td>
<td>5,271</td>
<td>143</td>
<td>2.71%</td>
</tr>
<tr>
<td>Public</td>
<td>121</td>
<td>5</td>
<td>4.13%</td>
</tr>
<tr>
<td>Total</td>
<td>5,392</td>
<td>148</td>
<td>2.74%</td>
</tr>
<tr>
<td>Bob - 4 man Athlete</td>
<td>748</td>
<td>40</td>
<td>5.35%</td>
</tr>
<tr>
<td>Public</td>
<td>98</td>
<td>0</td>
<td>0.00%</td>
</tr>
<tr>
<td>Total</td>
<td>846</td>
<td>40</td>
<td>4.73%</td>
</tr>
<tr>
<td>Luge – Double Athlete</td>
<td>2,160</td>
<td>90</td>
<td>4.17%</td>
</tr>
<tr>
<td>Public</td>
<td>0</td>
<td>0</td>
<td>0.00%</td>
</tr>
<tr>
<td>Total</td>
<td>2,160</td>
<td>90</td>
<td>4.17%</td>
</tr>
<tr>
<td>Luge – Single Athlete</td>
<td>20,540</td>
<td>395</td>
<td>1.92%</td>
</tr>
<tr>
<td>Public</td>
<td>1,387</td>
<td>3</td>
<td>0.22%</td>
</tr>
<tr>
<td>Total</td>
<td>21,927</td>
<td>398</td>
<td>1.82%</td>
</tr>
<tr>
<td>Skeleton Athlete</td>
<td>11,821</td>
<td>31</td>
<td>0.26%</td>
</tr>
<tr>
<td>Public</td>
<td>934</td>
<td>2</td>
<td>0.21%</td>
</tr>
<tr>
<td>Total</td>
<td>12,755</td>
<td>33</td>
<td>0.26%</td>
</tr>
<tr>
<td>Discovery Skeleton</td>
<td>106</td>
<td>0</td>
<td>0.00%</td>
</tr>
<tr>
<td>Skeleton/Bob</td>
<td>61</td>
<td>0</td>
<td>0.00%</td>
</tr>
<tr>
<td>WSC Sport Experience</td>
<td>19</td>
<td>0</td>
<td>0.00%</td>
</tr>
<tr>
<td>Total</td>
<td>43,266</td>
<td>709</td>
<td>1.64%</td>
</tr>
</tbody>
</table>

Table 7.5.1 Incident Summary
Figure 7.5.1: Plot of Incident Frequency

Incidents Plotted Where Location Is Given

Number of Incidents

Location (Corner)

0 50 100 150 200 250

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16

Outrun

Incidents Plotted Where Location Is Given
7.5.8 Interpretation of the Data

Not all data collected gave the full location where an incident occurred. In many cases the data indicates where the sled or rider ended up, not where the incident occurred. In general, the data did provide guidance as to where many of the incidents occur, and some idea of where to look to review the existing controls.

It was clear that there were no investigation reports associated with these incidents. These reports would give a better view of what controls were implemented or could be implemented in the future reduce the possibility of incidents occurring.

A summary of the data is presented in Appendix E.3.

7.5.9 Visual Analysis of the Safety Features

The Track design is required to keep the participants of the various sports in the Track during a run, and to prevent the intrusion of the outside world from entering the Track at that time. While coming off of a sled or overturning it during a run presents a degree of risk, this risk is acceptable to the sport as long as the vehicle and the participants do not impact another object. The only way they should be able to impact another object is to leave the Track surface they are sliding on, or to have something intrude upon that surface.

During the investigative portion of the audit a number of photographs of the Track were taken, starting at the end of the season, and again during the summer while the ice was out. These pictures formed a background for the audit which provided a reference to various features against the design parameters, the drawings, and markings which assisted in determining whether the safety features of the Track were adequate to protect the users, the operators and the spectators against known hazards.

Features which were included in this visual analysis were the Track surface, the entry points for the participants, the rails and barriers to prevent entry to the Track surface, and the barriers and walls designed to keep the vehicles and participants on the Track during a loss of control.

Of particular interest in the analysis is the identification of any feature which may be impacted by a participant, and identification of any clues or markings which may be present to indicate they have been impacted, and have either been adequate or not in performing their design purpose.

Input included: the observation of the Track operators and participants at the end of the sport season and again during the summer season; the design drawings; documentation of changes to the design; and pictures taken during the winter at the end of the season, and in the summer while the Track was not in use but other sports or activities were happening on the premises.

While over 300 photographs were evaluated and archived, only those items deemed potentially hazardous are included in this portion of the analysis.
7.5.10 Controls for Access to the Track

Examination of the starting stations, buildings and shelters, the bridges and tunnels, and comparison to the construction documents shows little or no deviation from the planned construction. Similarly, the placement of the rails and external barriers to prevent people from entering the Track appears to be the same as on the construction drawings.

A good example of this is the lower start area, near C2 (Figure 7.5.2) and the underpass just down from C11 (Figure 7.5.3). Note the concrete barriers and the rails to prevent Track access.

![Figure 7.5.2: Lower Start Area Viewed at Corner 2](image)

![Figure 7.5.3: Corner 11 Underpass](image)
The upper start is where the participants and support staff would congregate, while the lower area is in the public domain. It would be assumed that people in the start area would have some knowledge of Track operations and have been oriented in where not to go. In the lower area, the general public has access, and they have not been oriented. This means that other controls, such as supervision, would be needed to ensure the barriers were respected.

While visiting the Track in the winter, workers were witnessed and interviewed while clearing the Track, and inspecting for debris prior to a run. They were in position to control access, and had communication to the Track control tower to ensure the participants were not endangered by either debris on the Track or by unauthorized people on the Track while the run was in progress.

![Figure 7.5.4: CCTV Camera near C6](image)

Other controls observed to be in place included closed circuit TV and a public address system to inform everyone in the area when a run was in progress.

![Figure 7.5.5: CCTV Camera plus PA Horn at Finish line](image)
The operation of this system during the late winter runs was observed. Workers at the lower end would report the Track to be clear by radio, the tower operator would announce the run starting in 2 minutes, then the start. After the run, the tower would report the time, and that the Track was clear of participants before the workers would re-enter the Track to inspect for debris.

While there are gaps in the coverage of the CCTV, the placement appears to be the same as on drawing number A0-17.161-0123 (P6). (Appendix E.4)

7.5.11 Internal Controls

Internal controls for the purpose of this report are those controls designed to prevent participants from leaving the Track during an incident. Incidents which could cause this are a roll over, loss of control of the vehicle, or leaving the vehicle during an extreme loss of control. In any case the result could cause the sled, the occupant, or both to leave the Track.

Controls to prevent this from happening are the design of the Track structure, the ice surface preparation, and retaining walls on either side of the Track designed to keep the participant from leaving the Track unexpectedly.

The design of the Track and the ice preparation are designed to protect the safety of the participant in terms of the limit on the speed and G forces, and this is dealt with elsewhere in the overall report. This safety audit examines the walls, the placement of these walls and later the markings observed on the walls are examined to determine if they may or may not be adequate for the intended purpose.

The barrier walls are of two different designs. The first is intended for the inside of a curve, and consists of a roll-over barrier of limited height on the inside of a curve to prevent a sled that bounces off the outside wall from exiting the Track. The second is a crash barrier for the outside of a curve, and may have a roof built in to prevent the sled from climbing past the extent of the wall during extreme maneuvers. An example of both types of barriers is shown in the photograph in Figure 7.5.6.

Start Gate Safety Walls are incorporated at various locations along the track where sleds enter from different starting positions. The intention of the walls is to prevent sleds from entering the track simultaneously, from different locations, and to prevent a sled that started from a higher location sliding and catching openings in the walls created at the entry points. A detailed drawing of a typical Safety Gate Safety Walls was produced for the incorporation into the various cut out sections was developed. (E.4 – A0-17.031-44)
The typical construction of the roll over barrier is detailed on drawing A0-17-031-42. (Appendix E). This roll over barrier is of differing heights and lengths along the Track. Placement appears to coincide with the homologation recommendations.

The initial drawing is of steel supports covered with wood, painted white. A later variation on this theme is the addition of a puck board material over the wood to create a smoother sliding surface.

The crash barriers typically are constructed of plywood over a wood frame. The frame is anchored to the Track by steel bolts and the wooden supporting frame is anchored at the top by bolting to the roof structure. Again, the wall is coated with a puck board material to allow for a smoother sliding surface.

The intersection of crash barriers with the concrete is defined by a 6’ wide green tape to allow the athlete to better see the junction.

An examination of the documents did not identify the design placement of the barriers on the drawings. The only reference for the placement and size of the roll-over or crash barriers are in the homologation documents. These comments were general in nature, and while they gave guidelines for the construction, no engineered drawings or strength calculations were available for review. There were also no construction documents or any documents detailing reviews that may have led to modifications of these barriers.

The only firm date that could be established with the installation of a crash barrier was found from documentation associated with the wall constructed at the exit of C16 and along the beginning of the outrun. It was built during the night of the fatality, February
12, 2010. However, there were no design notes or calculations available to support the construction of that barrier (Figure 7.5.7).

Photographs and measurements were taken of that particular wall to determine if it was solidly constructed and properly anchored. The anchoring appeared to be sufficient and the wall was well constructed of plywood over a 2 x 4 frame (Figure 7.5.8).
7.5.12 Effectiveness of Barriers

While examining the barriers, traces of paint transfer, or marks on the barriers that indicated they had been struck by a sled were observed at various points along the track. The placement of these markings were examined more closely as an indicator of the adequacy in their intended purpose.

No markings existed above C10 on any of the barriers. The first area where markings were observed was in turn C11 where there were markings on the roof (Figure 7.5.9).
Coming out of turn 11 and heading across the overpass, the roll-over barrier showed markings as high as 6 inches from the top of the roll-over barrier (Figure 7.5.10).

The significance of these markings is an indication that the barriers here are doing their job. Whether they are adequate or not is open to interpretation. Crash barrier markings,
while serious, do not constitute the vehicle or occupant leaving the Track. Markings high on a roll-over barrier should be considered an indication of where a hazard exists. While marks continued on into C12 and C13, they were predominantly on the crash barrier, with little marking on the roll-over barriers until the exit of C13 where there were major indications of paint transfer (Figure 7.5.11).

Figure 7.5.11: Transition – C13-C14
Another area with significant marks is on the barriers at the beginning of the outrun, where indications of paint transfer continued right to the end of the barriers. In this case at the end of the barriers on either side, marks were clearly seen on or above the green tape, four to six inches above the concrete (Figures 7.5.12 and 7.5.13).

Observations which indicate the marks go past the end of the barriers may be an indication the length of barrier is inadequate for its intended purpose. A proper incident reporting system that includes near misses, would include an investigation of the functionality of barriers or the need for more barriers. In the absence of this system, it would be incorrect to assume the barrier in this situation needed modification.
Finally, clarification for the extra structural (brown) members on the barrier near C11 shown in the photo in Figure 7.5.14 should be documented.

Any time there is an addition there is a reason. In this case, is this a result of an undocumented near miss or just a precaution against someone falling through to the ground below? If it is for sleds leaving the Track, the structure could pose a risk of someone striking the structure and being severely injured as they leave the Track. Again without a proper incident reporting and investigation system it is not clear what the reason was for the additional wood and steel bracing.

7.5.13 Coroner’s Report

A review of the coroner’s report text concluded all actionable items were dealt with after the incident, with the single exception of this safety audit.

7.5.14 COR™ Benchmark Audit Summary

In order to provide a better picture, a series of telephone and Skype interviews were arranged with the current staff and management in place and a former employee.

The go2 Occupational Health and Safety Certificate of Recognition tool used to complete the COR™ audit resulted in a combined score of 68% for the completed audit. A score of 80% must be achieved in order receive a Safety Certificate of Recognition. A summary of the scores for each section of the audit is presented in Table 7.5.1.
<table>
<thead>
<tr>
<th>Section</th>
<th>Possible Score</th>
<th>N/A</th>
<th>Available (Possible - N/A)</th>
<th>Score</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section 1 Management and Leadership Commitment</td>
<td>170</td>
<td>25</td>
<td>145</td>
<td>122</td>
<td>84%</td>
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<tr>
<td>Section 2 Hazard Identification and Control</td>
<td>185</td>
<td>50</td>
<td>135</td>
<td>64</td>
<td>47%</td>
</tr>
<tr>
<td>Section 3 Safe Work Procedures and Written Instructions</td>
<td>190</td>
<td>110</td>
<td>80</td>
<td>64</td>
<td>80%</td>
</tr>
<tr>
<td>Section 4 Inspection of Premises, Equipment Workplaces and Work Practices</td>
<td>105</td>
<td>95</td>
<td>10</td>
<td>10</td>
<td>100%</td>
</tr>
<tr>
<td>Section 5 Investigation of Incidents/ Accidents</td>
<td>100</td>
<td>60</td>
<td>40</td>
<td>28</td>
<td>70%</td>
</tr>
<tr>
<td>Section 6 Training and Instruction of Employees</td>
<td>140</td>
<td>60</td>
<td>80</td>
<td>73</td>
<td>91%</td>
</tr>
<tr>
<td>Section 7 Program Administration</td>
<td>140</td>
<td>70</td>
<td>70</td>
<td>20</td>
<td>29%</td>
</tr>
<tr>
<td>Section 8 Joint Occupational Health and Safety Committee (JOHSC)</td>
<td>110</td>
<td>65</td>
<td>45</td>
<td>32</td>
<td>71%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1140</strong></td>
<td><strong>535</strong></td>
<td><strong>605</strong></td>
<td><strong>413</strong></td>
<td><strong>68%</strong></td>
</tr>
</tbody>
</table>

Table 7.5.2: Whistler Sliding go2 Audit Scoring Summary

It is important to note that this audit represents a sample composed more of managers and supervisors than workers. Based on the responses of the workers as compared to that of the supervisors, this score would likely have been lower if more of the seasonal workers were involved.

The comments from the auditor accompanying the audit should be viewed as opportunities for improvement of the Safety Management System and are limited to the scope of the audit instrument.

Based on the analysis of the COR™ audit interviews the following gaps categorized by the primary elements and specific questions of the audit, should be acted on:
7.5.14.1 Element 1: Management and Leadership Commitment (score 84%)

Question 1.1: Does the business have a written health and safety policy?

A safety policy for the Sliding Center should be developed, signed by the CEO and posted in areas the workers gather such as lunch rooms as well as at the head office.

Question 1.2: Are the aims of the health and safety policy clearly stated?

The safety policy is the statement by the CEO that sets the overall direction of the safety program and the goals. These should be specific and measurable as well as achievable in the next 12 months. This policy should be reviewed yearly and amended as the goals are achieved.

Questions 1.3: Does the health and safety policy clearly outline the responsibilities for the employer, managers, supervisors and workers?

Since the policy is signed by the CEO, it is also a directive that specifies the expectations for all levels in the organization. Safety responsibilities need to be identified in the policy so everyone knows this is coming from the top and will be managed. Examples of responsibilities could include complying with company policies and procedures, reporting incidents and complying with applicable legislation.

Questions 1.4: Does the employer inform the Employees about the policy?

The policy needs to be a part of orientations, regular safety meetings and posted so employees are aware of its content and requirements. Compliance cannot be achieved if it is not known what is expected.

Question 1.6: Are the following aware of their safety responsibilities—managers, supervisors and workers?

Once the safety responsibilities have been established for each level of authority, ensure each employee is aware of what is expected. Each level will have different responsibilities and to meet them they must be aware of them. They should be provided at the new worker orientation and returning worker orientations. They should also be reviewed in safety meetings and during training sessions.

Questions 1.7: Are health and safety responsibilities carried out?

Once safety responsibilities are established, they must be carried out. For example, workers may be responsible for conducting inspections, supervisors responsible for ensuring the inspections are carried out and corrective action taken on deficiencies and managers are responsible for reviewing reports on deficiencies that cannot be carried out at the supervisory level or require capital expenditures. Each level must meet their responsibilities for the next level to meet theirs. All responsibilities must be measurable and manageable and a documentation process should be put in place to record corrective action is taken.
Questions 1.8: Is there an effective system to ensure accountability for safety roles and responsibilities?

What gets measured gets managed. To ensure the safety responsibilities are being carried out, supervisors and managers need to have a system in place that is consistent and objective. This can be done with a scorecard system, a measurement system that counts the safety activities (for example, if an employee is responsible for conducting weekly inspections, there should be an inspection report for each week the worker was employed), or through an established system. It must be clear that the scorecard is a measure of safety responsibilities, not job responsibilities.

7.5.14.2 Element 2: Hazard Identification and Control (score 47%)

Question 2.1: Is there a process to analyze jobs, equipment and conditions for hazards according to risk?

Although this question is based on document review only, the interview process identified the formal hazard assessments have not been completed or conducted in some time. Hazards such as snow falling off of the roof on the shed over the finish line falling on the road, creating icy conditions, and potential for falling on a slider/visitor/employee causing injury was brought up as reported but was not controlled in the winter. Written hazard assessments are the basis for the entire safety program. Safety is about identifying the hazards and controlling them. Due diligence requires this to be done for the employees, but due to the operations at the WSC, the general public and users of the facility must also be protected. Hazards reported from any source should be evaluated for risk and controlled as appropriate. These documents must be kept on file and reviewed and the process repeated on a regular basis.

Question 2.4: Do workers report unsafe conditions?

This question did not have any points associated with it in the audit, but was identified in the interviews as an activity that is not being performed. Some interviews indicated the incidents for the athletes were being reported but not those of the employees. Encourage reporting from the workers, including the near misses and those they feel were not important such as skinned knuckles from working on the ice and the tools used. Without these reports, there will not be any changes to improve the hazard controls in place.

Question 2.6: Are the hazard identifications, assessments and controls reviewed regularly?

This question lost points because the interviews determined the process is not occurring. Written hazard assessments are the backbone of the safety program. This process should be continuous and conducted regularly. A policy needs to be in place and followed. Responsibilities need to be assigned and competent employees must be involved. Management must review the assessments to ensure the
hazards are being controlled and to track the progress of the new controls being implemented.

Question 2.9: Does the employer have a method to ensure compliance with the rules, safe work practices and job procedures? Is it being followed?

Interviews conducted with managers, supervisors and workers determined not all were familiar with the compliance/enforcement policy. To ensure consistent application of the policy, managers and supervisors must be familiar with it and workers need to know how their non-compliance will be addressed and that it will be applied equally to all workers.

Question 2.10: Are hazard controls communicated to workers?

Interviews conducted with workers have identified certain positions have their hazards communicated to them very well and other positions have very little communication about their job hazards. It is important to ensure that all positions have the job hazards communicated to them as well as their hazard controls explained so workers are protected from those hazards. Office personnel have different hazards based on their job tasks but still face hazards. This can be done through the new employee orientation and through safety meetings.

7.5.14.3 Element 3: Safe Work Procedures and Written Instructions (score 80%)

Question 3.7: Are there written emergency response plans? Is the emergency response plan readily available to all employees?

This question lost points on the observation portion because there were no plans accessible in the workplace and no posted evacuation routes were observed. Ensure up to date copies of the emergency response plan for the WSC are available at all locations, including the tower, the athlete lodge and all other fixed sites. All VANOC plans need to be updated to the WSC and positions identified with the WSC staff.

Question 3.9: Are emergency response plans evaluated to identify deficiencies and review accordingly?

This question lost points because the interview process determined there had been a lapse in drills being conducted over the past 12 months. The emergency response plan needs to be regularly tested to ensure it will be effective in the event an incident occurs. Each type of emergency should be drilled, whether it is a significant on-track incident, wildlife encounter (bear attack on a visitor) or an aggressive visitor. Ammonia release emergencies have a great potential for loss but others need to be evaluated as well. Tabletop exercises as well as practical drills all need to be evaluated afterwards to ensure there were no problems or deficiencies. All plans should be updated after the drill and dated to show the last revision.
Question 3.10: Does the organization have a workplace hazardous materials information system (WHMIS) program?

This question lost points on the observations because chemical storage observed at the shop indicated there were some gaps in the program regarding the storage of compressed gasses. WHMIS is a program that requires on-going inspections and evaluations. Although most organizations require workers to be trained when they are hired, many workers become complacent over time and over-familiarity with the chemicals can reduce the attention paid to them. Include WHMIS related items in the ongoing inspection program to ensure compliance is met.

7.5.14.4 Element 4: Inspection of Premises, Equipment, Workplaces and Work Practices (score 100%)

Question 4.6: Is there a system for preventing the use of defective/broken tools and equipment until it is repaired or replaced? Is it being followed?

Interviews conducted with supervisors and managers have determined there is a formal system in place for some areas of the Sliding Center and for others the system is not formal or consistent. Although it may be necessary for different departments to have different systems, the practise of following those systems should not be. All workers and supervisors must have a system in place that is effective and is followed consistently. Observation and follow up on training may be necessary to ensure the process/procedure is followed consistently.

7.5.14.5 Element 5: Investigation of Incidents/Accidents (score 70%)

Question 5.2: Have employees been made aware of the accident/incident investigation procedure?

Interviews conducted with employees have determined supervisors and managers are familiar with the process but workers are not. The purpose of the investigations is to ensure the incident does not reoccur. Workers need to be made aware of this so they are more comfortable in reporting their incidents. They also need to know what types of incidents will be investigated. Common responses from the interviews suggest only incidents involving athletes are being investigated so this perception needs to be corrected, and the investigations and their findings communicated to all employees.

Question 5.3: Are incidents/accidents investigated as per the company’s procedures?

Although the procedures were not available to compare the completed investigations against, interviews with managers, supervisors and workers determined investigations are only being conducted of serious accidents and only of those on the Track. Near misses need to be investigated as well and all incidents need to be included, not only those of athletes but of workers, seasonal workers and any incidents involving the public that are reported.

Question 5.4: Are the persons investigating incidents trained in investigation techniques?
Interviews conducted with the employees who are responsible for conducting incident investigations have not all received training on how to conduct the investigation. Training needs to be conducted with all supervisors on how to collect evidence, how to interview witnesses and how to analyse the results for root causes. This can be done in-house or can be a more formalized program. However, training materials need to be provided for resources and techniques practiced. One method of providing practice to an investigator is to use the emergency response drill as an incident. The investigator can then go through the process of interviewing the workers involved, collecting data and then identifying causes for the “accident.” Developing recommendations will also assist in refreshing hazard control methods and practices information for the investigator.

Question 5.6: Are employees aware of their responsibilities to report all incidents?

Although this question received full points, concerns were identified in workers not reporting first aid only incidents or incidents that occur on a regular basis because they are a 'part of the job' or 'the use of the tool.' These incidents are a sign of a bigger problem in that workers are determining what is important for management to know and censoring their information. If using a specific tool causes regular injuries and it is not reported, management will not be looking for a solution to the problem, whether it is a different tool or a new procedure. Enforcement of the reporting procedure needs to be done. This may require more supervision, more training or an incentive program.

7.5.14.6 Element 6: Training and Instruction of Employees (score 91%)

Question 6.2: Are employees trained on safe work practices and job procedures?

Interviews conducted with employees identified different functional areas of the WSC Center provide more training on job specific procedures than others. When new employees are hired, their orientation is robust, especially on the track or at the refrigeration plant. When employees are hired in one area, and then moved temporarily to another because of the slow season or a shortage of workers, they are not provided with adequate training for their new tasks. For example, if you are a medical worker and you have been asked to work on the track for the day, you will not have had the same training in the track procedures as someone who was hired to work on the track. Transferred employees or temporary workers are at a higher risk for injury because they are not competent in the work they are being asked to perform and will not necessarily ask for information if they are unsure of what to do. In general, the new worker is paired up with an experienced worker. According to some interviews, this does not always occur. New/temporary workers may be placed on the track alone, or under video surveillance, which may not be enough to ensure they are safe. Under staffing can put inexperienced workers in hazardous conditions, and at a higher risk. This must be identified and prevented.

Question 6.3: Is there a system to assess and ensure that all employees are qualified and are competently performing their duties in a safe manner?
Although this question scored full points, further discussion is needed. Interviews conducted with supervisors have determined their employees are deemed competent through various methods. This process needs to be formalized and documented. Conducting observations or working with the employee may tell their supervisor they are competent, but the records created will tell the other supervisors if they are competent or not. Each task and procedure that must be followed needs to be checked off showing the worker was observed doing the job safely, with little to no supervision and how he was trained. These competency records will assist in incident investigations, assigning safety responsibilities, and for promotion and job transfer. If a worker is assigned to the track and their competency records show they were trained for that task and can perform it competently, then they will require little supervision when they perform that task on a temporary basis.

7.5.14.7 Element 7: Program Administration (score 29%)

Question 7.3: Are the outcomes of the analysis of incident trends communicated to all employees?

Reported incidents and near misses need to be communicated to employees for a number of reasons. First, they can see that reports must be made. Second, they see that workers are not punished for reporting their incidents. Third, it shows employees that management is taking their reports seriously and finally, it shows that everyone contributes to safety. If incident trends are discussed with all employees, they can see they have an impact on how safety is handled and can also understand why management may be implementing a new procedure or bringing in new equipment.

7.5.14.8 Element 8: Joint Occupational Health and Safety Committee (JOHSC) (score 71%)

Question 8.5: Are minutes for the meetings made accessible to all employees?

This question lost points on the observation portion because there were no current meeting minutes observed posted at any of the fixed sites during visits to the Track. The meeting minutes are created to inform all employees about the issues discussed by the committee and the actions to be taken by management and the committee on safety issues. It identifies who the committee members are and allows workers to see safety concerns are being addressed. Ensure the most current copy of the meeting minutes are posted in all areas workers gather, such as the shop, refrigeration plant and lunch/change rooms.

Question 8.7: Do workers know how to find out who their representative on the JOHSC is?

This question lost points because employees could not identify who their committee members are. Some comments indicated that the committee had not met in several months. Many workers rely on the JOHSC to bring up safety issues they may not feel comfortable bringing up with management on their own. The JOHSC is an integral part of the safety program. Ensure the committee is operating, following
their terms of reference and post the names and photos of the committee members by the emergency information and safety bulletin boards. Include the most current committee member information in the new worker orientation program and remind workers in meetings or training sessions who they are.

Comments from the interviews that were out of the scope of the COR™ criteria but which were worth noting include:

During an examination of the engineered controls present on the track, there were no documented reasons or justifications for the location of the crash barriers. When the documentation was requested to confirm that these barriers were properly placed (Incident reports, engineering documents, or other documentation regarding the placement of these barriers) the explanation was that the placement of the barriers was often directed by someone pointing at a spot on the track, and saying, “I want a barrier from here to there about this high”.

As stated earlier it was noted that paint transfer from the sleds was present in locations on the barriers. Based on these pictures, we were able to deduce that some of the barriers had paint transfer at the end of the barriers above the level of the track. This would indicate the barriers were not adequate in some areas but no one recorded observations that would indicate the cause of the marks and subsequently lead to modifications of the safety barriers.

A concern, which was only mentioned by one of the staff, is the possibility of someone getting injured by snow falling from the roof over the outrun. It was mentioned the roof slides are frequent, often large enough to block the road, and fall onto the path that is used by workers, athletes, and emergency response vehicles. A complete formal hazard assessment should identify this hazard.

In general, comments from the employees interviewed were positive.

The auditors thank everyone for the time and effort in arranging and participating in the COR™ audit process.

7.6 Limitations/Dependencies/Variables

While this audit was being conducted there was difficulty in obtaining documentation specific to the WSC operations. The majority of the documentation presented either represented the athletes experience on the track, or were VANOC documents. As a result, the auditor does not believe the audit provides the complete and representative picture of the Safety Management System currently in place at the WSC.

Due to the season, the interviews carried out for the COR™ audit missed a large portion of the seasonal workers present when the track is in full operation in the winter.
7.7 Recommendations

The following recommendations were derived from the observations made at the track and the results of the COR™ audit:

1. It is recommended that a Change Management procedure be formalized. During this audit, it was difficult to verify details about changes to the safety procedures, construction, or the reasons for such items, from the documentation. The procedures detailing the recommendation for change, the authorization, date of the change, details of the changes made (Work Orders or dated updates for policy or procedures), and sign-off by management indicating their approval in both completion and quality, form the basis of both a Quality Management System and a Safety Management System and should be integral to the Change Management procedure.

2. It is recommended that all near misses and incidents both on the Track and off the Track be reported and documented. There are indications the hazard controls in place are not effective and need to be improved. Reporting needs to be encouraged from those using the Track, such as the athletes, and those involved in Track activities, such as coaches and visitors. Asking athletes for anonymous reporting will encourage reporting. Stressing input from coaches will assist in protecting the athletes and will also encourage reporting.

3. It is recommended that the Track management trains all staff involved in incident investigation, and assign the trained staff to investigate all near misses and incidents which occur at the facility.

4. It is recommended that the collection of data both on-and-off the Track and in the facility be improved to gather more relevant data in an organized fashion.

5. It is recommended there be ongoing reviews of the emergency response system throughout all operating phases and seasons of the year. This can be done internally as well as conducting exercises that include outside emergency services. All emergency response drills should be documented and the plans reviewed to ensure there are no gaps in the plans, there is an active and available communication system, and instructions provided to the public are accurate and effective.

6. It is recommended that there be a sign-off sheet for visitors indicating they were provided with information about the hazards and the rules to be followed on the property. This includes staying out of the Track and what to do when there is a bear encounter. This may require more specific control of access to the facility while the Guest Services Centre is open, larger and more frequent signs specifying the rules, and warning signs for those who visit the site when Guest Services is closed.

7. It is recommended there be a monitoring process of visitor activities to ensure site rules are enforced.

8. It is recommended that a procedure and record management system be developed to measure and record worker safety training and skill competency.
The records should be reviewed regularly (at least annually) and become part of an employee’s employment file.

9. It is recommended that all of the VANOC forms and policies applicable be reviewed and converted to WSL forms and policies. The VANOC forms and policies should be retired and archived.

10. It is recommended that all barriers on the track be identified, documented and reviewed on a regular basis for their purpose, their functionality, their integrity and a proper risk analysis be done to determine the adequacy of the barrier, as identified with the example of the wood and steel bracing structure in C11.

11. It is recommended that the Federations (FIBT and FIL) develop detailed specifications for roll over barriers (walls and roofs) based on crash worthiness testing and include guidelines and documentation procedures for location and the size of the barriers.

12. It is recommended that an additional review of all safety or loss control measures related to off-Track operations be performed, with an objective of identifying the hazards and potential for loss to the facility for any off-Track operations. Of particular note is the facility is in operation year round. In the winter the Track is in operation, and in the summer it is a tourist attraction. During both winter and summer there are activities taking place at the facility which do not involve the Track. The review should include the operations of such additional attractions such as snowmobile tours, ATV tours and rides, and any other operation which would be done at the facility, or accessed through the facility.
APPENDIX

The content included in the Appendices is available upon request from Whistler Sport Legacies.

Appendix A. Survey Data
A.1 Control Traverse Data for Whistler Sliding Centre Track
A.2 Control Coordinate Comparison After Helmerts Transformation
A.3 Coordinate List for Helmerts Transformation Results
A.4 Appendix D - Filed Notes for Precise Leveling Circuit

Appendix B. As-Designed to As-Constructed Comparison
B.1 As-Designed to As-Constructed 2 Dimensional Cross Sections
B.2 As-Designed to As-Constructed 3 Dimensional Contours (link to software and folder)

Appendix C. Design and Construction Documents
C.1 IBG Consulting Engineering Drawings
  • Drawing (Unnumbered) Final Design – Ground Plan, Var03a, July 5, 2004
  • Drawing WSC 001 Bobsleigh and Luge Track, Polygon of Centre Line, Version 4, dated May 6, 2006
  • Drawing WSC 04.1 Bobsleigh and Luge Track, Longitudinal Section/Part 1, Version 4, dated May 5, 2006.
  • Drawings WSC, Phase 1, 402.1 through 402.6, Version 2, Concrete Profile – Curve: C2/S102 Section-Cross Section, dated November 7, 2005.
    • 402.1
    • 402.2
    • 402.3
    • 402.4
    • 402.5
    • 402.6
  • Drawings WSC, Phase 2, 502.1 through 502.6, Version 0, Jig Profile-Curve: C2/S102 Section-Cross Section, dated November 7, 2005.
    • 502.1
    • 502.2
• 502.3
• 502.4
• 502.5
• 502.6

C.2 Stantec Architecture Ltd. Documents for VANOC Contract No. V5051

Specifications for Whistler Sliding Centre Track and Foundations

• Specification Section 01010 Work Under This Contract, dated January 5, 2006.
• Specification Section 03713 Shotcrete, dated January 5, 2006.
• Drawings (Complete listing of all drawings, plans and sketches that are part of the Bid Documents).

Drawings for Whistler Sliding Centre-Contract No. C-1524 Buildings and Civil Works

• Drawing A0-17.021-400 Drawing List and Legend, Revision P5, dated February 13, 2006.
• Drawing A0-17.021-401 Track Geometries, Revision P5, dated February 15, 2006.
• Drawing A0-17.021-403 Typical Track Sections, Revision P4, dated December 21, 2005.
• Drawing A0-17.021-407 Track Grading/Water Main Plan and Profile, Sta 0+15 to Sta 0+140, Revision P5, dated February 15, 2006.
• Drawing A0-17.021-408 Track Grading/Water Main Plan and Profile, Sta 0+140 to Sta 0+330, Revision P4, dated December 21, 2005.

Drawings for Whistler Sliding Centre-Contract No. C1524 Structural Works

• Drawing A0-17.031-000 Drawing List and Legend, Revision P7, dated February 15, 2006.
• Drawing A0-17.031-01 Structural Notes, Revision P6, dated December 22, 2005.
• Drawing A0-17.031-02 Track Foundation Plan, Sta 0+014 to Sta 0+041, Revision P7, dated February 13, 2006.
• Drawing A0-17.031-03 Track Foundation Plan, Sta 0+046 to Sta 0+130, Revision P7, dated February 13, 2006.
• Drawing A0-17.031-04 Track Foundation Plan, Sta 0+135 to Sta 0+232, Revision P7, dated February 13, 2006.
• Drawing A0-17.031-24 Bobsled Track Details, Revision P7, dated February 13, 2006.
• Drawing A0-17.031-25 Bobsled Track Details, Revision P7, dated February 13, 2006.
• Drawing A0-17.031-26 Track Reinforcing Details, Additional Reinforcement at Supports, Revision P7, dated February 13, 2006.
C.3 DIALOG Three-Dimensional Model of the Surfaced Track
Document: As-Designed Concrete Surface Model Renderings, dated October 12, 2011

C.4 Epic Scan Comparisons Between the As-Designed and As-Constructed Track Surfaces
Viewing 3D contour comparisons requires Geomagic Qualify Software.

Documents:
110923_WSC_CONCRETE_vs_AS-DESIGN_SUMMARY, dated October 12, 2011
110923_WSC_CONCRETE_vs_AS-DESIGN, dated September 23, 2011

C.5 IBG Drawing Review Notes
Document:
IBG Drawing Review Notes – Whistler Sliding Centre Trajectory Study, Prepared by DIALOG, dated August 17, 2011

C.6 Doug Bush Survey Services Ltd. Bench Marks
Document:
Drawing 110640-CONTROL, Sliding Centre Control, Revision 0, dated May 27, 2011

C.7 Epic Scan Best-Fit Comparisons Between the As-Designed and As-Constructed Track Surfaces
Document:
111003_WSC_CONCRETE_vs_AS-DESIGN_BEST_FIT, dated October 3, 2011
Appendix D. Trajectory Simulations and Summaries
   D.1 Ice Geometry Modifications
   D.2 Four Man Bobsleigh Trajectory Summary
   D.3 Singles Luge Trajectory Summary
   D.4 Two Man Bobsleigh Trajectory Summary
   D.5 Skeleton Trajectory Summary
   D.6 Doubles Luge Trajectory Summary
   D.7 Trajectory Video Library

Appendix E. Safety and Construction Diagrams
   E.1 COR™ Audit Detailed Summary
   E.2 Audit Photographs
   E.3 Incident Analysis Data
   E.4 Construction Diagrams for Safety Elements

Appendix F. Ice to Concrete Comparison
   F.1 Ice to Concrete 2 Dimensional Cross Sections
   F.2 Ice to Concrete 3 Dimensional Contours

Appendix G. Medical Databases – UBC
This Appendix contains the databases used to carry out the retrospective analysis of track incidents and safety systems as it relates to athletes, visitors and personnel. The databases contain personal information and under the Research Ethics Board application to obtain the information cannot be released for public viewing.