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Rocket Sled Based High Speed Rail Track Test Facilities: A Review

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ABSTRACT

The present study introduces and compares several high–speed track based ground test facilities available all over the world to simulate high–speed dynamic events for selected portions of flight trajectories. The scope of performing high–speed flight–testing is addressed, which is followed by the requirements of these track based test facilities. The facilities deliver flight test articles under controlled conditions to achieve high velocity impact, acceleration, aerodynamic and other related testing for small and large test articles depending upon the requirements. Sled is designed in such a way so that it can carry the test articles like aircraft, payloads, warheads, missiles and many other ballistic systems to achieve high velocities ranging from subsonic to hypersonic by accelerating these sleds using solid rocket motors over the rail track. Such facilities provide instrumentation for large set of trial data acquisition and offline analysis for both recovery and non-recovery (impact) trials, which makes such facilities important for test, research and evaluation purposes.

Here, the detailed description of test facilities, which are available in many countries such as India, United States (US), Japan, United Kingdom (UK), France, and others countries based on their technical characteristics is presented. Additionally, a brief history and introduction into basic rocket sled test facility aspects, essential technical characteristics and major features to support high–speed testing at these facilities as an accurate testing technique based on quality of construction and engineering design are also covered in this paper. Compilation of available or under development facilities is done in one place which provides the information about facilities' technological gaps. The paper concludes with an explanation of the role, major capabilities and limitations of these test facilities in the present global scenario.

Keywords: Captive flight testing; High speed rail track; Instrumentation; Rocket sled; Test facility

1. INTRODUCTION

Rapid advancement in the design of highly sophisticated systems like aircraft, weapons, and many others ballistic systems with their required relevant data has made it necessary to invent or plan well and highly accurate techniques for testing. Investigation of aircraft munitions systems, hypersonic environments, and aerodynamic related effects are always required. To meet these requirements, high-speed sled track testing techniques are designed and continually being refined and extended. These have proved very valuable technique in obtaining data to meet development and research requirements.

Typically, ballistic ranges use solid boosters' charges for firing the test system or article through sled on rail track or in free flight. Test articles mounted over the sled can be fired at high velocities depending on requirement but somehow they are limited in weight, shape, size, and the type of instrumentation possible. The main feature of ballistic ranges is that they are proficient in producing very high Mach values (M) which are already in use for recovery as well as non-recovery trials in various atmospheric environments. Rocket mounted on sled over the rail tracks are used to allow the acceleration of large heavy bodily test systems to achieve large velocity. These track based test facilities are capable for impact testing of missiles, warheads, aircraft or other weapon systems, even enabling testing of full-scale test articles. In the early cold wars, due to risk of using heavy articles directly in pilot aircrafts, rocket sleds were used for extensive acceleration of systems. The equipment were installed along track with required instrumentation such as real time data capturing unit and telemetry system mounted on sled i.e. on-board instrumentation for testing under high speed conditions. The sled was then accelerated along the precisely levelled and straight test rail track according to the experimental requirements for data recording. On 16th March 1945, during World War II, a rocket sled was used to launch a winged strategic RM through tunnel. Also, in 30th April 2003, world's highest speed record of Mach 8.5 (2868 m/s) in history was achieved by 04 stage rocket mounted sled at Holloman Air Force Base station (AFB)[1]. Overseas, the facilities have been set up to attain velocities ranging from subsonic to hypersonic[2]. These type of test facilities are located all over the world, in countries like India where Rail Track Rocket Sled (RTRS) facility is located in Haryana[3], United States: Holloman High Speed Test Track (HHSTT), New Mexico[4], Supersonic Naval Ordnance Research Track (SNORT) in China Lake[5], Supersonic Military Air Research Track (SMART) in Hurricane Mesa[6], Sandia in Albuquerque New Mexico[7] & Redstone Technical

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Test Center Sled Track 2 and Redstone Arsenal, Alabama (AL)[8] and others. This paper has discussed various rocket sled based test facilities across the world with their capabilities and has a scope of acting as a source of information on rocket sled test facilities across the world for research and development. It can be a ready reckoner covering knowledge and information for users, specialists and researchers working in this field and will be useful for users in planning and execution of various design & development cycles of systems and sub-systems. A detailed technical review of the facilities available across the world were studied and summarised in this paper.

2. GENERALIZED BLOCK DIAGRAM OF ROCKET SLED BASED TRACK TEST FACILITY

A track based rocket sled test facility consists of a precision aligned test track, sled fabrication and qualification facilities, instrumentation and data recording facilities, both on-board and through telemetry, data processing and analysis capabilities and high-speed videography. Depending on test requirements, trial is conducted where various testing processes are evaluated.

The sled operates on the rail track that rides over the rail lines on shoes called slippers (slides over the rails). Size and configuration of sled varies as per the test needs and can be recovered for post-run inspection, reuse and evaluation except of high-speed impacts or destructive explosive trials. Sleds are generally propelled by solid fuel RMs to meet the test requirements at limited track distance for high acceleration g levels. For sled operation activities like carrying test articles, RMs, explosives, ejection seats for testing, dispersing bomblets and sub munitions, parachutes, wing opening mechanism, carrying instrumentation, cameras and data acquisition systems are involved[9]. Sled is designed in such a way so that it can carry test article, which is to be propelled by RM along the steel rails. To establish confidence in test equipment or article, sleds are used under various conditions of velocity, shock, acceleration, aerodynamics effects like pressure, drag, temperature, lift and vibrations and weather related effects10. Analytical study of sled should be precise as most of trials are unique, costly and risky. Other than sled based testing, other methods can be used such as flight–testing, vibration testing, centrifuge testing and others. It has been seen that sled based testing is ground based unique testing in the form of versatility, functional performance and less expensive than flight-testing and others[11].

Further, track testing is conducted in full scale in a controlled environment to protect system from failure due to vibration loads as readiness of rail track is also important to meet precise needs of test activities. To ensure, rail track must be constantly realigned and repaired. Welding, lubrication, paints, thinners, air compressors and solvents are involved for realignment[9]. Along with this, development and testing of high performance RM is required. The whole system is assembled and integrated on rails before the dynamic test. Further, Pre-trial instrumentation testing is done which is mounted over the sled system. The instrumentation used during testing is divided into various categories such as equipment/systems where loads are applied or measured, data acquisition or logging system and high-speed recording in form of high imaging or videography. Full-scale testing of system plays a key role before final execution to testing. Dynamic trial is conducted after successful integration and testing of system and by applying analytical models on the acquired data, data processing and analysis is done to report the successful testing. The detailed flow graph from system designing to testing process is shown in Fig. 1.

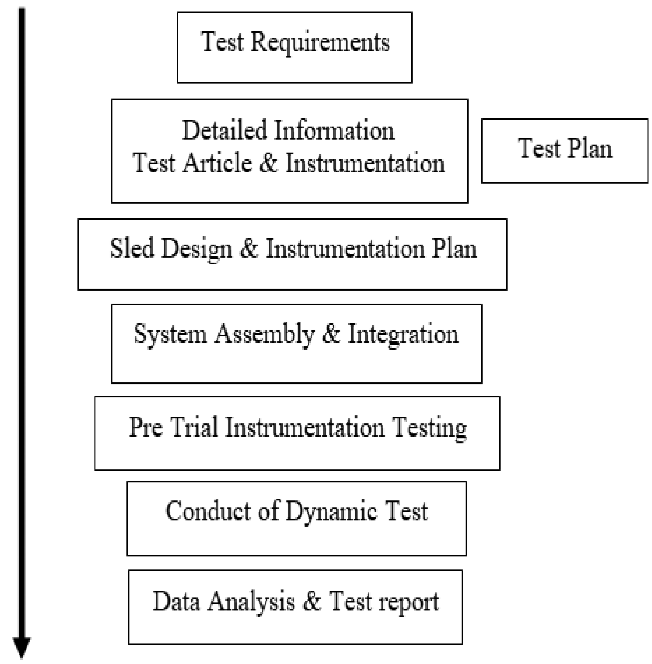


Figure 1. System design, detailing and testing process.

3. ADVANTAGES OF ROCKET SLED BASED TRACK TEST FACILITY

Track based test facility presents applications for the designing and testing of highly sophisticated ballistic systems. The major advantage of using rail track based testing is that it carries test articles and accelerate them in wide range of speeds ranging from small to large size can be attain speed from sub sonic to hypersonic. Instead of testing captive flight systems in flight mode, these facilities have capabilities to test them at ground level and often attain actual flight by fulfilling the user's requirements. It also provides the option of close monitoring of test article during trial for further observation and analysis with help of instrumentation coverage, on-board instrumentation used with sled and recoverability of test items used. In addition, track testing eliminates the possibility of losing article for test (AFT) in real time. Tests can be designed in such a way so that maximum data can be provided for each test and to provide unique scenarios simulation. Post analysis can be done in recovery trials which makes it effective and economical where repetitive testing and assessment is required under best possible simulated environmental conditions for laboratory tests, track and flight tests[12].

With the increase in cost and complexity of development, integration and testing of test articles, high-speed rocket sled based test facilities are being widely used as ground test methods.

It reduces technological risks, implementation cost and safety hazards during testing than in actual flight-testing. Track based ground testing fills the gap between lab based prototype testing and full-scale mode flight testing[9]. Ground based rail track test facilities provide an alternative to highly complex and expensive dynamic as well as static tests in form of efficiency, safety and cost. AFT flight can be adapted by setting up various events of testing which occur at predetermined points of the flight path under certain conditions with the allowance of event coverage through high-end photography. Test conditions can be repeated at high accuracy by testing in stages in controlled environment. AFT can be recovered for offline examination, assessment, and reuse. Track based tests can be conducted in cost effective way involving its full-scale flight mode tests. As compared to the full flight testing, ground based track testing provides higher safety of the involved personnel.

4. ROCKET SLED BASED TRACK TEST FACILITY IN INDIA

India is among a handful of countries possessing a unique test facility named Rail Track Rocket Sled (RTRS), National Test Facility which is located in Terminal Ballistic Research Lab (TBRL), a laboratory under Defence Research and Development Organisation (DRDO), located in Haryana since 1988 and is upgraded from time to time to meet the requirements of armament, missile systems, aerospace systems and many others. RTRS facility consists of levelled rail track system where test article called payload is mounted over the designed sled for testing. Sled can be launched at any location along the track. Rocket motors in clusters are used to generate required dynamic conditions and accelerate sled over the track. Facility provides flight mode environment for carrying out aerodynamic based studies and kinematic studies of variety of test articles[13]. A supersonic penta-rail supporting five rail lines is precision aligned and capable of withstanding high level of loads as shown in Fig. 2. The track has been extended to 4 km length with multiple lines of wider gauges, with continuous welded tracks to accommodate variety of payloads. Evaluation of many payloads for national programs has been done in RTRS facility. RTRS possesses capability for development of rockets, aerodynamic sleds and advanced instrumentation systems. RTRS is unique facility with the combination of experience and ingenuity for research evaluation and testing purposes.

Trials consist of recovery and non–recovery trials or

Figure 2. RTRS penta rail supersonic track facility[14].

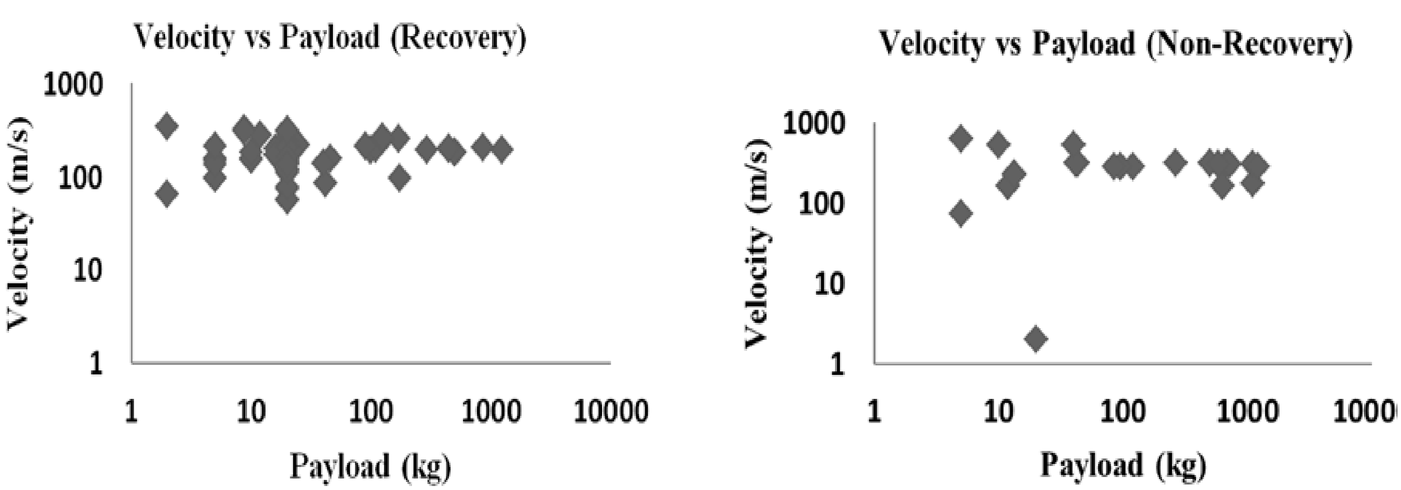


Figure 3. Trials capability at RTRS for recovery and non-recovery trials (representative data in log scale).

impact trials for wide variety of payloads of various masses and dimensions at a single place. Trials are conducted on a regular basis year-round. Till date, more than 1000 number of trials (recovery and non-recovery) have been conducted at RTRS facility from velocity ranging from low subsonic to supersonic. Figure 3 shows representative data spectrum of recovery and non-recovery trials conducted at RTRS facility. The maximum velocity achieved so far is Mach number of 2 in non-recovery trial[15].

RTRS is a captive test facility which is utilised by various users during design and development of various armament and aerospace systems. Rocket sled tests are done based on customised requirements of various users because every test is planned from the requirement point of view in discussion with user. At RTRS essential test requirements are taken care and tests are planned. Captive test up to Mach 2 has been conducted in this facility. Data acquired through on-board and ground instrumentation modes is retrieved, and then processed for performance assessment. With this, Photo-instrumentation is an important means of data collection in the form of images and videos for all types of tests involving various major events such as impact, parachute deployment, ejection, release, and payload separation. Major applications of RTRS test facility include proximity fuze testing, ballistics studies, performance testing of missile systems, sub-systems, multi-stage warheads, evaluation of bombs with explosives, parachute recovery systems, navigation systems, armament systems and escape system of fighter aircraft.

5. ROCKET SLED BASED TRACK TEST FACILITIES IN REST OTHER COUNTRIES

5.1 Rocket Sled based Track Test Facility in USA

As per open literature, there is a mention of more than 15 track based test facilities available in USA, out of which, two facilities named as extended high-speed rocket sled track and Supersonic Military Air Research Track (SMART) are terminated in the early 60's[16]. In 1940, the first test facility established was B–4 in China Lake, California of 2073 m track length with rail gauge of 1.435 m. In 1954, Holloman high speed test track (see Fig. 4a) was established and located in Holloman AFB in New Mexico. It is a longest and capable test track in the world, ~15536 m in length[17]. It has been used in research of rocket sled testing since 1950, and also holds the speed record title in 1982 of testing 11.34 kg payload up to Mach number of 8[18]. The facility has 02 parallel rails R1 and R2 with a 2.1336 m gauge. Additionally, facility provided third parallel rail R3 of 6100 m length with 0.66802 m of gauge[19]. These test tracks are capable of conducting trials at low to high speeds. Till now, rocket sled had achieved maximum velocity of 2737 m/s (Mach number of 8), 'a world land speed record'[20]. A fourth stage rocket sled travelled 5186 m over a track, out of which, it travelled 3353 m through 4.67 m of diameter tunnel filled with lightweight helium gas. A sled had covered >1609 m length in just 6.04 s[18]. Holloman Maglev track is also provided in the same facility since 2004, which is 6000 m long and has tested systems up to Mach number of 0.8[20]. Maglev facility is limited for testing various ballistic systems such as missiles, munitions, and flares test articles, but full aircraft ejection seat systems. Support and test facilities included in Holloman facility are track side rain simulation, ballistic rain field for operating and controlling the rain system, ejection & blast test sites, various block houses, track data center, propulsion storage, fabrication, repair and maintenance buildings and instrumentation facility. Various tests are conducted in facilities such are hypersonic aerodynamic testing, crew escape systems, rain erosion, ballistic rain, deep penetrating warhead systems, dispenser systems, aero propulsion, free flight trajectory system, high gravity testing and many others[9].

Supersonic Naval Ordnance Research Track (SNORT) is other test facility, which was established in 1953. It is located at the US Naval Ordnance Test Station, China Lake, California and having ~6598 m of precision aligned 02-rail parallel track[21]. This facility is used for captive flight testing of RMs, missiles, warheads, aircraft and their components and rocket–powered sleds are used for testing up to Mach number of 4. SNORT is a two rail heavy duty track with 1.4351 m of gauge as shown in Fig. 4b. SNORT has set a world record for producing the highest thrust for a rocket sled test that is 517095.3 kg in about 0.9 s which is the largest amount of thrust that has ever been attempted anywhere in the world. The sled of 33565.8 kg travelled more than 4145 m in about 30 s and achieved 16.8 g of acceleration. Water braking was used to bring the sled to a stop over a distance of about 2414 m[22]. Other test facility by US Naval Ordnance Test Station, China Lake, California, is G-4, which is 914 m long with gauge of 0.86 m[1].

Another USA based test facility is Sandia, located in Kirtland AFB, Albuquerque, New Mexico. Sandia[1] facility was first established in 1951 with track length of 610 m. Subsequently, it was extended in 1966 as Sandia 2 facility with length 3048 m and 0.56 m gauge[23]. It provides rocket sled track for high velocity, acceleration impact trials, and other related testing for both small and large test articles. The facility provides Sandia 1 for testing items at high speeds, and Sandia 2 for testing very large and heavy articles at moderate speeds. Capabilities included certification of track handling of weights up to 45360 kg for velocity 30 m/s and velocity up to 1829 m/s for 227 kg of weight)[24], 3D extensive imaging diagnostics, on-board and off-board instrumentation for data recording and analysis. As per this facility, the sled-testing technique appears to be the most promising technique and had achieved velocity of Mach number= 6.53 in early 60s[25]. Major test activities include projectile impact tests, propellant test and explosive testing, free flight testing, fuze testing, parachute test vehicles and fire weapons test systems. Other test activities include studies of testing of electronic components, materials and structures, aircraft, missiles and telemetry systems, high-speed impact simulation studies of weapon, their shapes, structures and components to understand design integrity, performance evaluation and fuze functioning[23].

Other test facilities in USA are Energetic Material Research and Testing Center (EMRTC) Sled Track Test Facility, Edward North Base Track 'G-Whiz', Redstone Technical Test Center (RTTC), Eglin Track and General Dynamics Ordnance and Tactical Systems.

EMRTC Sled Track Test Facility is located in Socorro, New Mexico. It is a 300 m monorail system. This facility had conducted various dynamic tests of penetrators, warheads and shaped charges. The facility has a capability of testing articles at velocities up to 550 m/s (Mach number of 1.6) and provides a dynamic testing of non–recovery or impact trial studies of systems like penetrators, development of hard target penetrators and conducting of proof of concept testing[29].

In 1944, Edward North Base Track ‘G–Whiz’ test facility was established. It is located in Edwards AFB, California. It is a 609 m long track with two rail lines. The facility was known for human test trial on sled, which was first conducted in 1947. The first human who ride the sled was Captain J. Stapp, Air Force medical researcher, entitled with ‘The Fastest Man on Earth’. From 1947 to 1951, >250 sled tests were done using dummies, animals or humans. The facility had developed a vehicle to test the deceleration forces effect on human body and related equipment for studying aircraft crashes, seat ejections and parachute-opening shocks. Volunteers subjected themselves and survived up to a deceleration force of >35 g’s on tests[30]. In the test trial, 1814 kg of rocket thrust blasted him down the track and into the braking system and he endured 48 g where human body could probably survive no more than 17–18 instantaneous g[31]. Human tests were suspended in 1956, but it was proved that a pilot could survive a high–speed and high altitude ejection, if adequately protected. Facility conducted the first-ever crash tests with dummies after suspending human tests and designing of escape systems[32].

(a)

Redstone Test Center (RTC) is subordinate organisation to the US Army Test and Evaluation Command[33] which is responsible for testing and evaluation of developmental systems and ballistic systems. RTC is located in Redstone Arsenal, Alabama[34]. RTC’s provides the testing of aviation, missiles, and space aircraft survivability systems[35]. The origin of RTTC was established in 1956. RTTC center provides advanced testing in two major areas. One is flight-testing for small rockets and guided missiles and other is life cycle advanced testing for weapon system components and subsystems[36]. Two monorail rocket sled tracks of 305 m and 610 m are used to conduct static and dynamic testing at this facility[37]. Facility has capability in testing flight control systems, aviation propulsion system, expertise in miniature high data rate applications, hypersonic kinetic-energy missiles up to Mach number of 2[38], Research and development testing of weapon system, warhead testing, missile flight testing, and capabilities for planning, conducting, analysing and reporting test results on tested ballistic systems[39].

A short reference is made on other US based facilities as per open literature available. Eglin track is 609 m long with gauge of 1.435 m, located in Eglin AFB, Florida. Other test facility is General Dynamics Ordnance and Tactical Systems, is located in Rock hill, FL, which is 200 m long.

(b)

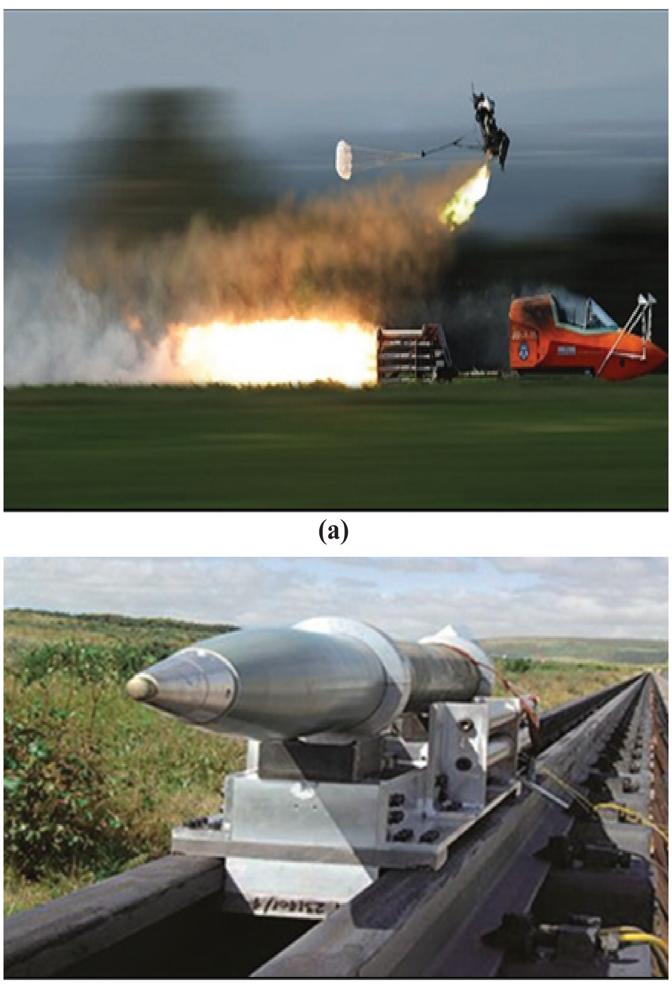
(c)

Figure 4. (a) HHSTT Rocket Sled System[26], (b) SNORT[27] and (c) Sandia Rocket Sled Track Facility[28].

5.2 Rocket Sled based Track Test Facility in UK

Major track based test facilities available in UK are Martin Baker Langford Lodge and Pendline Test Track with various capabilities. Since 1946, Martin-Baker Company was involved in the design, development and testing of various ejection seat escape systems and developed a unique set of capabilities to ensure aircrew safety. In 1971, Martin-Baker Langford Lodge rocket sled test track facility (Fig. 5a) was established, which is located at Langford Lodge, Northern Ireland[40]. It is an 1829 m long track which is straight within a tolerance of 0.00025 m over 38 m with high accuracy for high-speed travelling. This high-speed test facility has been used to qualify the escape systems of various systems such as Mk 16A ejection seat for Euro fighter typhoon and has been tested to perform up to speed range of 308 m/s. Various test activities are conducted such as parachute deployment, penetration testing, seat ejection testing and also used for ejection seat research, design and development using a specially fabricated test vehicle. Capabilities involve Alpha Jets, Grumman EA6B Prowler, Dassault Mirage F1B, TF 104 Starfighter, Aermacchi 339, CASA 101Aviojet, SAAB Gripen IAI Kfir, IAI Lavi and other testing.

Other test facility in UK is Pendline Test Track[41], a high-speed test track which is located at MOD Pendine military range (area of 20.5 km²) in West Wales and used for dynamic weapons trials testing, evaluation and training. The track was completed in 1956, was developed to meet the increasing demand of trials. Facility consists of three test tracks as short track test (STT), Impact test track and long test track (LTT) as shown in Fig. 5b. STT has a facility of testing small set of systems of rail track length 200 m. It can accommodate velocities with respect to weight in between 45 kg at 500 m/s to 250 kg at 250 m/s. It was extended to track length of 450 m in 1989 called impact test track which was used for small payloads testing within a speed range of 120m/s. The impact rail track was extended as LTT track up to 1500 m of rail gauge 0.3048 m. Initially, huge variety of trials were conducted such as terminal ballistics against all types of target, delivery of representative threat versus airborne or land borne platforms, rain/erosion characteristics of materials, deployment of aircraft ejection seats, escape systems and other associated systems, and new propulsion systems[41]. The Range's LTT facility is used for high–speed rail track dynamic trials. It provides the dynamic testing of warheads, ground attack systems and missile, has achieved up to Mach= 3 with acceleration of 130 g. The recognised facility offers clients a wide range of services critical to weapons development and platform



(a)

(b)

Figure 5. (a) Martin Baker Langford Lodge facility[40] and (b) Pendline long test track (LTT) facility[42].

(a)

(b)

Figure 6. (a) HSTT test facility of 3000 m length and (b) SSTT test facility of 100 m length[44].

survivability. It provides measurement systems for velocity, pressure, stain, moment of inertia related data acquisition and analysis, photography and high-speed video capturing, static and flash x-ray systems, doppler radar and hybrid tracking platform (HTP) instruments. Post processing and analysis of trial data is provided by instrumentation such as radar tracking, telemetry system, and optical instrumentation is also carried out.

5.3 Rocket Sled based Track Test Facility in Japan

The Japanese first High Speed Test Track (HSTT) was established in 2009, for academic use in Shiraoi town, Hokkaido and is now open for researchers or research organisation working in this field[43]. First research study was initiated on a prototype 300 m long rail track, with gauge of 1.43 m. It was further extended to a length 3000 m[44]. Acceleration/deceleration studies are done by incorporating water brake, water lubrication and an accurate prediction tool. In addition to the HSTT test track (Fig. 6a), there is sub-scale test track (SSTT) which is 100 m in length of 0.14 m gauge (Fig. 6b). The facility is able to achieve Mach number of 0.6[45]. It has the capability of developing aerodynamic measurement system, specifically on ground effect for the spacecrafts[46].

5.4 Rocket Sled based Track Test Facility in Turkey

The Target Ballistic Rail System Dynamic Test Infrastructure (HABRAS) is a 2000 m long, supersonic European test track facility located in Ankara, Turkey (Fig. 7). It was established in June 2017 at the Scientific and Technological Research Council of Turkey (TUBITAK)[47]. The first test was done with the 113 kg warhead for a miniature bunker buster on the track[48]. This facility is able to provide 555.5 m/s (Mach number of 1.6) of speed. The facility has carried out the successful tests of cruise missiles with high-explosive warheads capable of penetrating concrete bunkers[49]. In future, it claims to be used for testing the rocket engines and ejection seats based escape systems.

Figure 7. HABRAS track test facility[50].

5.5 Rocket Sled based Track Test Facility in other Countries

Based on the available literature, other available track based test facilities are discussed here.

The track based test facility in France (Biscarrosse) is Centre Dessais Des Landes Single Rail. At first stage, 400 m of track length was used for testing with square beam rail type. In 1962, it was then extended to 1200 m of monorail length with square beam type of segmented rail. The facility provides telemetry, remote control and trajectography. Missile flight testing from ground launch pad is done in this facility.

Other test facility is established in Russia, 50 km away from Zvezda. Facility consists of 2500 m long segmented type rail track.

In 1985, test facility 'Alkantpan Rocket Sled Range' was established. It is located in Alkantpan Test Range, in South Africa with a rail track of 200 m length of 0.50 m gauge and single or double I-beam rail type1.

In Germany, there is one single facility of track based testing of I-Beam rail type[1]. The present status of facility is unknown due to limited information available.

6. DISCUSSION

Studies on rocket sled based testing date back to the 1940s where rockets were used to accelerate equipment for boost launch[51] & piloted aircraft testing[1]. Since then, this approach has been adapted by many facilities for captive mode flight testing of various ballistic systems at ground level. These facilities simulate high-speed dynamic environment for various events for selected portions of the flight trajectories during development phase. Testing here has the advantage to create diagnostic data which is helpful to prove functionality of the systems or improve the subsystem and repeat these tests. Also as compared to the full flight testing, rocket sled test based track testing provides higher safety of involved personnel at a fraction of cost and complexity.

The major track based test facilities which have adapted rocket sled test approach has been summarised in Table 1 along with key findings from the literature. The paper presented the worldwide available 28 track based rocket sled facilities; around 16 facilities in United States of America (USA), 09 facilities in Europe, 01 facility in Africa and 02 facilities in Asian region. These facilities are not only limited for testing but have capability for the successful design and development of high-speed aerospace and armament systems. These facilities are continuously ~~in~~ upgrading and enhancing their capabilities through understanding the requirements, potential and limitations. Each facility has its own competence such as in INDIA, RTRS is the only test facility available with penta (05) rail lines[14] for testing various armament systems as per user requirements and has achieved testing speed up to Mach 2. In USA, the available rocket sled based test facilities have their own expertise. HHSTT facility has already achieved world's highest speed in ground and the capability to test the systems in hypersonic speed within ~15536 m of track length[17]. The first human test was done in Edward North Base Track (G–Whiz) facility to study human body's ability to withstand maximum acceleration level[30]. Martin-Baker Langford Lodge is an UK based test facility which has an expertise in testing ejection seat based escape system[40]. There are other well established facilities which have capability to conduct rocket sled based high-speed trials. As this paper has explored all the existing test facilities based on rocket sled and provided the information about their capabilities, expertise and limitations, it is a ready reckoner which has covered the knowledge and information for users, specialists and researchers working in this field and will be useful for users in planning and execution of various design and development cycles of systems and sub-systems. Also, countries with available facilities can self-analyse the availability, shortcomings of track based facilities and efforts that are needed may be applied for facility's upgradation. The major track based test facilities adapted rocket sled approach has been summarised in terms of information and capabilities in Table 1 along with key findings from the literature.

Table 1. Capabilities of major track based test facilities

	Name	Location	Length (meters)	Gauge (meters)	Year	No. of rails	Maximum velocity achieved in Mach number	Capabilities
INDIA								
	Rail Track Rocket Sled Test Facility	Terminal Ballistics Research Laboratory (TBRL), Haryana	3840	0.7– 4.8	1988	05	2	• Penta rail supersonic test facility. • Logged more than thousand trials. • Conducts both recovery & non-recovery trials. • RTRS facility provides testing of fuze, ballistics studies, missile system/ subsystems' performance analysis and evaluation of bombs with explosives aircraft related navigation system, armament systems, testing of parachutes, escape system of fighter aircraft and others.
USA								
	Holloman High Speed Test Track (HHSTT) Rails 1 & 2	Holloman AFB, New Mexico	15536	2.1	1954	02		• Achieved world's highest ground speed. • It is a hypersonic test facility. • Conducts both recovery & non–recovery trials. • HHSTT facility provides testing of hypersonic aerodynamic, crew escape systems, rain erosion, ballistic rain, deep penetrating warhead systems, dispenser systems, aero propulsion, free flight trajectory system, high gravity testing and many others.
	Holloman High Speed Test Track (HHSTT) Rail 3	Holloman AFB, New Mexico	6157	0.67	–	01	8	
	Holloman High Speed MagLev Test Track (HHSMTT)	Holloman AFB, New Mexico	6000	–	2004	02	0.8	• Vibration loads are reduced at hypersonic missile vibration environment level. • Facilitate test articles like missiles, munitions and warheads.

Supersonic Naval Ordnance Research Track (SNORT)	US Naval Ordnance Test Station, China Lake, California	6598	1.44	1953	02	4	• Conducts both recovery and non– recovery trials. • World's 2nd longest test track. • World record for producing the highest thrust for a rocket sled test i.e. 517095.3 kg.
Sandia 1	Kirtland AFB, New Mexico	610	–	1951	02	6.53	• Supports 3D extensive imaging diagnostics. • Tests include both recovery and non–recovery trials.
Sandia 2	Kirtland AFB, New Mexico	3048	0.56	1966	02		• Studies are done on components' materials, structures, shape to verify design functioning, integrity, and performance.
Supersonic Military Air Research Track (SMART)	Hurricane Mesa, Utah	3658	1.435	1955–1963	02	1.3	• Facility had capability to conduct escape system and missiles testing. • Facility was placed on standby in 1961 and closed in 1963.
Energetic Material Research and Testing Center (EMRTC) Sled Track Test facility	Socorro, New Mexico	300	Monorail	–	01	1.6	• Dynamic testing is provided of various ballistic systems such as warheads, payloads, penetrators, and shaped charges articles.
Edward North Base Track 'G–Whiz'	Edwards AFB, Edwards, California	609	–	1944	02	0.9	• Human tests were done on human body to study the ability to withstand g forces. • Facility conducted the first-ever crash tests with dummies. • "The Fastest Man on Earth" title was given to Capt. John Stapp who endured 25 g's which was the equivalent to Mach 1.6 ejection at 12192m.
Redstone Technical Test Center (RTTC) Sled Track 1	Redstone Arsenal, Alabama	610	Monorail	1956	01	2	• Static and dynamic testing is conducted in facility. • Research and development testing of weapon system, warhead testing, missile flight testing. • Provide technical expertise, planning, execution, analysis and reporting of test results on systems, subsystems and components. • Facility provides the mobile based multi sensor, time, space and position information of test system and a unique high-tech optical tracking system is provided.
Redstone Technical Test Center (RTTC) Sled Track 2	Redstone Arsenal, Alabama	305	Monorail	–	01		

UK								
	Martin–Baker Langford Lodge	Langford Lodge, Northern, Ireland	1890	0.762	1971	02	0.9	• Expertise in testing the escape systems of various systems such as Mk 16A ejection seat for Eurofighter typhoon. • Conduct both recovery and non-recovery trials.
	Pendine Short Test Track (STT)	MOD Pendine military range in Qinetiq, West Wales	200	–	1956	02	1.45 for 45 kg to 0.7 for 25 kg	
	Pendline Impact test track	MOD Pendine military range in Qinetiq, West Wales	450	–	1989	02	0.35 for small payloads	• MOD Pendine facility has workshops for designing, armoury, and magazine. • Successful trials are done on dynamic testing of system like warheads, missiles, ground attack systems etc. • Environmental affects like Rain/erosion characteristics of materials, systems are provided.
	Pendine Long Test Track (LTT)	MOD Pendine military range in Qinetiq, West Wales	1500	0.3048	–	02	3	
JAPAN								
	Sub–Scale Test Track (SSTT)	Shiraoi town, Hokkaido, Japan	100	0.14	2009	02	0.6	• Capability of developing aerodynamic measurement system for designed spacecraft.
	High Speed Test Track (HSTT)	Shiraoi town, Hokkaido, Japan	3000	1.43	–	02		
FRANCE								
	Centre Dessais Des Landes Single Rail R1	Biscarrosse, France	1200	Monorail	1962	01	–	• The facility provides telemetry, remote control and trajectography.
	Centre Dessais Des Landes Single Rail R2	Biscarrosse, France	400	Monorail	–	01		• Missile flight testing from ground launch pad is done.
TURKEY								
	Target Ballistic Rail System Dynamic Test Infrastructure (HABRAS) Facility	Ankara, Turkey	2000	–	2017	02	1.6	• Latest established test track in Europe. • Successful test of cruise missile with a high-explosive warhead. • In future, it is projected to test various rocket engines, ejection seats of military aircraft.

7. CONCLUSION

Track based ground test facilities provide the testing method for highly sophisticated ballistic systems, an alternative to highly complex dynamic as well as static tests in terms of efficiency, safety, complexity and cost. The test article trajectory can be tailored for optimum data gathering by arranging various events of testing which occur at predetermined points of the flight path under certain conditions with the allowance of event coverage through high-end photography. Test conditions can be repeated at high accuracy from test to test in closely controlled tolerances. As compared to the full flight testing, rocket sled test based track testing provides higher safety of involved personnel at a fraction of cost.

Track based rocket sled facilities are available worldwide and the study presented a comparison of 28 high-speed track based test facilities in the American (16), European (09), African (01) and Asian (02) continents. A comparison of different facilities cannot be accomplished easily due to limited data availability. The facilities have grown over the years by keeping pace with the requirements of bigger and faster systems. The facility that is superior in one aspect might be less useful in another. A great majority of the operating test facilities are in the American continent and a comparison between test capabilities of these facilities has been brought out. Major decisional parameters in building a new one or intrinsic characteristics of the existing ones are system mounting and monitoring, instrumentation, testing capacity, dimensions of the test platform, maximum length of track, maximum velocity of the sled, among others. It is not possible to say which test facility is best, since each one has specific capabilities and advantages over the others.

By acknowledging all the capabilities and limitations, it is to be noted that high-speed experiments in the rocket sled track facilities are providing data and information that is valuable in present-day for the successful development of high–speed ballistic systems. Further, to design hypersonic based ground test facility, these test capabilities will be helpful in understanding today's design limitations and potential for future system enhancements. Capabilities of some test facilities have increased over the years and improving continuously, such as new methods for scaling results, or instrumentation to acquire the most information from the test environment. Nevertheless, the test facilities with larger dimensions and capacities have achieved hypersonic speeds, expertise in advanced instrumentation such as 3-D imaging of test article for offline analysis, expertise in designing, testing and implementation of escape based system and up to penta (05) rail lines over the track for testing various test articles. The facilities provide testing ranging from recovery to impact trials for evaluation of warheads, missiles, aircraft and other ballistic systems from subsonic to hypersonic velocity regime.

The paper has summarized the available rocket sled based high-speed rail track test facilities worldwide and to the best of authors' knowledge, this paper is the first attempt to conduct the review on all available or existing rocket sled test facilities and provides the information about facilities' capabilities, their responsibilities and technological expertise. In addition, every country can self-analyse the shortcomings of track based facilities and efforts that are needed can be applied to upgrade the facilities. This paper has a scope of acting as a source of information on rocket sled test facilities across the world where everyone can self–analyse the availability, shortcomings of track based facilities & efforts that are needed can be applied for facility's upgradation. It is a ready reckoner covering knowledge and information for users, specialists and researchers working in this field and can be useful for users in planning and execution of various design and development cycles of systems and sub-systems.

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