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*Review*

# A Review of Accelerated Pavement Testing Applications in Non-Pavement Research

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**Abstract:** Accelerated pavement testing (APT) facilities has been demonstrated for years as a multi-purpose solution for pavement and non-pavement research. Even though APTs are widely known in the pavement industry, little has been publicized about their successful applications in non-pavement research. This paper provides a survey of APT applications in non-pavement research. The purpose of the survey is to review and encourage APT owners and agencies to explore the opportunities that APT facilities can present to promote non-pavement research initiatives. The survey demonstrates the ability of APTs to conduct research for bridges, transportation technology, drainage, geotechnical engineering, automobiles, environmental engineering, highway safety, among others. Non-pavement research can be incorporated into APT programs to diversify funding sources for research operations and promote cooperation with other agencies. Finally, suggestions for future and current APTs are made in this paper, including evaluating connected vehicles, work zone applications, smart infrastructure, truck platooning effects on bridge performance, sustainable drainage systems, bridges, advancement in geotechnical methods, sustainable fuels, and unmanned aerial systems.

**Keywords:** accelerated pavement testing; bridges; sustainability; non-pavement testing

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## 1. Introduction

Accelerated pavement testing (APT) facilities are widely known for evaluating pavement response and performance under in-service conditions in a compressed time interval [1]. These facilities are generally developed with the overall intention to provide cost-effective solutions to improve pavement performance and reduce life-cycle costs. Even though the focus of research efforts has centered on pavement systems, APTs have effectively been utilized by various agencies for non-pavement research to address strategic issues confronting society. They have been applied in the areas of transportation infrastructure and operations; automobile systems; traffic safety; national security assessments and for environmental impact evaluations [2–5]. Therefore, APTs can be described as multipurpose facilities that can be used for various research applications in different disciplines. Thus, APTs can be described as applicable and beneficial to both pavement and non-pavement industries.

Due to benefits associated with APT facilities, the Wyoming Department of Transportation (WYDOT) intends to build a state-of-the-art test road facility to monitor pavement performance and spearhead sustainability and innovations in pavement design, construction, and preservation research unique to the dry-freeze climatic region. A full-scale road track is proposed along the existing Interstate 80 (I-80) in Wyoming. The test road facility will allow for a comprehensive long-term performance evaluation of pavements under real world traffic loading, climate, and layer material properties. The test road will consist of experimental test sections built of asphalt, Portland cement concrete and composite pavements to carry existing real-world traffic of approximately two million equivalent single axle loads (ESALs) per day. The objective of the test road initiative is to improve pavement performance and reduce life-cycle cost of pavements in the dry-freeze climate. It will be the foremost full-scale test road in the dry-freeze climate region of the United States (U.S). WYDOT and the University of Wyoming (UW) are currently conducting a feasibility study to evaluate the effectiveness of constructing the test road facility in Wyoming. Part of the feasibility study involves exploring opportunities to use the test road for non-pavement research.

This paper presents a review of the applications of APT facilities for non-pavement research based on experiences from around the world. The applications of APT in non-pavement research over the years are put under nine broad categories for the purposes of this paper: (1) bridge experiments; (2) transportation technology; (3) drainage experiments; (4) geotechnical engineering experiments; (5) automobile experiments; (6) environmental experiments; (7) highway safety; (8) calibrations, measurement, and testing devices; (9) other miscellaneous applications. Publications on APTs have primarily focused on pavement performance evaluations with little attention to the non-pavement aspect of it. This paper provides a review with an intent to fill that gap and raise the awareness and familiarity of applying APTs for non-pavement research activities. The paper further makes suggestions for the proposed Wyoming test road facility and other APTs regarding non-pavement research applications.

## 2. Background

Accelerated pavement testing (APT) facilities are traditionally used for pavement evaluation under in-service conditions of traffic, environment, and other pavement design parameters. "APT is defined as the controlled application of a prototype wheel loading, at or above the appropriate legal load limit to a prototype or actual, layered, structural pavement system to determine pavement response and performance under a controlled, accelerated accumulation of damage in a compressed time period. The acceleration of damage is achieved by means of increased repetitions, modified loading conditions, imposed climatic conditions, the use of thinner pavements with a decreased structural capacity and thus shorter design lives, or a combination of these factors. Full-scale construction by conventional plant and processes is necessary so that real world conditions are modeled" [6]. There are two main types of APT systems: full-scale systems and small-scale systems. For full-scale systems, a standard truck tire or combinations of tires are used to apply the loadings to the pavement system. Examples of full-scale systems are test tracks (National Center of Asphalt Technology (NCAT) Test Track, Minnesota Road Research Project (MnROAD)), circular or linear tracking devices. In the case of small-scale APTs, a scaled-down version of the truck tire and load is applied to the pavement system e.g., model mobile load simulator (MMLS3) [7]. Figure 1 shows a few of the different types of APT facilities used across the world. In the U.S, test track facilities have provided in-depth understanding of pavement performance, design and construction and have been beneficial to different customers [4]. In addition, APTs have contributed significantly to pavement materials, designs, rehabilitation alternatives and innovation. Nonetheless, APT facilities have been utilized successfully for non-pavement studies. According to [4], APTs are able to balance their primary objectives in pavement research with non-pavement research without any conflicts. At times, non-pavement research evaluated using APTs complement the overall performance of pavements. In addition to this, a key measure of a successful APT facility is its ability to meet the needs of different customers with different research needs and focus. Most of the different customers of APT research programs are governments, transportation agencies, private industry, and academia [4].

In general, collaboration in scientific research has seen tremendous growth in recent decades [8] with the growing research needs arising due to population growth, changing demographics, economy, climate change, environment, energy, and technology. Therefore, addressing issues that confront societies require multidisciplinary collaborations; integration of theories, methods and instruments from diverse fields [8]. In addition, these research collaborations can be made through policy and research–management initiatives [9,10]. Research collaborations can either be among institutions in the same or different fields [8]. Tompkins and Khazanovich [11] believe that the Minnesota Road Research project, also known as MnROAD, is attractive for any experiment that requires the effects of the environment. Moreover, the security of the environment makes the facility unique for experiments, including non-pavement research [5]. APTs can relate to expected performances in the real world. A report attributed MnROAD's successes in non-pavement research to the versatility of its engineers and the protection of the experiments from damage or disturbances [5].

Using APTs for non-pavement research may come with its own benefits. According to [4], MnROAD and the NCAT test tracks have benefitted from non-pavement research. APT facilities can engage in non-pavement research to generate funds to cover operational costs which appears to be a major challenge to these facilities [4]. Operation costs and the lack of consistent institutional support partly due to political changes are major hindrances to the activities of APT facilities [4,12,13]. The building of experimental sections alone can be costly [14,15], and thus make partnerships and collaborations, imperative for cost-effectiveness [16]. Therefore, the ideal to incorporate non-pavement research in APT programs encourages partnerships among agencies from diverse fields. In addition to this, partnerships in APTs helps to diversify funding needed for fiscal stability, successful operations, prolonged existence, and resilient [4].

(**a**)

(**b**)

**Figure 1.** *Cont.*

(**c**)

(**d**)

**Figure 1.** Pictures of different types of APTs around the world: (**a**) the Florida Department of Transportation (FDOT) HVS Mk IV device [17]; (**b**) MnROAD test road [18]; (**c**) Canterbury Accelerated Pavement Testing Indoor Facility (CAPTIF) at the New Zealand Transport Agency [19]; (**d**) the FABAC machine [20].

## 3. A Review of APT Applications in Non-Pavement Research

A review of APT applications in non-pavement is presented in the following subsections along with some findings where they have been made public. It is important to note that not all detailed information on non-pavement research is published with its findings since some of the studies are sponsored by private industries. Readers are referred to the respective references that have been provided for more details. The broad spectrum of studies conducted using APT facilities since the American Associate of State Highway Officials (AASHO) Road Test in 1956 [21] is quite diversified. In Figure 2, the various applications of APTs covering both pavement and non-pavement research are summarized. In several instances, the studies included the use of test roads, the HVS and the MLS. This section of the paper covers an interesting aspect of APT facilities that is not widely appreciated by the public. The information should provide a useful basis for application of APT facilities in other areas apart from pavement research.

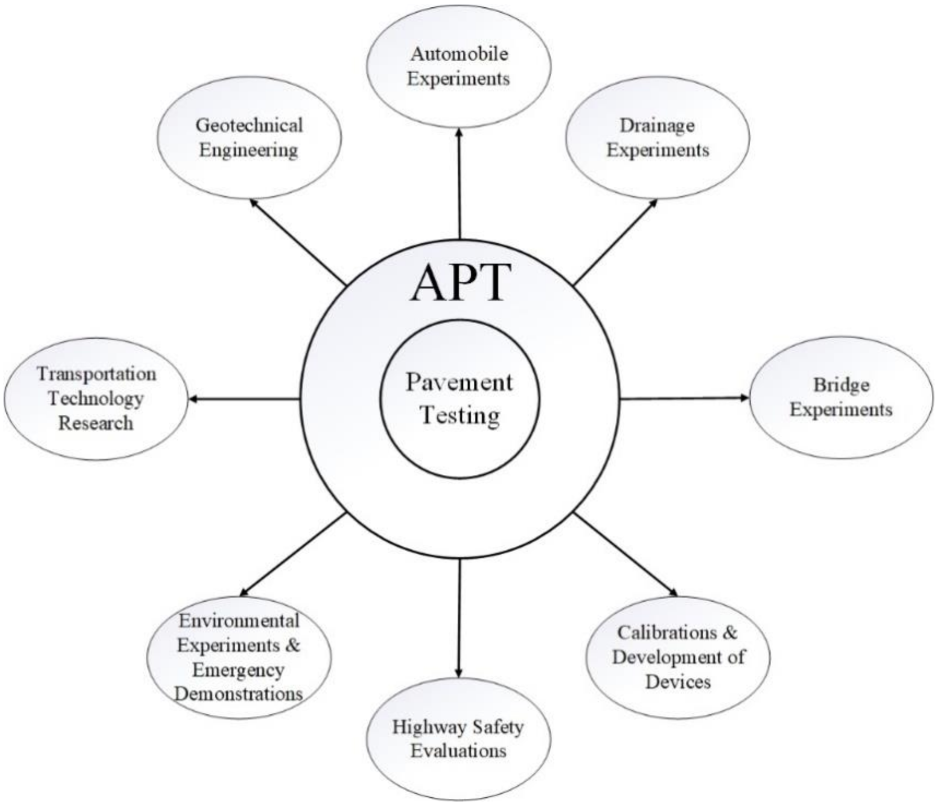


**Figure 2.** Schematic of pavement and non-pavement research applications of APT facilities.

### 3.1. Bridge Research

Bridges are key components of surface transportation infrastructure systems. They provide safe transportation connections between networks over obstacles. According to the American Society of Civil Engineers infrastructure report card [22], the U.S. has 617,000 bridges with an overall grade of C. It reports that structurally deficient bridges constituted 7.5% in 2021 and carry an average of 178 million trips daily. In addition, there is a nationwide bridge rehabilitation backlog of $125 billion while the number of bridges approaching the end of their design life keep increasing. On the other hand, studies on recent bridge failures in the U.S. categorized principal causes of bridge failures as deficiencies in design, detailing, construction, maintenance, use of materials, and inadequate consideration of external events [23]. According to [24], bridge decks deteriorate faster than the other parts due to the direct exposure to traffic and environmental conditions. High traffic loadings and high moisture and freeze–thaw cycles, facilitated by the corrosive effect of deicing chemicals [25], deteriorate bridges faster. Research efforts to understand bridge responses to traffic loading is imperative to design, construction and maintenance. Few APTs have been applied in bridge research to evaluate new technologies and materials to give bridge engineers insight into building and preserving bridges. APTs have made some significant research efforts to improve the bridge industry.

According to the Highway Research Board [21], the AASHO Road Test was used to conduct studies on bridges. Trafficking of the bridge section is shown in Figure 3. It investigated different types of short-span bridges to understand their in-service behavior under repeated overstress loading. A detailed study was also conducted to determine the response of bridges to the effects of moving vehicles. The study featured steel, prestressed concrete and reinforced concrete bridges and became a landmark research facility in bridge designs [21,26]. The AASHO Road Test appears to be the only test road facility that had dedicated on-site bridges for research purposes. Additionally, the facility was also used to investigate stress–relaxation characteristics of samples of prestressed wires and strands used in prestressed concrete beams, as well as the testing of creep and shrinkage characteristics of concrete samples used for prestressed concrete beams. The AASHO Road Test had significant impacts on the bridge industry. The Pennsylvania Transportation Institute (PTI) used their test track facility to investigate the overload behavior of an experimental precast prestressed concrete segmental bridge [27]. The same facility has also been involved in the investigation of bridge loadings, designs, construction, monitoring, and evaluation [3]. Seismic expansion joints were again tested for the construction of the new San Francisco-Oakland Bay Bridge using the California APT. The author of this study concluded that the heavy vehicle simulation (HVS) method can evaluate bridge deck components effectively to provide rapid solutions to problems confronting the bridge industry [2]. A smaller version of an APT, called the Model Mobile Load Simulator, third scale, (MMLS3) has been used to test bridge joints and other transportation infrastructure applications [28]. Testing bridges under real world conditions, while costly, can offer the best approach to understand their responses and performance.

**Figure 3.** Bridge testing at AASHO Road Test [21].

### 3.2. *Transportation Technology Research*

The U.S Departments of Transportation (USDOT) is collaborating with agencies at the local and state levels, the automobile industry, and the general public to test and evaluate technologies that enable cars, buses, trucks, trains, roads, and other infrastructure to communicate with each other. Connected vehicle technology is regarded as an effective way to reduce the number of fatal and serious crashes on our highways [29]. Some APT facilities are using their test roads to promote the development and deployment of smart transportation systems. MnROAD promoted the development of Minnesota DOT (MnDOT) Intelligent Transportation systems (ITS) in Minnesota [5,11]. The MnROAD testing facility was used to investigate and test assistive or autonomous vehicles and other associated technologies to improve driver safety [30–32]. Figure 4 shows an example of such applications on MnROAD, where a driver assistive system (DAS) was equipped with a snowplow truck to assist tracking the position of the truck and avoiding unwanted paths that may lead to collision. The Nevada road track facility, also known as WesTrack, made significant contributions to the area of autonomous vehicle technology. It provided tracks for the testing of autonomous truck controlling systems [33]. Even more recently, a new autonomous vehicle research facility has been built at NCAT's test track facility in

Alabama [34]. The facility's oval test track is being used as the main test site for autonomous vehicle technology and applications [4].

Another significant contribution of APTs is in the area of truck platooning, which is regarded as the future of freight transportation. The NCAT test track facility was used to develop and evaluate truck platooning technology, according to [35]. The benefits of truck platooning include lower fuel consumption, improved driver output, fewer crashes, less congestion, and reduced carbon emissions [36]. The PTI test track was also utilized for comprehensive testing of new bus models, trucks, and train. The facility has been recognized as a designated testing ground for autonomous vehicles by the U.S DOT since 2017 [3].


**Figure 4.** Snowplow equipped with driver assistive system (DAS) technologies at MnROAD [37].

### 3.3. Drainage Experiments

Drainage significantly affects the pavement performance [38] due to the effect of moisture on soil strength and properties. According to [39], proper drainage systems increase the service life of pavements by 50%. It also impacts the safety of motorists as water that remains on the surface of pavement can cause hydroplaning. Therefore, proper drainage is important to ensure the long life of pavement and the safety of users. A survey found that several APT programs explored the effects of water on pavement performance [1]. Research on drainage systems complements the overall research efforts on pavements. With regards to drainage structures, a study conducted at MnROAD evaluated the performance of large thermoplastic (e.g., corrugated polyethylene) culverts for three and half years. Recommendations for the minimum depth of covers for culverts were made based on the findings of the study. The researchers found that culverts could perform well and showed no signs of increased deflections [5,11].

In addition, a study mentioned that the APT facility operating at the Federal University of Rio Grande do Sul, in Porto Alegre, Brazil, was used to evaluate the performance of PVC pipes used in culverts [40]. Highway agencies continue to explore ways to improve drainage designs and maintenance. The Florida Department of Transportation (FDOT) has recently built a 4.0-km (2.5 mile) concrete test road, which is expected to open for real traffic in 2023. The research will consist of in-service evaluation of concrete pavement technologies and innovations, including dedicated test sections that would be used to investigate the effectiveness of edge drains. The drainage research will consist of 16 test sections [41].

### 3.4. Geotechnical Engineering Research

Knowledge of geologic and subsurface conditions is critical to the design and building of foundations, earthwork structures and pavement subgrades since all the construction of structures are founded in or on the ground. Some APTs have been utilized to investigate and understand geologic and subsurface conditions. The whole 309-acre site of the NCAT test track serves as an ideal ground for geotechnical investigations because the whole site has been mapped as a National Geotechnical Experimentation Site (NGES). Consequently, it has been used for geotechnical research purposes [4]. Similarly, MnROAD made its facility available for the development of new technologies and systems in geotechnical engineering. In 2004, the MnROAD test track was used by engineers to demonstrate continuous compaction control (CCC), also known as the intelligent compaction (IC). IC is a novel technology that uses instrumented compactors to provide real time verification of in situ properties of soil or asphalt during compaction. It can also adjust compactive efforts when needed [42]. According to research, IC technology has shown promise in quality control during construction [43]. A model of the compactor that was used for this study is shown in Figure 5, which illustrates the BOMAG variocontrol technology for continuous compaction control. Additionally, MnROAD partnered with the U.S. Department of Energy to investigate the physical and environmental properties of highway base materials stabilized with high carbon fly ash [44]. The U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory (USACE CRREL) operates an HVS (known as HVS Mk IV) and it was utilized to evaluate the effectiveness of using geogrids to reduce pavement thickness requirements [17].

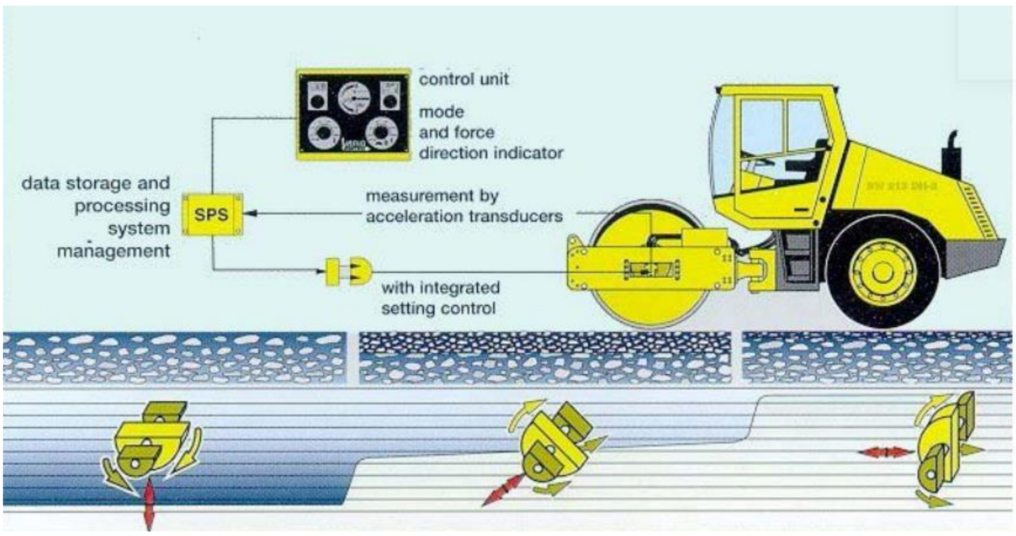


**Figure 5.** Schematic of BOMAG compactor used for the IC demonstration at MnROAD [42].

The circular facility of the University of Los Andes in Colombia investigated various techniques used in soil stabilization using accelerated pavement testing [40]. In order to provide geosynthetic solutions to weak formations, the authors of [1] reported that APTs have made significant impacts in terms of advancements in the field stabilization of marginal materials to improve pavement performance and promote the implementation of geofabrics for ground reinforcement purposes.

### 3.5. Automobile Research

The automobile industry constitutes a significant portion of the U.S. gross domestic product (GDP) quarterly [45]. In the automobile industry, some of the product quality criteria includes safety, product design and functional qualities [46]. The U.S. passenger automobile has gone through evolutionary changes in response to changing energy, environmental, and safety concerns. The contributions of APTs cannot go unnoticed in this regard. Test track facilities have collaborated with several agencies including the military and the trucking industry to investigate relevant issues related to tires, alternative fuels, and suspension systems, among others. The AASHO Road Test for instance, investigated the dynamic effects of commercial construction equipment and dual-tire truck units. The findings from the research led to the developments of new heavy vehicle suspension systems and improved vehicle tires [21]. Moreover, the PTI was used for advanced research on hybrid, electric, and other alternative-fuel vehicles [3]. Likewise, NCAT was involved in a study that valuated alternative fuels for vehicles [35]. These are great step towards reducing carbon emissions, fuel cost, and providing alternate power to vehicles. Furthermore, the NCAT test track has contributed towards the development of advanced propulsion systems and vehicle rollover prediction systems, including providing opportunities for the valuation of improved vehicle electronics and safety [35]. Under vehicle operations, MnROAD initiated a study to investigate the relationship between road characterization, vehicle dynamics, and fuel consumption. The ideal was to find out the factors that contributed to fuel consumption [44]. With regards to transport modes, the NCAT test track was used for transit bus testing [4]. In 2009, the FDOT heavy vehicle simulator (HVS) investigated new-generation wide-base tires and made significant recommendations to the trucking industry [47]. The FABAC machine, which is a small linear traffic simulator, was used to validate the behavior of electric road system (ERS) embedded in asphalt pavement in 2019 [20]. The FABAC traffic simulator was considered for the evaluation due to the limitations of the laboratory to represent real world conditions [48]. The ERS was developed by Alstom to charge and supply power to heavy goods vehicles over long distances to reduce greenhouse gas emissions. The authors of [20] noted that subsequent full-scale testing using a 50-m track would be used to validate the safety of the technology before the technology would be deployed on a large scale.

### 3.6. Environmental Research

Human activities, such as urbanization, deforestation, and pollution, can have negative impacts on the environment. Hence, the rapid environmental changes demand a new direction and innovative solutions. Some of the APTs have allowed agencies to develop solutions to environmental problems, such as pollution, erosion, etc. The NCAT test track conducted erosion control studies to learn about the best erosion management practices [4]. MnROAD successfully conducted research on environmental biology. The study was successful as the environmental setup was not disturbed, and the experiment was done under real-world conditions that were closely monitored. The constant recording of environmental data also helped biologists to validate their field data. Biology-related research investigated how to improve the design of roadside ditches to decrease transportation-related pollution of surface water. The investigation involved the ability of roadside plants and a constructed check dam to remove pollutants from pavement surface runoff, as shown in Figure 6. The research concluded that the mechanism could reduce pollution by 54% [49]. In another study, MnROAD investigated "the effects of novel soil amendments on roadside establishment of cover crop and native prairie plant species" [50]. The experiment aimed to explore treatment methods to establish plants near the in-slope of roadsides. The study found that there was no improvement in the establishment of plants within 2 m of the roadside using the treatments [5,50]. Other activities that have been done off-track at MnROAD include studies on sinkholes and herbicides [4].

**Figure 6.** Pollution control research showing the check dam at MnROAD [5].

*3.7. Highway Safety Research*

Highway engineers continue to explore several techniques including using APTs to improve highway safety. Efforts to use such facilities to conduct research towards improving highway safety was traced to the late 1960s. The U.S. Army Personnel Research Office used the AASHO Road Test to conduct driver behavior studies to determine the attentiveness of test vehicle drivers. In relation to traffic control devices, NCAT test track investigated pavement striping and markings [4]. Transportation agencies in the U.S. and Canada invested about $1.5 billion on pavement markings in 2000 [51]. Pavement markings provide visual guidance by delineating the travel lanes and other roadway features to improve safety [52]. They have the potential to reduce roadway crashes [51]. Considering the significant amount of money highway agencies invest in pavement markings, it is imperative to evaluate their long-term service performance before making recommendations for implementation on a mass scale. In 2005, FDOT evaluated the structural integrity and retroreflectivity of raised pavement markings with accelerated pavement testing using the HVS machine [53]. The U.S Federal Aviation Administration (FAA) also utilized HVS-Airfields Mark VI to evaluate the performance of different "rumble strips" configurations, as well as paint stripes made from methyl methacrylate (MMA) [17]. According to [54], the Model Mobile Load Simulator, third scale (MMLS3) is a feasible alternative to evaluate the performance of transverse pavement markings; moreover, the PTI has been utilized to investigate the performance of transverse pavement markings under dry and wet conditions [54]. An important roadway departure countermeasure is the rumble strip. Rumble strips have proven to be effective in reducing lane departure crashes on urban and rural freeway segments [55]. They can reduce roadway departure crashes by 20–50%. Often in urban areas, bicyclists encounter rumble strips extended from the road shoulders. The PTI test track was used to develop bicycle user-friendly rumble strip configurations for the state of Pennsylvania [55]. The objective of the research was to develop a new rumble strip design that mitigates the level of vibrations bicyclist experience when they traverse them without compromising the level of stimuli needed to alert distracted or drowsy motorists [55]. Snow fall creates slick pavement surface conditions which increases the risk of crashes of motorists in northern Europe and America. According to [56], U.S roadways record more injuries and vehicle damages on snow fall days than on dry days. Therefore, highway agencies employ snow and ice control strategies to restore pavement surfaces to safe driving conditions. In 1997, the United States spent about $1.5 billion in direct costs on snow and ice control for their roads. The cost includes maintenance activities, such as plowing, salting, and sanding road surfaces [57]. Considering the investments made in restoring road surface conditions, it was necessary to evaluate the effectiveness of these ice control operations.

In Canada, the Integrated Road Research Facility (IRRF) test road located in Alberta, was used by researchers to investigate the effectiveness of plowing and sanding operations using three different application rates on winter road conditions, as shown in Figure 7. The study found that plowing did not provide significant benefits on ice, but medium to high sanding operations improved friction over plowed ice and snow [58]. Similarly, the PTI circular test track was used to investigate the effectiveness of applying hot sand for winter ice control [59].

**Figure 7.** Sand applied on icy road surface at the IRRF test road in Canada [58].

### *3.8. Calibrations, Measurements and Testing of Devices*

The AASHO Road Test was used for other special studies, including the development of nuclear testing devices used for the measurement of in-place density of pavement layers. A nondestructive device for measuring frost depth was developed at the same facility. In another study, a dynamic pavement testing device, which was developed by Waterways Experiment section and the U.S. Army Corps of Engineers, was evaluated and demonstrated using the AASHO Road Test [59]. WASHO Road Test was used by A.C. Benkelman to develop the Benkelman Beam, a pavement deflection-measuring device in 1953 [60]. After years of existence, the New Zealand Transport Agency (NZTA) used the Canterbury Accelerated Pavement Testing Indoor Facility (CAPTIF) to explore an electronic upgrade of the Benkelman Beam to capture full bowl deflections [61]. The upgraded device was inexpensive, reliable, and easy to operate. It is effective device that measures the deflection of flexible pavements under loads. The work in [4] outlined other major initiatives of the NCAT test track, including the certification of inertial profilers used to collect profile data for calculating the international roughness index (IRI). Traffic data and loadings are important design parameters in pavement design. With regards to traffic data collection, Intercomp Inc. collaborated with MnROAD to develop license plate readers and a weigh in motion (WIM) technology. MnROAD used the low-volume road (LVR) loop and a semi-tractor trailer to develop and calibrate a portable WIM for installation in Minnesota [44]. Furthermore, the MnDOT used MnROAD's semi-tractor trailer and operator to undertake a state-wide calibration of WIM systems in Minnesota. In other non-pavement studies, MnROAD partnered with International Road Dynamics Inc. (IRD) for the development of traffic detection devices including WIM [44]. Furthermore, during the intelligence compaction studies at MnROAD, the guidelines for using a light weight deflectometer (LWD) and the dynamic cone penetrometer (DCP) were developed for quality control assurance purposes [62], and the ground penetrating radar (GPR) [63]. The GPR is a non-destructive device used to locate underground utilities and gives a profile of subsurface conditions and bridge condition evaluation. Based on research findings, the GPR was adopted by MnDOT for use across the state of Minnesota [63,64]. Consequently, MnROAD is a described as a site for equipment certification [11,65,66]. The California Department of Transportation (Caltrans) initiated various studies to fast-track the implementation of warm mix asphalt technology in California using the APT. Figure 8 shows a transportable flux chamber developed and assessed over the course of the study to measure and characterize volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOCs) emissions during hot mix asphalt (HMA) paving [67,68].


**Figure 8.** Measuring VOCs using the transportable flux chamber [67].

### *3.9. Other Miscellaneous Applications*

According to Federal Emergency Management Agency (FEMA), emergency exercises help to prepare for threats and hazards by providing a cost-effective environment with a low-risk to test and validate plans, policies, procedures, and capabilities. It also helps to identify resources needed, strengths, and weakness, and areas that need improvement and potential best practices [69]. The NCAT test track has been used to undertake emergency response exercises [4]. Likewise, the MnROAD farm loop was used to demonstrate the dangers associated with improper hauling of trailers and goods on roadways [47]. In the area of national security issues, APT facilities have shown some successes. Anti-terrorist policies can either be defensive or proactive [70]. Terror attacks in Nice, Berlin, Barcelona, and London in recent times involved vehicles ramming into the crowds of vulnerable people, killing people and leaving several others wounded. The modus operandi of these terrorists revealed some vulnerabilities in the system. This led to the need to find ways to safeguard pedestrians in crowded areas [70]. PTI utilized its test track facility for crash testing of anti-terrorists barriers [3].

## 4. Findings

### *4.1. Summary of Non-Pavement Research Using APT*

The contributions of APT facilities to non-pavement research is summarized in Table 1. The test roads appeared to have been extensively used for various aspects of non-pavement research for years. This may be attributed to large amount of space required for test road facilities and real-world conditions they provide for research. It appears that most of the non-pavement applications using APTs are connected to the transport sector. Research on bridges, drainage, geotechnical investigations, and automobile have relationships with the structural or functional performance of pavement.

**Table 1.** Non-pavement applications with different APT types identified during the review.

| Research Application | APT Type | | |
|---|---|---|---|
| | Test Road | HVS | MLS/Circular Tracks |
| Bridges | AASHO Road Test<br>PTI | Cal-APT | |
| Transportation Technology Research | MnROAD<br>WesTrack<br>NCAT Test track<br>PTI | | |
| Drainage Experiments | MnROAD<br>FDOT Concrete Test Road | | Brazil APT |
| Geotechnical Investigation | NCAT<br>MnROAD | USACE CRREL | University of Los Andes in Colombia |
| Automobile | AASHO Road Test<br>PTI<br>NCAT Test track<br>MnROAD | FDOT | FABAC machine |
| Environmental Research | NCAT Test track<br>MnROAD | | |
| Highway Safety | NCAT Test Track<br>PTI | FDOT<br>FAA<br>IRRF | MMLS3 |
| Calibrations, Measurements and Testing Devices | AASHO Road Test<br>WASHO Road Test<br>NCAT Test Track<br>MnROAD | Cal-APT | CAPTIF |
| Miscellaneous<br>Emergency response<br>Haulage<br>Utilities<br>Security | NCAT Test<br>MnROAD<br>PTI | USACE CRREL | |

### *4.2. Applying Text Analytics to Understand the Trends in Non-Pavement Research Using APT*

Text data mining helps to derive high quality information from large amounts of natural text and identify trends and relationships. Understanding trends is important to have an idea of which non-pavement research topics are most widely investigated using APTs. Text analysis is conducted on preceding sections that mentioned the application of APT in non-pavement research to extract meaning out of the text. This technique has been used in other studies to analyze trends in conferences proceedings [71,72]. The Voyant tool, which is an open-sourced text reading and analysis environment [73], was used to analyze the text of reviewed studies and related reports. Even though the previous studies used the topic modeling technique called latent Dirichlet allocation (LDA), the Voyant tool (with a simple approach without any coding) is used in this paper to get a sense of the trends in non-pavement research. The LDA method involves some extensive coding techniques. The text analysis was done on texts from publications, conferences proceedings, and reports that involved non-pavement research using APTs. The aim is to identify trends related to non-pavement research. Figure 9 below visualizes the most frequently used terms in a word cloud using the Voyant tool. In the word cloud, the size of the word is directly proportional to how important it is. Words with similar importance have the same color.


**Figure 9.** Word cloud describing non-pavement application terms using APT.

Table 2 shows the results of words that appeared four times or more based on the counts and representative trends. The count represents the number times the word is mentioned in the text dataset, while the trend is the frequency weight. An analysis was done using two different categories: the "Word Term", which stands for the objectives and applications of using the APTs in these research studies, such as "investigate", "develop" or "measurement". Another category was the "Non-Pavement Term", which classified the type of assets and infrastructure used in testing, such as "Bridge", "autonomous vehicles", or "marking". It appears that the APT facility focuses on investigating (word count of 11) ideas or issues of interest related to non-pavement research, as shown in Table 2. Research on bridges (word count of 6) appears to be the most frequently used non-pavement topic among the non-pavement terms investigated previously. Autonomous vehicle testing appears to be the second most-researched topic using APT under non-pavement research. This corpus or dataset has 1 document with 494 total words and 213 unique word forms.

**Table 2.** Terms used more than four times in the text and their relative frequencies.

| Rank | Word Term | Non-Pavement Term | Count | Trend |
|---|---|---|---|---|
| 1 | investigate | | 11 | 0.022267 |
| 2 | develop | | 10 | 0.020243 |
| 3 | evaluate | | 9 | 0.018219 |
| 4 | test | | 9 | 0.018219 |
| 5 | | bridge | 6 | 0.012146 |
| 6 | | | 6 | 0.012146 |
| 7 | | autonomous | 4 | 0.008097 |
| 8 | | markings | 4 | 0.008097 |
| 9 | measurement | | 4 | 0.008097 |
| 10 | pavement | | 4 | 0.008097 |
| 11 | systems | | 4 | 0.008097 |
| 12 | | WIM (weigh-in-motion) | 4 | 0.008097 |

## 5. Future Research for the Proposed Test Track in Wyoming and Other APTs

This section explores the potential application of APT facilities for non-pavement research. APTs facilities have shown success in other areas outside of the traditional testing of pavement structures.

### *5.1. Connected Vehicles Work Zone Warning Applications*

Full-scale test tracks have the potential to provide a conducive site to evaluate the safety benefits of CV work zone warning (WZW) applications for driver behavior under real-world conditions. Moreover, the impact of connected vehicle technology on traveler information messages (TIMs) on the speed selection of drivers and the safety benefits of speed harmonization can be evaluated.

### *5.2. Smart Infrastructure Systems*

Many technologies are being developed to collect and provide transportation system-level condition assessments and predictions to improve safety and mobility. Several approaches can be investigated at the proposed regional facility to accelerate the deployment of intelligent transportation systems in the region. The proposed experiments will assess the interactions between vehicles and smart features, such as adaptive signal control and smart streetlights. In addition, smart electronic tolls can be tested for traffic data collection and congestion verification, which have been demonstrated by existing APTs. Moreover, the facility will make enormous contributions to the rapidly growing area of smart mobility.

### *5.3. Effects of Freight Truck Platooning on Bridges*

APTs can explore opportunities to evaluate and get a clear understanding of the potential effects of truck platoons on bridges, in terms of loading models, truck configurations, stress ranges, travel speed of platoons, braking effects of platoons, etc.

### *5.4. Innovative Sustainable Drainage Systems*

Innovative storm water drainage systems could be installed and evaluated at test track facilities to optimize road drainage and minimize flooding risks, which are easy to transport, handle, and install and, more importantly, reduce differential settlements. Technologies could be explored to inspect, rehabilitate and manage drainage assets cost-effectively.

### *5.5. Bridge Research*

The proposed testing facility in Wyoming will present a great opportunity to monitor bridge structures under real-world traffic conditions while exploring new technologies to build and maintain bridge decks with better performance. Bridge decks require frequent maintenance and rehabilitation compared to the other bridge components [23]. Monitoring and inspections are important to achieve bridge performance objectives and goals and maximize returns on investment. While promoting the use and understanding of bridge management systems, future APTs could include bridges with detailed inspection programs. These programs will help determine the cause of deterioration and strain, and recommend necessary corrective actions and maintenance, distinct to the dry-freeze climate. Other experiments will evaluate the cost-effectiveness of using innovative techniques for bridge inspections, such as real-time monitoring sensors and unmanned aerial systems (UASs). The experiments can be implemented with various structural features and design spans, depending on regional research needs. When the proposed Wyoming test road becomes fully operational, it will be the only test road with real-world traffic conditions to evaluate bridge responses and performance since the AASHO Road Test in the 1950s.

### *5.6. Advanced Geotechnical Methods*

Site characterization impacts infrastructure project schedules and costs. A comprehensive site characterization can identify potential geologic and subsurface conditions which may affect design and instruction. Advanced geotechnical techniques could be explored and validated at test track facilities in addition to available technologies that optimize subsurface exploration to reduce the cost of construction, risks, project delivery, and increases the confidence of geotechnical characterizations.

### *5.7. Sustainable Fuels*

Hydrogen is seen as the future of fuels for mobile and fixed machinery to limit carbon emissions. APT facilities have proven to be effective in exploring alternative fuels for vehicles. To facilitate the transition to hydrogen as fuel in trucks and construction machinery, APT facilities serve as testing sites.

### *5.8. Unmanned Aerial Systems (UASs)*

UASs offer a technological revolution for highway transportation, asset management, traffic incident management, and inspections (bridges, tunnels and construction sites) and delivery of packages (logistics). Full-scale test track facilities can be utilized for the training and explore other opportunities to expand UAS applications in other areas. The benefits of UAS applications include promoting safety, accelerated construction and data collection, asset maintenance, and efficient emergency management.

## 6. Summary and Conclusions

The versatility of APTs is evident. Successful applications of APT facilities for non-pavement research have been reviewed in this paper. Some APT facilities have been able to balance pavement and non-pavement research without undercutting the objectives that established them. The decision for APTs to engage in non-pavement research is a management initiative that promotes research diversity and the image of the facility. The overall intent of this paper is to raise awareness and encourage the participation of APTs in non-pavement research. Different APT types have the capacity and the expertise to meet the needs of different customers. Moreover, the staff of APT facilities have demonstrated the capacity to adjust to different research fields. However, it appears that the test roads have been explored more extensively for non-pavement research than HVS, ALFs and MLS. It is evident that both HVS and test road tracks are effective in evaluating bridge responses and performance. APT facilities can effectively evaluate road markings, pavement markers and rumble strips, geotechnical experiments, and electric road systems (ERS). Test roads appear to be more ideal for connected and autonomous vehicle technology, truck platooning testing, drainage testing, emergency response demonstrations, and intelligent compaction technologies; however, it is evident that very few APTs have been utilized for bridge research, though the topic of bridges appears to be very popular. From the text analytics of the literature review conducted in this paper, all the APT techniques appear to often be involved in investigating, developing, or evaluating non-pavement topics related to bridges, autonomous vehicles, and markings. The paper suggests non-pavement research areas where the proposed Wyoming test road facility could be utilized for incorporating non-pavement research initiatives in APT programs, diversifying funding sources, and promoting partnerships for successful operations, longevity, resilience and the image of APT facilities.

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