FINAL REPORT

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Wyoming Department of Transportation, State of Wyoming

A FEASIBILITY STUDY FOR ESTABLISHING A REGIONAL ROAD TRACK PAVEMENT TESTING FACILITY IN WYOMING

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16. Abstract:

This report discusses the benefits of full-scale pavement testing and the use of Accelerated Pavement Testing (APT) to collect pavement performance data under actual experimental conditions. The report highlights the development and operation of road test tracks, such as the Minnesota Road Research Project (MnROAD) and the National Center for Asphalt Technology (NCAT) test track, and their use in various climatic zones across the United States. The report proposes the establishment of a new test track in Wyoming along an I-80 corridor, which will be the only test track of its kind in the dry-freeze region. The report documents the feasibility study conducted by the Wyoming Technology Transfer Center and the Wyoming Department of Transportation to evaluate the effectiveness of constructing a state-of-the-art APT facility in Wyoming. The study aims to identify potential partnerships, effective frameworks for building and managing the proposed test track, suitable locations, research priorities, and feasibility in terms of benefits and costs. The proposed test track in Wyoming will allow for comprehensive in-service monitoring of pavement performance under representative climate and traffic loading conditions and promote technology transfer, setting WYDOT as pioneer in pavement engineering innovation.

17. Key Words

APT, NCAT, WYDOT, UAS, Wyoming

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ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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LIST OF ACRONYMS

AASHO	American Association of State Highway Officials
ADT	Average Daily Traffic
ADTT	Average Daily Truck Traffic
APT	Accelerated Pavement Testing
CIR	Cold In-Place
CY	Cubic Yard
FDOT	Florida Department of Transportation
FT	Foot
GIS	Geographic Information System
HMA	Hot Mix Asphalt
IRI	International Roughness Index
JPCP	Jointed Plain Concrete Pavement
LCCA	Life Cycle Cost Analysis
LVR	Low-Volume Road
MCA	Multi-Criteria Analysis
MEPDG	Mechanistic Empirical Pavement Design Guide
MI	Mile
MnROAD	Minnesota Road Research Project
NCAT	National Center for Asphalt Technology
NPB	Net Present Benefit
NPC	Net Present Cost
PCC	Portland Cement Concrete
RAP	Reclaimed Asphalt Pavement
SFT	Square Foot
SY	Square Yard
UAS	Unmanned Aerial System
WDOT	Wyoming Department of Transportation
WIM	Weight in Motion
WMA	Warm Mix Asphalt

CHAPTER 1: INTRODUCTION

Full-scale pavement testing provides methods to collect pavement performance and related data under actual experimental conditions of traffic loading and surrounding environmental conditions. Collecting performance-related data on pavement through a real-world experiment can contribute to the development and verification of pavement design methods and material specifications. It can also evaluate emerging technologies and practices to better design, construct, and manage pavement and other infrastructure effectively. Because of the long service life of in-service pavement structures, Accelerated Pavement Testing (APT) provides a logical method to accelerate the failure on the full-scale pavement test sections using different loading techniques, including full-scale road test tracks and traffic simulation devices. Such accelerated manners can increase the rates of pavement deterioration to reach the end of the service life of test sections in a timely manner.

Several state agencies are developing pavement testing experiments using conventional and accelerated testing facilities. Road test tracks are considered the largest testing facilities for full-scale pavement testing. This is due to the large number of test sections constructed on the mainline of the test track that is distributed along a road segment of more than two miles in length. The AASHO test track is one of the leading road test tracks developed back in the 1960s. Two major test tracks are currently operated in the United States (U.S.): the Minnesota Road Research Project (MnROAD) in Minnesota, and the National Center for Asphalt Technology (NCAT) test track in Alabama. The test track can be operated separately using dedicated loading trucks (such as NCAT) or existing large traffic volumes to load the test sections (such as MnROAD). Another major concrete test track is being established by the Florida Department of Transportation (FDOT). A comprehensive background of APT techniques and testing programs in the U.S. is documented in Appendix A. Although cost-effective enhancements are being developed from APT programs, pavement conditions are treated differently in distinct climates. This is due to the different impacts of environmental conditions on pavement responses, stresses, and performance. Across the U.S., four main climatic zones are defined by the FHWA: dry freeze, wet freeze, dry no freeze, and wet no freeze. The MnROAD test track is located in the wet-freeze zone while NCAT is located in the wet-no-freeze zone. Although the dry-freeze zone exhibits challenging conditions for pavement performance and covers almost 13 states in the midwestern United States, no test track has been developed for regional pavement research. The numerous benefits associated with APT programs and the need for a more realistic approach to evaluating pavements under closely simulated in-service conditions have prompted WYDOT and the University of Wyoming (UW) to propose a new test road track in Wyoming along an I-80 corridor.

The main objective of the proposed APT program test track is to continuously improve the performance of pavements in the dry-freeze region cost-effectively and promote technology transfer. The facility will be unique when established in that region since it will be the only test track of such a large facility in the dry-freeze region. The environmental conditions of the dry-freeze region will distinguish this test road from MnROAD, NCAT, and FDOT test tracks. The proposed test track in Wyoming will allow comprehensive in-service monitoring of the performance of pavement systems, technologies, material properties, construction practices, and preservation treatments under representative climate and traffic loading conditions. It will also further set forth WYDOT as a global leader in technology and innovation in pavement engineering.

Since establishing a regional test track requires major investments, the Wyoming Technology Transfer Center (WYT2/LTAP) initiated a feasibility study in collaboration with the WYDOT to evaluate the effectiveness of constructing a state-of-the-art APT facility along I-80 in Wyoming. This report documents the efforts conducted to assess the feasibility of the proposed test track considering several factors, including potential partnership and cooperation, test facility layouts, proposed locations, economic benefit-cost impacts, cost estimates, and future research programs. The current study focuses on obtaining sufficient relevant information for building and operating the regional testing facility in Wyoming. The intent is to establish a preliminary understanding of APTs in the region and measure the level of readiness for such a major testing facility in the region. The study also ensures that all stakeholders and partners are well coordinated to present beneficial participation. In this phase, pavement types, structures, and materials will be investigated to prioritize the suitable design of experiments according to the scope of the regional research. Information about the geometric design of pavement will be collected, including road track lengths and the number of test sections recommended for the proposed test track.

Study Objectives

This study was undertaken to evaluate the effectiveness of constructing a new regional road test track in Wyoming to conduct research studies for the dry-freeze region. The following objectives are addressed to achieve this goal:

- Define methods to share resources and expertise to promote partnership for the proposed test track.
- Identify an effective framework for building, managing, and operating the proposed test track in Wyoming considering the regional and national experiences of future partners.
- Document best practices of design, construction, and instrumentation of pavement test sections.
- Investigate potential locations of the regional test track to elevate the suitability of testing and construction conditions so that the outcomes of the regional research are maximized.
- Identify and prioritize the research needs currently urgent for the improvement of pavement performance in Wyoming and surrounding states.

- Present a review of the applications of APT facilities for non-pavement research based on experiences around the world.
- Determine the feasibility of the testing facility in terms of expected benefits and associated costs.

Report Organization

The report is organized into seven chapters. The first chapter discusses the study motivation, outline, and objectives. The second chapter identifies the interest of potential partners and reports best practices for managing and building the APT facility considering the feedback from partnership surveys and lessons learned from virtual meetings with the major test track officials. The third chapter documents the potential locations of the proposed test track along I-80 defined using spatial data and GIS processing. Also, the field demonstration of evaluating the actual conditions of the potential location is introduced using Unmanned Aerial Systems (UAS). The fourth chapter discusses the economic evaluation of the proposed test track considering the benefit-cost impacts of future research programs. A summary of the expected benefits in dollar values is also provided in this chapter. The fifth chapter provides the results of the cost estimates for the main elements of the test track using related construction references and WYDOT bid prices. The sixth chapter outlines the collaboration between the University of Wyoming and WYDOT in conducting future research studies on the proposed test road facility, as well as other related programs of training and technology transfer. Finally, the seventh chapter summarizes the findings and conclusions of the study and presents recommendations.

CHAPTER 2: PARTNERSHIP SURVEYS AND VIRTUAL MEETINGS

Background

The accelerated pavement testing programs are usually sponsored by several partners due to the high cost of construction, instrumentation, testing, and operations throughout their life cycles (Brown et al., 2002). The available literature shows that no pavement testing facility has been operated self-sufficiently (Steyn, 2012). Such large testing facilities offer a suitable environment for cooperative research activities for states' transportation agencies to improve pavement design, economy, and performance. In addition, pavement industrial entities can evaluate innovative products and technologies to accelerate their implementation in pavement construction, and materials. Additionally, the collaboration between different partners is essential to transfer knowledge, innovation, and resources for the development of pavement research regionally. The major challenges facing APT facilities are cost (Powell, 2012a), inconsistent funding (Worel et al., 2020), and lack of technical support (Worel et al., 2020). Hence, promoting collaborations and partnerships in APT programs is key to improving data quality (Saeed and Hall Jr, 2003), making greater research impacts (Gibson et al., 2008), improving fiscal responsibility and technology transfer, and optimizing resources and device improvements (Harvey et al., 2008; Steyn, 2012).

A preliminary step in the feasibility study of the proposed test track in Wyoming is to establish partnership and technical support by reaching out to all potentially regional partners and officials of major APT test tracks in the nation. In this study, several lessons and feedback are received which are expected to support the decision-making of building and operating the test track in Wyoming (Fosu-Saah et al., 2022). There are several organizations and industrial entities that can benefit from the proposed road track. This study presents a unique opportunity for all states in the dry-freeze region to become active partners to advance pavement research and implementation of the test track. The current objective is to reach out to all interested states to share their experience and thoughts on building and operating the proposed testing facility.

Partnership Survey Questionnaires

Online survey questionnaires were developed and disseminated to the regional 13 states in the dry-freeze zone to collect important feedback about the layout design of the APT facility, test sections, design of experiments, pavement data collection, and research needs proposed for the regional testing facility. Such information is intended to achieve the following objectives:

- Secure feedback from state DOTs about the importance of building a regional APT facility for research.
- Prioritize research interests and needs
- Inquire from industry, contractors, and associations about their interests in the commercial evaluation of products and technologies using the APT facility.

- Measure the level of readiness of potential partners to participate in pooled fund studies and sponsor the building of the APT facility.
- Identify how the respondents intend to support the APT project.
- Identify the best practices during planning, construction, operation, instrumentation, maintenance, and data collection based on the experiences of existing APT test road facilities in the country.

Such information is critical to producing a reliable APT facility that is beneficial for the region while monitoring pavement performance. Two main survey questionnaires were created as described below.

Regional State DOTs Survey

The first online survey was sent out to representatives of 13 state DOTs in the dry-freeze region, including Alaska, Colorado, Idaho, Kansas, Montana, Nebraska, Nevada, North Dakota, Oregon, South Dakota, Utah, Washington, and Wyoming. These state agencies have various research interests aimed at improving pavement performance and its life cycle. Hence, this survey asked how the proposed test track will serve the state DOTs needs. It also identifies their future interest in sponsoring pooled fund studies on the test track. Feedback was received from 17 respondents representing 12 state DOTs of the dry-freeze region. The complete survey questionnaire is shown in Appendix B.

Industry and Associations Survey

Contractors and associations have research interests related to the implementation of innovative techniques and technologies. The proposed test track in Wyoming will provide these entities with the unique opportunity to evaluate potential new products and technologies. Such commercial evaluations are expected to prove their cost-effectiveness in providing solutions to the challenges of pavement materials, maintenance, and construction. Participation and sponsorship in pooled fund research and technical support can facilitate the implementation of such products. Hence, the second survey sought potential partnership from the pavement industry. Thirteen pavement industrial agencies responded to the survey, including state, national, and regional associations. The complete survey questionnaire is shown in Appendix C.

Virtual Meetings with Major APT Test Track Officials

A significant aspect of the APT partnership investigation included meeting with the officials of major APT facilities from MnROAD, NCAT, and FDOT test tracks. The objective was to gain technical support and increase the learning from the vast experiences of these facilities through consulting about best practices in planning and research needs. The lessons learned are documented in this chapter for the benefits of the proposed test track facility's design, construction, and instrumentation. MnROAD, NCAT, and FDOT have experienced and learned from challenges in APT operations over the past 20 years. They have several experiences with full-scale pavement testing techniques, including construction, funding, instrumentation, operations, data collection, and management.

Results of the Survey

The results of the online surveys are presented in the following subsections.

Importance of Building A new Test Track and Expected Benefits

Pavement testing facilities have made significant contributions to the pavement industry. First, the survey asked all participants about the importance of building a new test track facility for the dry-freeze zone. The results are shown in Table 1. Seventy-seven percent of participants in the state survey confirm that building a regional test track facility is very important for research. Similarly, 60 percent of industrial respondents consider the facility to be very important for the evaluation and implementation of products and technologies related to pavement engineering. Hence, in both surveys, the proposed test track facility is considered a very important asset to the states in the dry-freeze region.

Table 1. Importance of building the test track facility for the region.

Importance level	Percentage Responses (%)	
	State Respondents	Industry Respondents
Absolutely essential	12%	20%
Very important	65%	40%
Of average importance	24%	40%
Of little importance	0%	0%
Not important at all	0%	0%
Total number of responses	17	10

The survey also asked about the expected benefits of the test track research program to the potential partners. The results show that 71 percent of state respondents expect to benefit from improved material specifications and guidelines. Refinements in the Mechanistic-Empirical Pavement Design Guide (MEPDG) was also highly expected. Such refinements are expected by calibrating pavement distress transfer functions with pavement inputs. Other important benefits are improvement in the selection of asphalt and concrete materials specifications. These specifications would address the expected long-term aging, and crack in asphalt binders and pavement surfaces. Additionally, the respondents expect to improve the structural design and performance of both flexible and rigid pavements, assess innovative materials and maintenance practices, and increase regional coordination through cooperative research. The results from the survey of industrial partners show that 74 percent of participants anticipate the proposed test track to facilitate improvement in pavement design, performance, maintenance, material specifications, regional and national cooperation, and technology transfer through innovation. Generally, the respondents of both surveys expect pavement performance and cost-effective designs to be improved through innovation, technology transfer, material selection, and understanding of pavement behavior in the dry-freeze climatic zone.

Proposed Layout and Test Sections

A conceptual layout of the dry-freeze RTPT facility is illustrated in Figure 1. The facility includes two road tracks: a mainline on I-80 and an additional low-volume road (LVR) test track. The test tracks are expected to carry in-service traffic volumes on both the interstate and existing LVRs. This would reduce the operating costs for pavement loading.

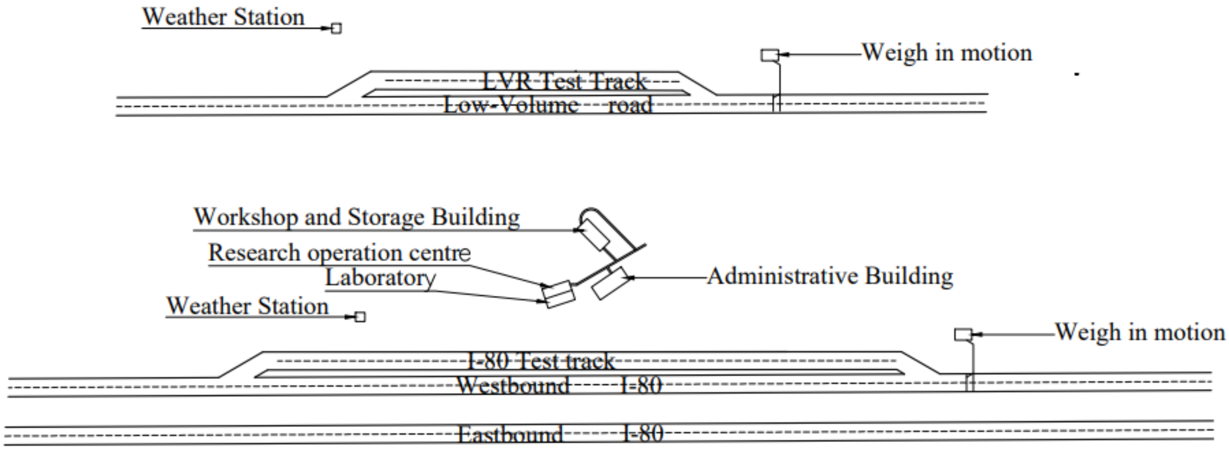
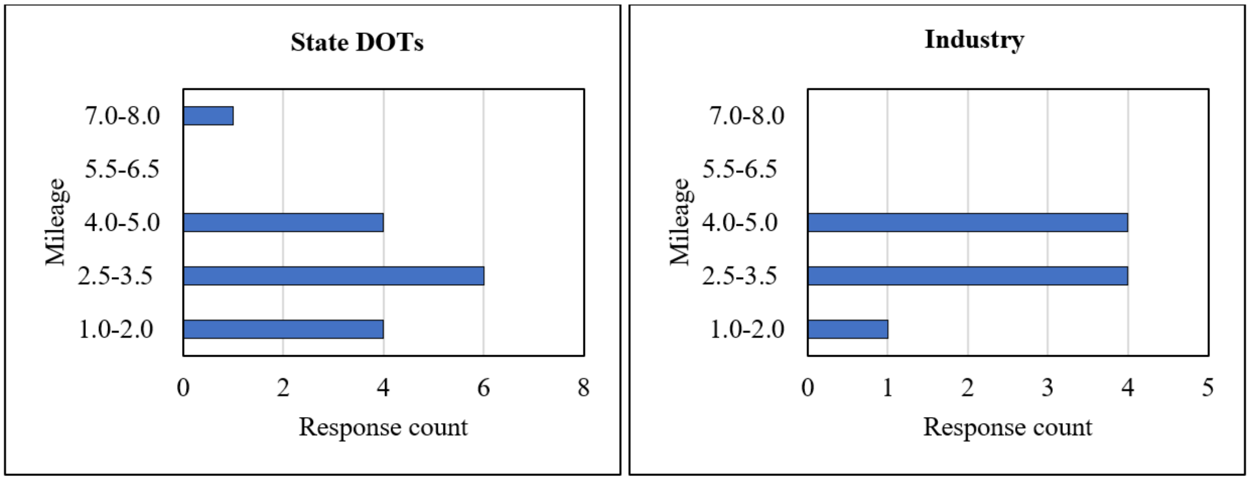


Figure 1. Conceptual layout of the test track facility.

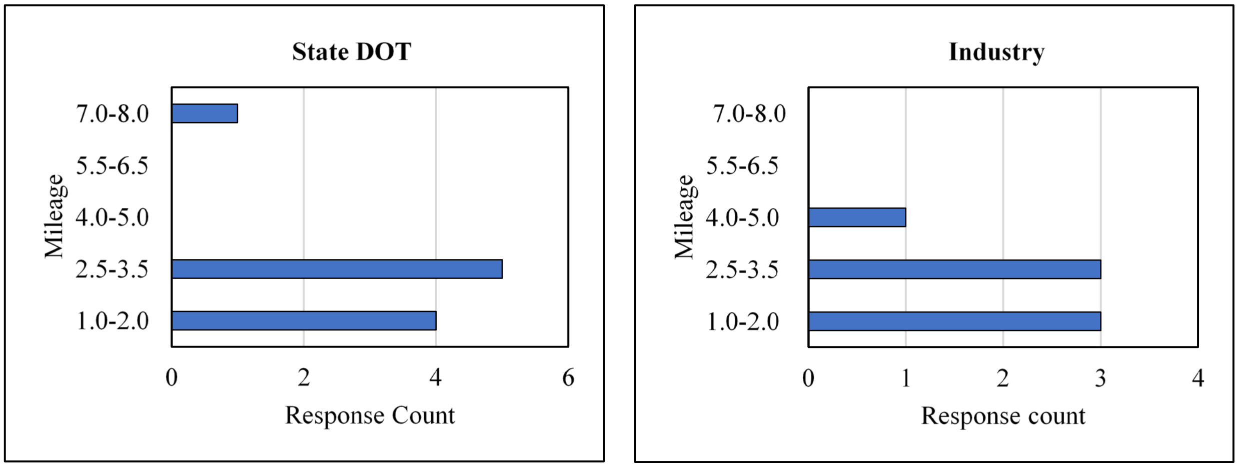
Another important aspect affecting the costs of the test track facility is the total length of the tracks. Both surveys asked about recommended lengths for the facility, and the results show that 40 percent of participants in the state DOT survey and 44 percent of industrial respondents recommend considering a total length for the I-80 test track to ranging from 2.5 to 3.5 miles, see Figure 2. Other feedback was received that the total length may depend on the number of participating agencies and the research needs of each agency. However, the balance between the expected number of test sections and total costs should be considered.



(a) **(b)**

Figure 2. Recommended mileage of I-80 test track: (a) state DOTs survey results; (b) industry survey results.

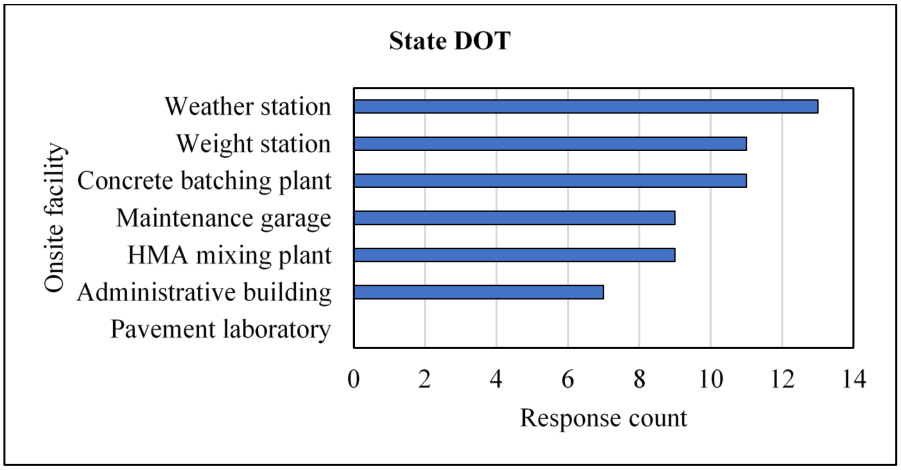
For LVR regional research, the utilization of the LVR test track is found to be recommended by 71 percent of state participants and 80 percent of industrial participants who responded to the survey. The mileage of the LVR was suggested to be from 2.5 to 3.5 miles as shown in Figure 3.



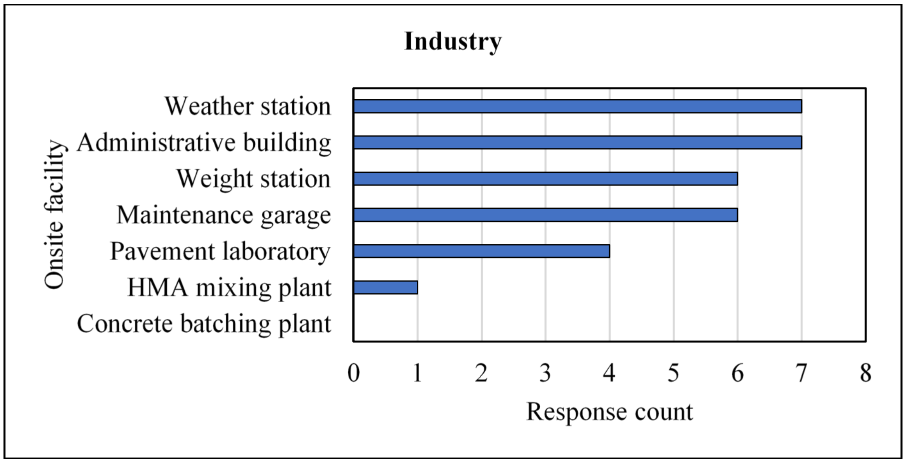
(a) **(b)**

Figure 3. Recommended mileage of LVR track: (a) state DOTs survey results; (b) industry survey results.

The survey asked the respondents for their recommendations of supporting facilities relevant to the test track research program implementation. Respondents were able to make multiple selections. As shown in Figure 4, all the respondents in the state DOTs survey recommended the building of a weather station, a laboratory, weigh station, an administration block, and maintenance and storage garage facilities. For the industry survey, 97 percent of the respondents agree with the recommendations of the state participants on the supporting facilities.



(a)



(b)

Figure 4. Recommended supporting onsite facilities: (a) state DOTs survey results; (b) industry survey results.

The survey included questions about the interest of state agencies in bridge research at the facility. The results show that 82 percent of the respondents in the state survey and 70 percent in the industry survey do not support building bridges at the testing facility for the first research phase program.

The test sections are another major focus of the test track research programs. Test sections will be constructed based on research objectives instrumented to provide continuous feedback on pavement behavior. First, agencies were asked about the pavement type that should be evaluated at the proposed test track facility. Participants were able to select multiple choices. Table 2 summarizes the survey responses. Research on rigid and flexible pavements is highly recommended by the state DOTs. Conventional flexible pavements are highly recommended for both the I-80 and LVR test tracks as shown in Figure 5. This could be due to the fact that conventional flexible pavements are extensively considered in the participating states. In terms of asphalt mixtures, 71 percent of the state respondents are interested in research on hot mix asphalt (HMA) while only 18 percent showed interest in research studies on warm mix asphalt (WMA) and bituminous surface treatments. The high interest in research on HMA by the state respondents could be attributed to the high percentage of road networks being HMA flexible pavements in the participating states. For concrete rigid pavements, most of the state DOT participants recommend research on the jointed plain concrete pavement (JPCP) with an unbound base and subbase layer system.

Table 2. Regional interest in pavement test sections.

Pavement Type	Percentage of Response
Asphalt flexible pavement	34%
Concrete rigid pavement	39%
Composite pavement	27%
Total number of responses	17
Skipped	0

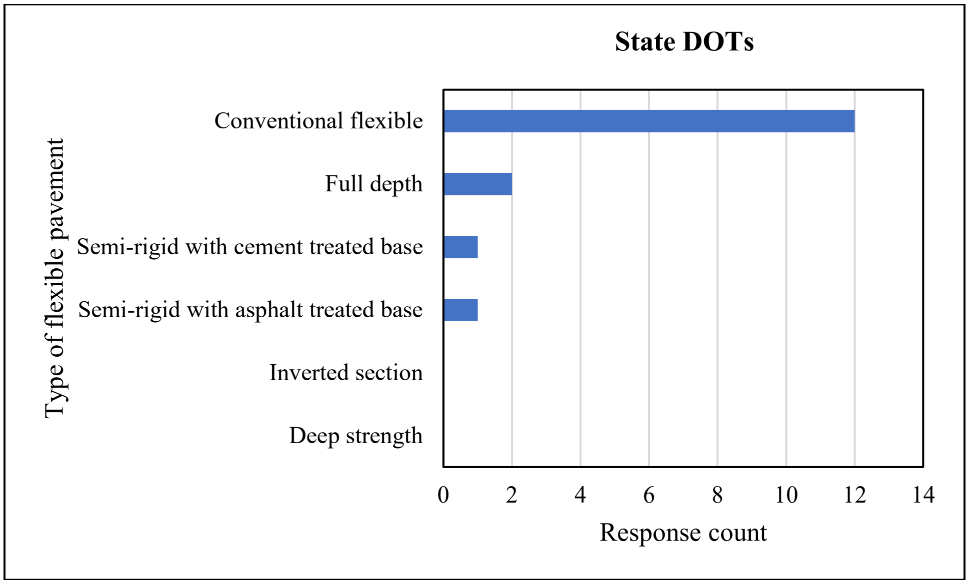


Figure 5. Flexible pavement types recommended for research.

Data Collection and Sharing

The survey included questions that focused on data collection and sharing techniques. As mentioned previously, the test tracks will be loaded with existing traffic volumes. Hence, the survey asked about the types of traffic data recommended for collection as well as any suggested techniques for data collection. The results show that 64 percent of the state survey recommend considering average daily traffic (ADT) and average daily truck traffic (ADTT) measurements on the test tracks. The rest also recommended the consideration of weigh-in-motion (WIM) data sets. All thirteen states in the dry-freeze zone collect pavement condition data. States use different pavement condition indices to describe the "health" of pavements. Figure 6 shows the list of the most commonly used pavement condition indices used by states in the region. International roughness index (IRI) and rut depth were considered the most widely recommended condition indices for the proposed test track research program.

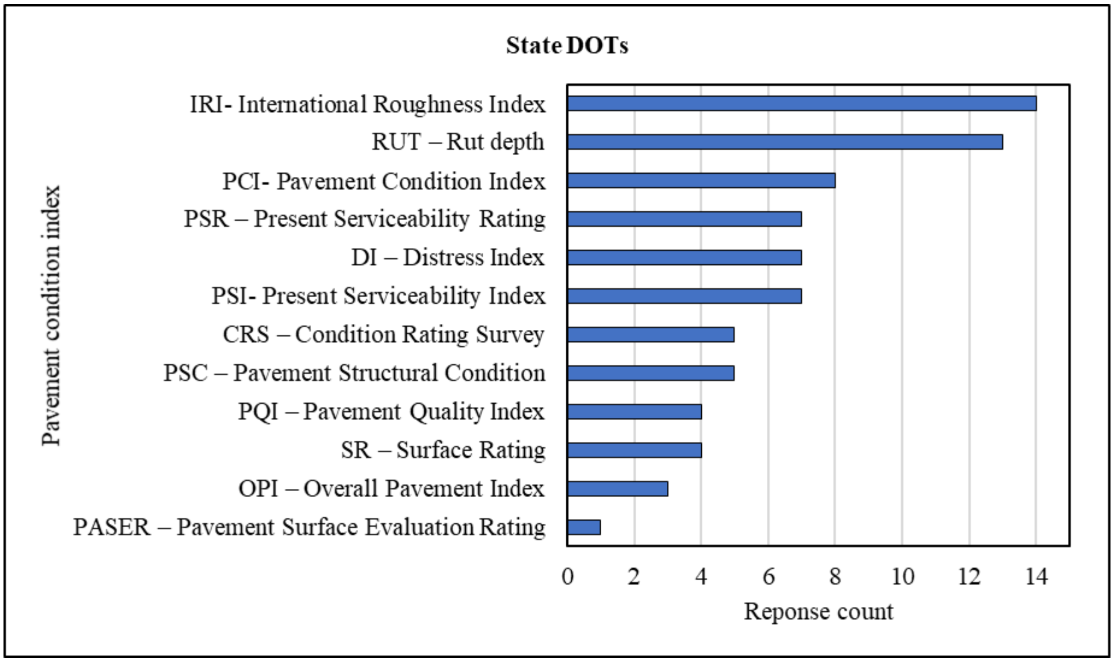
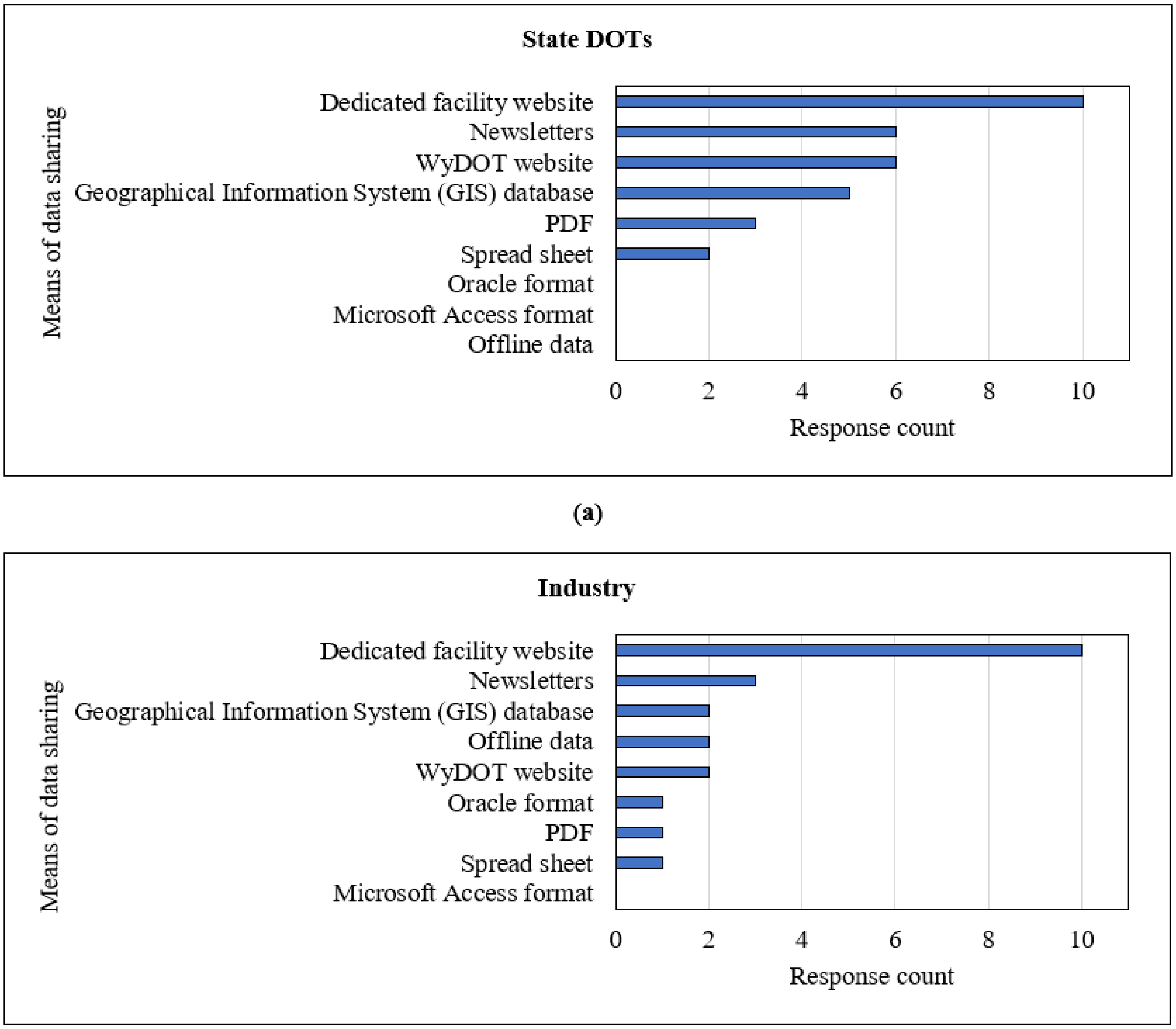


Figure 6. Most common Condition indices recommended to collect for the test sections.

The full-scale test track research information can be disseminated using various means. According to available literature, the data can be put into seven categories of elements: administrative, load application, pavement description, material properties, environmental conditions, pavement response, and performance. Data collection and analysis of test sections are critical to the conclusions and recommendations made by the research program (Saeed, 2003). The survey asked the participants about how research data and publications should be shared with the public and other test track facilities. Respondents in both surveys mainly indicated that a dedicated facility website should be created for the collection, storage, and retrieval of all information associated with the testing program as shown in Figure 7.



(a)

(b)

Figure 7. Recommended means of sharing data and research information: (a) state DOTs survey results; (b) industry survey results.

Research Needs

The research needs for the dry-freeze zone are defined considering two sources. The first source was based on an extensive literature review. In this review, different applications for pavement and non-pavement research were identified from related APT experiments around the world. Then, a text data analysis is conducted to show the trends of the main field of pavement and non-pavement testing using text data mining techniques. The broad discussion of this review and results of the text data mining are shown in appendices D and E for pavement and non-pavement research needs, respectively. The second source of defining the emerging research needs on the proposed test track is based on feedback received from the partnership surveys which is discussed in this section.

A broad scope of research interest was evident from the responses. However, the answers show that topics related to the refinement of the MEPDG of flexible pavements, evaluation, and validation of flexible pavement structural response models, low-temperature cracking, the relationship between laboratory-measured characteristics of HMA and field conditions, and long-term aging of asphalt mixtures are popular among the states. In terms of maintenance and rehabilitation, the majority of participating states showed strong interest in optimal timings of preventive maintenance practices and developing best practices for HMA overlays related to the density and reflective cracking, chip seals, crack seals, and micro-seals in HMA pavements.

On the other hand, MEPDG evaluation and calibration of rigid pavement structural model and high-performance Portland cement concrete (PCC) designs, and materials, optimizing concrete mix components, fiber-reinforced concrete, pervious and compacted concrete received more interest. Respondents suggested that preventive maintenance should be prioritized. Sixteen respondents showed interest in geotechnical-related research at the facility.

Briefly, the prominent research needs identified include:

- Local calibration of the MEPDG for rigid, flexible, and composite pavements.
- Pavement preservations research
- Recycled materials
- Additives and rejuvenators

For bridge research, a little interest was shown by participating states. The little interest in bridge research using the APT may be due to the high cost of constructing bridge test sections. However, future research phases may consider bridge research when the need arises, considering the critical role of bridges in surface transportation infrastructure.

Industrial Evaluations

The industry survey included a section to determine the interest of industrial partners in novel products and technologies in rigid, flexible and composite pavements for evaluation using a real-life testing environment on the proposed test track. Most respondents indicated an interest in evaluating HMA additives, asphalt modifiers, rejuvenators, hot mix asphalt, reclaimed asphalt pavement (RAP) in HMA, and recycled asphalt shingles (RAS) in HMA. Moreover, 20 percent of the respondents showed interest in alternative cementitious materials, concrete additives, admixtures, fiber-reinforced concrete pavements, and supplementary cementitious materials (SCM). Aggregates constitute a significant proportion of asphalt concrete mixtures and PCC. There have been concerns about enormous pressure on the usage of virgin aggregates. Numerous research efforts have been made over the years to explore other alternative sources. Respondents showed interest in evaluating manufactured aggregates, recycled concrete aggregates, light weight aggregates, tire-derived aggregates, and recycled asphalt in concrete pavement. Respondents also recommended the evaluation of crack sealants, concrete cold patches, low-noise diamond grinding, and fiber-reinforced thin concrete pavements.

In the area of paving technology, most respondents in the industry survey recommended research evaluation of interlocking concrete pavements, intelligent compaction, paver-mounted thermal profile, concrete pumping aids, paver-mounted thermal profile, joint spray systems, and asphalt temperature measurement and mapping. Industries involved in the manufacture of laboratory devices and other field-related pavement equipment can evaluate and calibrate devices at the facility. The devices are either destructive or non-destructive. In the survey, 42 percent of the respondents intend to evaluate devices for nondestructive testing of pavements and devices for pavement condition survey. However, 56 percent of participants recommended the evaluation of devices for nondestructive testing of bridges, construction materials, retroreflective measurements, geotechnical, real-time monitoring sensors, and unmanned aerial systems. In addition, the survey included questions intended to identify the interest of the industry in other transportation technologies.

Respondents also showed interest in non-pavement-related research, including reflectivity of traffic signs and markings, adaptive signal control, connected vehicles, crash avoidance, smart infrastructure systems, smart work zones, and autonomous vehicle technologies, among other interests of industry for commercial evaluation at the proposed test track facility. According to responses from participants, commercial evaluations and implementation of novel products and technologies are expected to promote cost-effectiveness, environmental sustainability, safety, and performance of pavements for both new construction and maintenance.

Potential Partnership and Cooperation

The available literature on testing facilities has shown that research programs have been successful and economical through pooled fund studies, such as State Planning and Research (SP&R) funding. This section intends to get feedback on the interest of respondents in taking part in pooled fund studies, advisory support, technical support, and construction support to address research needs commonly recommended to the DOTs. For the potential sponsorship, a complete list of responses for questions 49 through 54 is provided in Table 3 for the sate DOT survey. The proportions of the percentage of interest in pooled fund studies are shown in Figure 8 for both state DOTs and industrial partners. However, most respondents indicated a preference for further discussions with stakeholders prior to making a decision. At this stage of the project, 11 state DOTs (with “yes” and “maybe” responses) appear to be willing to consider sponsorship on the proposed test track. It is also clear that the strategic partnership with MnROAD and/or NCAT testing facility is highly recommended by most of the respondents to share expertise and resources with the proposed test track. For the industrial part, eight industrial entities showed interest to participate in pooled fund projects on the proposed test track.

Table 3. Feedback summary of potential partnership and cooperation for state DOTs.

Dry-freeze state	Interest in pooled fund study (Q49)	Advisory support (Q50)	Technical support (Q51)	Construction Support (Q52)	Form of sponsorship (Q53)	NCAT/MnROAD partnership recommendation (Q54)	Notes
Alaska	N/A	N/A	N/A	N/A	N/A	N/A	No Comment
Colorado	Yes	Yes	Yes	Maybe	• Research sponsorship • Participation in pooled funds	Maybe	Our SP&R funds is about the only way CDOT could participate
Idaho	Maybe	Maybe	Maybe	Maybe	Skipped	Maybe	No Comment
Kansas	Maybe	Maybe	Maybe	Skipped	Skipped	Skipped	No Comment
Montana	Maybe	Maybe	Maybe	Maybe	• Research sponsorship • Technical support	Yes	No Comment
Nebraska	Maybe	Maybe	Maybe	No	Skipped	Yes	No Comment
Nevada	Yes	Maybe	Yes	Maybe	• Research sponsorship • Technical support	Maybe	No Comment
North Dakota	Yes	Yes	Yes	No	• Research sponsorship • Technical support	Yes	No Comment
Oregon	No	No	No	No	Skipped	No	No Comment
South Dakota	Maybe	Maybe	Maybe	Maybe	• Research sponsorship • Technical support	Maybe	No Comment
Utah	Maybe	Maybe	Maybe	Maybe	• Research sponsorship	Yes	Impacts of COVID may not enable to consider currently but interested in continued discussions and direction.
Washington	No	No	No	No	Skipped	Maybe	Non-voting members
Washington	Maybe	Maybe	Maybe	No	• Technical support	Yes	Non-voting members
Wyoming	Yes	Yes	Yes	Yes	• Construction funding • Research sponsorship	Yes	No Comment

Note: N/A = Not applicable because no feedback received.

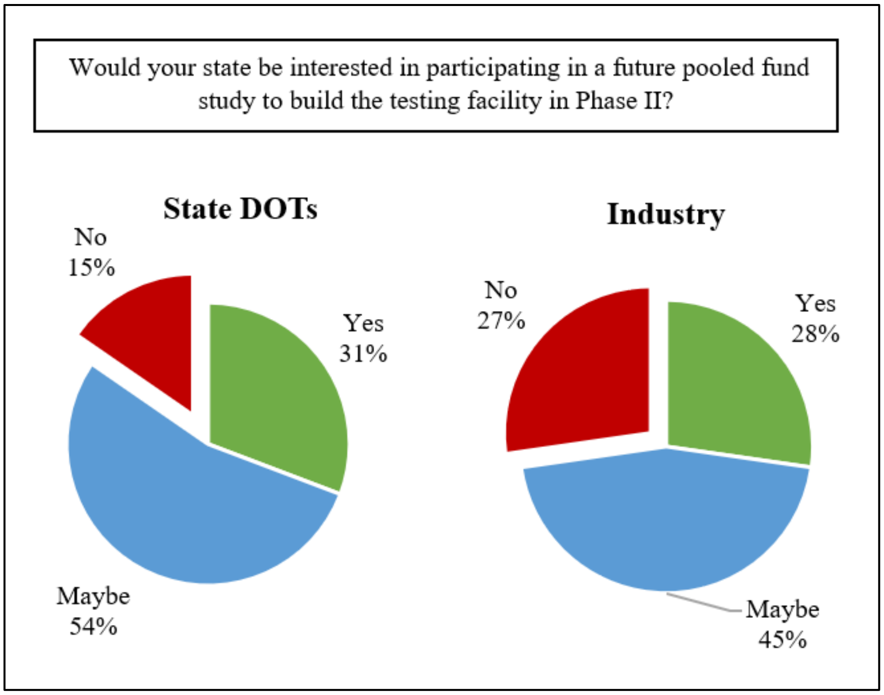
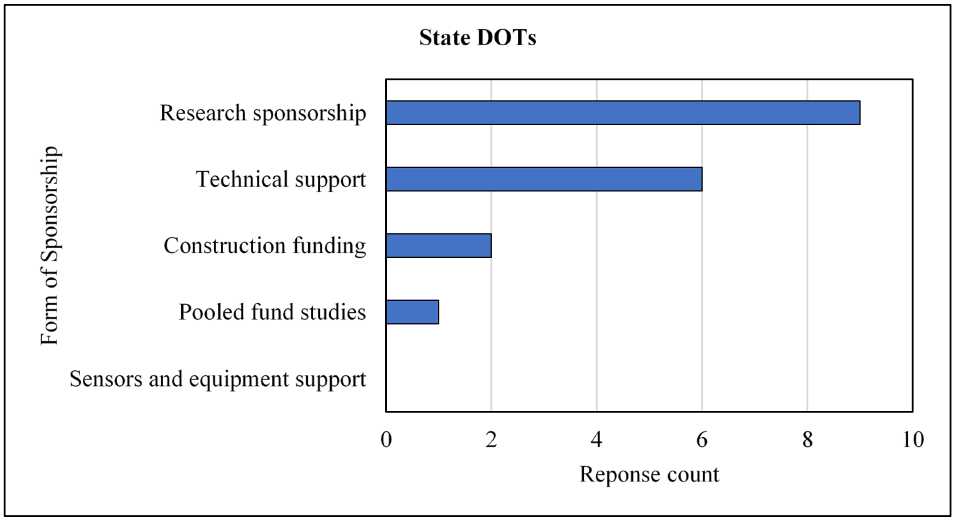


Figure 8. Interest in partnership of potential pooled fund studies on the proposed test track.

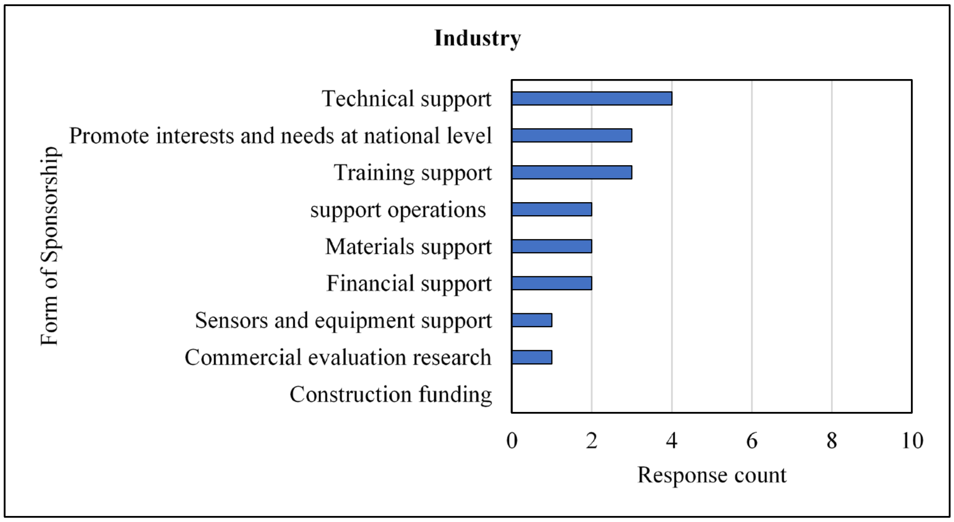
For the proposed test track in Wyoming, an advisory board will be constituted to have oversight of the pooled fund studies. The board will set the objectives and goals, and determine all future research studies, including a budget based on the recommendation at the proposed APT facility. Twenty-six respondents representing 22 agencies (with “yes” and “maybe” responses) from both surveys appear to be willing to join and take a seat on the advisory board.

As far as technical support, the membership of the technical subcommittees will constitute experts in asphalt, Portland cement concrete pavements, geotechnical engineering, and pavement maintenance. The team will focus on new and rehabilitated pavements and prioritize long and short-term research programs. The feedback indicates that 67 percent of respondents in the industry survey showed interest in joining technical subcommittees. On the other hand, more than 70 percent of state DOTs showed interest in joining the technical subcommittees.

There are different forms of sponsorship that can be adopted by agencies on the proposed test track. Figure 9 shows a summary of the types of sponsorship indicated. At this stage of the project, there was a high interest in state DOTs to sponsor research programs. Providing technical support, funds for the facility's construction, and participating in pooled fund studies are areas surrounding states intend to invest in to make the regional APT a reality. Respondents indicated high intentions to provide technical support to the research program. Other forms of support they intend to deliver include training, promoting the facility's interest, operations, materials, research dollars, sensors, and equipment.



(a)



(b)

Figure 9. Forms of sponsorship indicated by partnership respondents: (a) state DOTs survey results; (b) industry survey results.

Lessons Learned from the Virtual Meetings

The following lessons are learned from the discussions with the officials of major test track facilities in the nation, including MnROAD, NCAT, and Florida DOT (FDOT) testing facilities.

Test Site

Selecting a suitable location for the test track is a significant task yet daunting in the planning process. The site acquired for the APT facility should be large enough to allow for future expansions if needed. It is desirable to have sufficient space to design the facility and the test sections so that a large number of test sections can be built and allow room for the construction of new ones. Factors considered in selecting the sites of the APT facilities include:

- Proximity to the agency's materials/researcher's office promotes easy mobilization to the site for data collection, construction of test sections, and quality control and assurance.
- The facility should be located where there is adequate truck traffic to accelerate the failure of the test sections within a compressed time interval. Traffic should be similar to interstate traffic.
- The site should have minimum access driveways or side streets to the highway to minimize the interrupted flow of traffic and research operations.
- The affordability of land and Right of Way is recommended to consider because the cost and availability of land will impact the initial cost of the APT program.
- Proximity to an international airport presents an additional advantage for facility owners and partners, and it allows easy access to the site for domestic, regional, and international partners. APT programs attract significant visits from different countries and states. An NCAT Annual Report in 2020 lists the top visitors by country to the site; U.S (18,425), China (2,155), India (1,034), Japan (991), and Canada (706) (NCAT 2020).
- The test track facility should be constructed in a representative climate since variability in climate can be a limitation to the implementation of research findings. Moreover, the location should be selected where enough sunlight is provided during summertime. The shadowing effect of the sunlight should be avoided to reduce the biases of temperature-related pavement performance being tested.
- The site selected for the proposed facility should have easy access to utilities: electricity, water, sewer lines, and internet connections.
- Other aspects of the test location include minimal flood risks, environmental, and economic impacts.

Partnerships

The successes of the MnROAD and NCAT test track programs are partly attributed to the strong partnerships the facilities formed over the years. The partnership is crucial to avoid duplication of research topics. These test road facilities established and nurtured relationships with existing facilities, industry, and state DOTs to improve data quality, expand research impacts, and improve funding. The partnerships have helped APTs to overcome the limitations of operating solely. The MnROAD and NCAT partnership has helped to bridge the climate gap towards addressing national challenges with pavements. The alliance has promoted the need to understand pavement and performance and how the different climates affect it. Consistent support and funding have been the backbone of these APT programs as managing a test track facility are expensive. NCAT has been operational successfully because it has been entrepreneurial about the research program and created value for prospective sponsors, including incorporating non-pavement research to offset operations costs to promote financial stability and independence. The role of the private sector in promoting APT cannot be underestimated. Industries have provided support to these test roads through the construction and maintenance of the test tracks by donating materials, equipment, and technical support. A “call for innovations” program instituted at MnROAD to invite associate partners, academia, industry, and private companies to fund research based on their needs and interests has contributed to innovation in pavement engineering.

System of Operation

The facility can be set up in three main ways: conventional system, remote system, and hybrid system.

- Conventional system of operation – This system involves building onsite facilities to accommodate staff who operate entirely at the site. MnROAD is a test track that falls under this category. It operates with additional facilities to ensure the track is fully operational. The layout of the test track shall include onsite buildings, offices, conference rooms, a laboratory, a data collection controlling room, a pole barn of equipment storage, a maintenance unit, a parking lot, stockpile area, among other elements.

- Remote system of operation – The facility can be set up such that data collection can be monitored remotely from the operator’s offices outside of the facility's premises via the internet as in the case of the FDOT concrete test road. There will be no full-time staff resident at the site and no office buildings for the facility to reduce the overall cost. Under this category, the onsite facilities can be reduced to include only data side cabinets, a controlling room, and other minor elements. Apart from being a cost-effective way of operating, it ensures continuous data collection in the event of a pandemic like COVID-19, where lockdowns could be imposed.

- Hybrid system of Operation – This system is a combination of remote and conventional methods. This system shows that APTs can operate both conventionally and remotely like the NCAT test track. Existing facilities can integrate or upgrade their response data collection system to go remotely.

Test Track Construction

Over decades, the test sections have been sponsored by state DOTs, FHWA, and industry either individually or through pooled funding. To reflect local conditions and promote the implementation and applicability of research findings, local construction materials (aggregates) could be hauled from sponsoring states to construct the test sections. The haulage can be included in the cost of the research. The test sections are built with conventional highway construction equipment and techniques. Comprehensive quality control tests are utilized to meet the specifications and satisfaction of the sponsoring agency and they contributed to the success of APT. Under state procurement laws, private contractors can be selected to build the test sections through competitive bids or Turnkey contracts administered by the agency. Hiring experienced contractors with exemplary quality control records has helped the APT programs obtain quality results with reliable findings. However, the test sections can be built in-house with the staff of the facility to reduce costs. Being the prime contractor allows flexibility to make changes to the scope of work at any time without financial consequences and contractual breaches. Traditional design-bid-build, procurement, and contracting with private partners are the leading construction contracting methods. However, each contracting process has its pros and cons, and APT programs can use any of them depending on the needs of research sponsors. The development of partnership agreements is essential for the successful delivery of research goals and implementation. The geometry of the test section is typical of the interstate highway while the minimum test section of 200 feet in length is ideal since short test sections can render construction difficulty.

Traffic Management

Effective traffic management plans are needed using road signage to make research operations and traffic diversion easier and safer for the occasional traffic switches. Trained personnel and equipment should be secured, including authorized vehicles, portable changeable message sign, safetycades barriers, and comprehensive communication to smoothly undertake traffic switch operations. A complete safety protocol has helped to create a safe working environment for these test roads.

Instrumentation

The in-situ pavement responses and conditions of the test sections are measured occasionally. The commonly used instrumentation embedded in the wheel path of the test section includes strain gauges, pressure cells, displacement gages, and temperature and moisture sensors. The APT facilities have been using weather stations to record rainfall, humidity, temperature, and wind speed. The selection of instrumentation is based on the past experiences of earlier test roads and conducting some experimentation to determine what works well at which facility. Instrumentation has been procured using the state's procurement processes to invite bids. Other important selection criteria for sensors include performance, reliability, availability, and compatibility. Monitoring wells with tipping buckets developed at MnROAD have been used to monitor the level of the water table in the pavement structure. The use of two weigh-in-motion stations for traffic data collection allows continuous data collection if one of them breaks down or needs calibration.

Data Collection, Measurement, and Sharing

The condition of each section is routinely monitored to evaluate rutting, cracking, friction, roughness, falling weight deflectometer measurements, densification, and other related data.

MnROAD teamed up with the FHWA to develop an LTPP-InfoPave system to share APT data. The shared data is related to designs of test sections, layers, laboratory results, performance monitoring results, traffic, and the weather. In January 2020, FHWA launched the InfoMaterials^{TM} portal, which is currently hosted on the LTPP web portal to share datasets of the pavement performance and all related monitored data in the LTPP, as well as MnROAD. The feedback received in 2020 indicates that the web portal has enabled better and smoother access to the data sets for the benefit of research conducted and sponsored by FHWA (FHWA, 2021). For the proposed test track in Wyoming, WYDOT can decide how the different databases will be shared at the beginning of the project and with the consent of sponsors.

Staffing and Organizational Structure

A well-structured staffing organization at these facilities defines the workflow to achieve the goals of the APT program. The staff of the APT programs comprises managers, research engineers, mechanical engineers, electronic technicians, labourers, laboratory technicians, truck drivers, administrative staff, etc. The hiring of a construction management expert has helped NCAT with its operations to effectively plan and monitor the building of test sections in-house. Likewise, a contracts and grants specialist included in the team is highly beneficial to write, negotiating, finalize, and administering contracts with external parties. The structure will depend on how the APT program is set up (e.g., conventional, remote, or hybrid).

Site Meetings and Implementation Follow-ups

Communication and good relationships are essential for successful research partnerships and projects. Partners get involved and engaged during the entire research project. Occasional onsite sponsor/stakeholder meetings during the testing cycle at NCAT have been of tremendous benefit. Onsite meetings held at the facility include a physical inspection of test sections, providing feedback and making relevant changes to meet their needs, and sharing initial findings. The meetings also promote the implementation of research findings. NCAT officials also travel to sponsor states to present the research results and assist with the implementation of findings. The funds for hosting the meetings (including airfares) are included in the sponsor fees. The COVID-19 pandemic presented additional challenges in 2020 for APT operations in which onsite sponsor meetings had to be held virtually at NCAT. Regular meetings with potential contractors and the research team are necessary to aid and create a better understanding of how to build test sections and reduce contractual risks. A kick-off meeting with the contractor(s) is recommended to establish lines of communication at the commencement of the meeting.

CHAPTER 3: POTENTIAL LOCATIONS

Background

The site selection for the APT program is a critical aspect of the planning process. The decision to select a particular site for the APT facility will influence the operating cost, research findings, and implementation decisions. Wyoming's test track facility is proposed parallel to Wyoming's I-80, which is a major freight corridor with heavy trucks, to achieve the accelerated damage required for APT. However, Wyoming's I-80 is characterized by mountainous and rolling terrain with significant vertical grades. There are several sites along the 402-mile interstate segment where the facility could be located. But the potential site should be carefully selected based on certain predetermined criteria and experiences from similar facilities in the U.S.

This chapter presents the findings that identify favorable potential locations that satisfy predetermined selection criteria for the development of the proposed test track facility. The selection process involves two main stages: *1*) preliminary site screening using spatial data and Geographic Information System (GIS) tools and *2*) detailed site evaluation using Unmanned Aerial System (UAS) applications. The potential sites that would satisfy the initial screening criteria can be taken through a detailed evaluation for future consideration.

Study Area

I-80 is almost 402 miles in length and located at the south border of the state. It is a major freight rural corridor connecting the eastern and western parts of the U.S. It transports almost 32 million tons of freight annually (U.S DOT, 2022). The expansion in crude and gas production in the state has resulted in a corresponding increase in traffic volumes and axle loads. Heavy truck traffic on Wyoming's I-80 comprises almost 50 percent of the 7080-vehicle-per-day annual average daily traffic (AADT) (WYDOT, 2021).

The outstanding feature of Wyoming includes its majestic mountains and high plains. The mean elevation is 6700 feet above sea level (Wyoming State Geological Survey, 2021). Hence, the I-80 corridor is characterized by challenging mountainous road geometry (i.e., sharp horizontal curves and steep grades) and inclement weather conditions that significantly contribute to crash occurrences.

The proposed location of the test track is studied along the I-80 segments located in Laramie and Albany counties, as shown in Figure 10. The reason relates to the proximity of the UW and WYDOT to the main offices for mobilization and technology transfers, as well as data collection and monitoring. The location of the proposed test track can be investigated by considering practitioners' recommendations. However, various engineering and environmental criteria should be taken into consideration before a decision is made. Some criteria involve different behaviors in a way that combining these criteria may lead to conflicting objectives. For example, some road segments on I-80 may display low-crash rates; however, they are located in mountainous and hilly terrains making the construction more difficult. The Spatial Analyst Tool in Arch -GIS can play a critical role in spatial decision-making to find and map locations that show the best suitability or the most hazardous of particular interest.

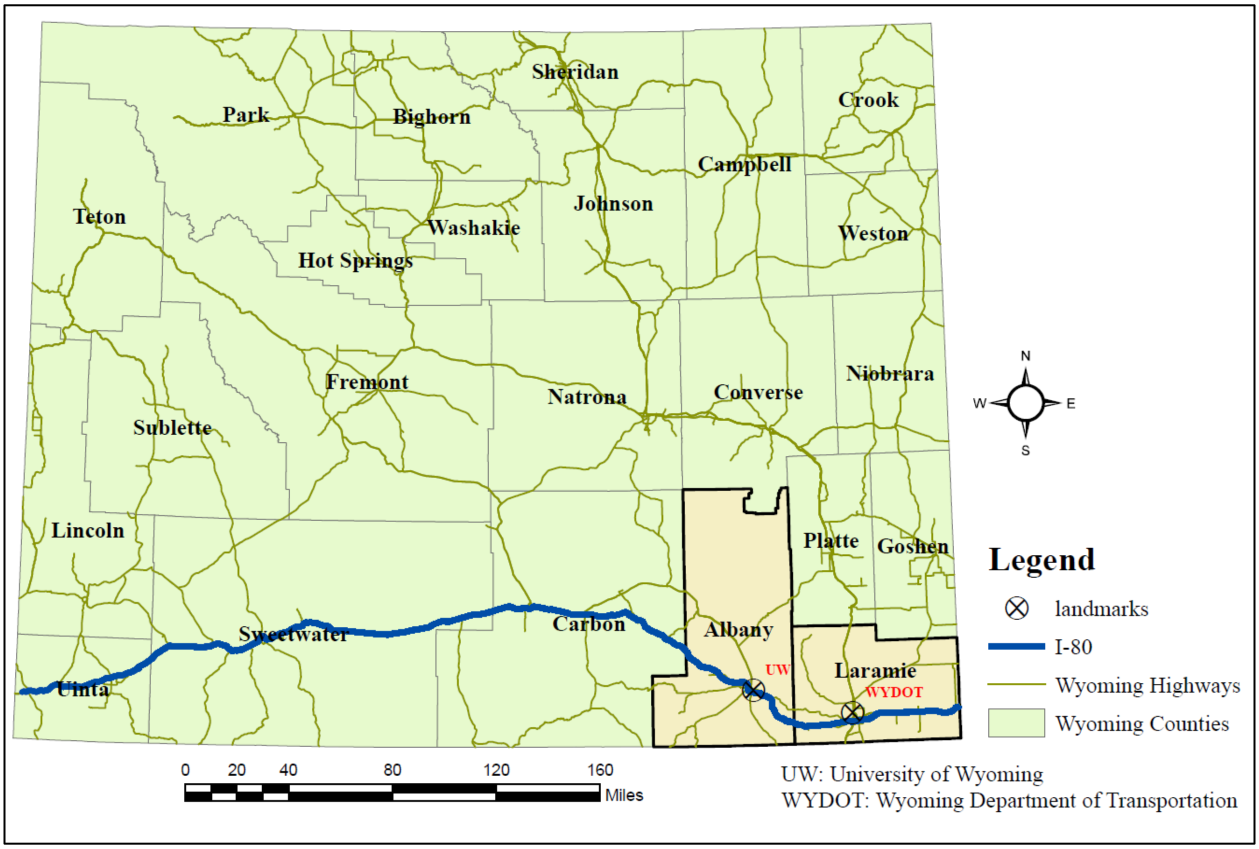


Figure 10. The map of the study area on I-80 in Albany and Laramie counties.

Therefore, the priorities of selecting an appropriate location for the test track are set to identify a flat-level area where cuts and fills are minimized. The site also is to be located on a section of the roadway where there is adequate truck traffic to accelerate pavement damage. In terms of traffic safety, the site is to be located on a portion of the roadway with low crash records over the years. In addition, the right of way must provide sufficient land space for the test road, stockpile sites, office buildings, and parking lot. Finally, the site is also to be located where environmental and social impacts could be minimized. Before, selecting the location, the following section describes the two main conceptual layouts recommended for the proposed test track to get an idea about the length and the geometric features of the test track.

Conceptual Layout

Based on the feedback received from APT practitioners and consultants, two conceptual design layouts are proposed for Wyoming's test track facility as described below.

Full-Stage Test Track

The first option is to adopt a full-stage test track including all the supported buildings, offices, laboratories, and maintenance units. Figure 11 shows a sketch of the full-stage test track. The descriptions of onsite facilities are listed in

Table 4. This strategy will consider more areas for onsite buildings, parking lots, and stockpile areas. The expected total area for this option will be 120 acres.

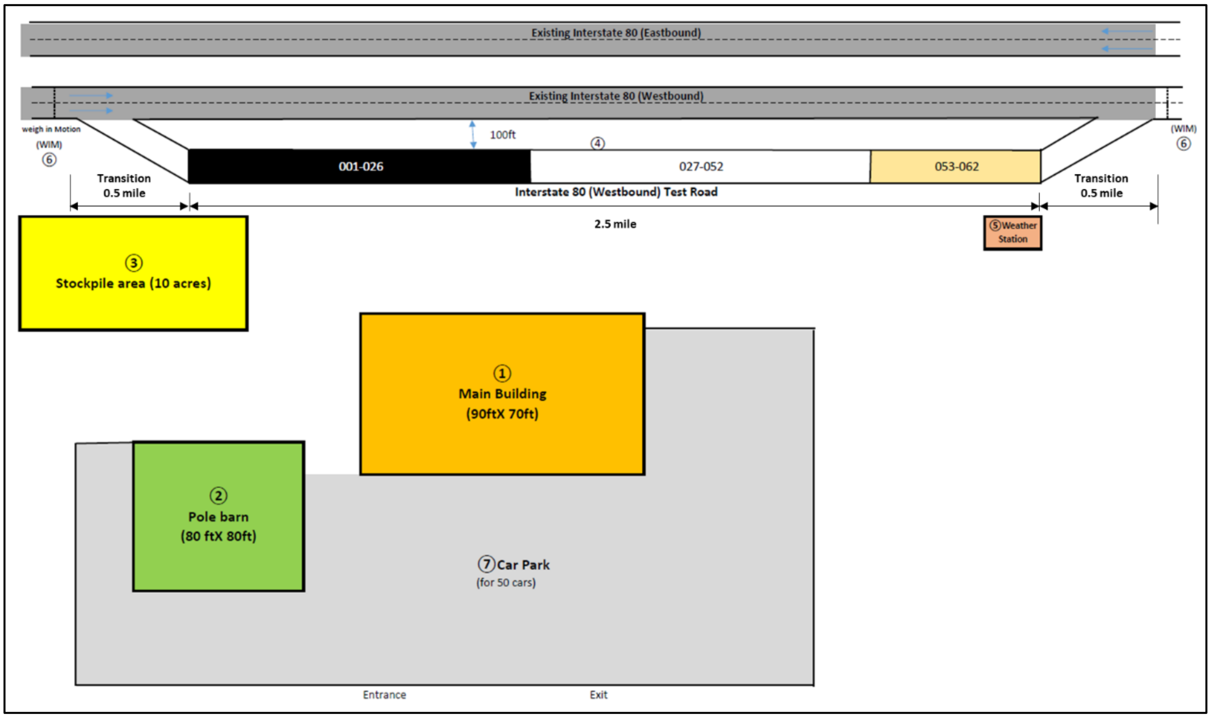


Figure 11. Full-stage testing facility conceptual design on a westbound segment of I-80.

Table 4. Element descriptions of the full-stage test track proposed in Wyoming.

Serial	Element	Description
1	Main building	• Offices for 20 dedicated staff • Washrooms • Conference room (2000 square feet for a capacity of 50 persons) • Breakout rooms • Laboratories
2	Pole barn	• Tool storage • Work area • Sample storage on racks • Parts storage • Equipment storage (e.g., FWD, 3D distress van, etc.)
3	Stockpile area	• Construction and maintenance materials storage area, including aggregates and mix plants.
4	Test track	• Typical I-80 sections of interstate roads (see test section layout)
5	Weather station	• Climate data collection and recording
6	Weight-in-motion (WIM)	• Two WIM stations allow continuous data collection if one of the stations is inoperative or needs calibration.

Based on the feedback received about the best practices, standardized test sections are proposed on the mainline of the test track. Three main test-section groups will be considered: 1) a group for HMA experiments, 2) a group for PCC experiments, and 3) a group for preservation experiments. Each group will consider different designs for both asphalt and concrete pavement depending on the practices followed by sponsoring agencies and the regional research needs. A sketch of the proposed test sections is depicted in Figure 12. The first set of test sections includes the HMA structural experiments. In this set, 26 test sections will be constructed primarily to investigate the different HMS thicknesses, types, and performance. Each test section will have a standard length of 200 feet according to previous experiences and practices on MnROAD. However, sponsors can implement their research projects in multiple sections according to their needs. Other experiments will include two test sections to allow for control cases to be compared with the adjusted conditions of testing asphalt. The second group will include experiments for concrete pavement slabs. According to the literature search for the rigid pavement practices of the states in the dry freeze-zone, most of the experiments will be related directly to the jointed-plain concrete slabs. Therefore, the cost estimates for the concrete testing sections will be conducted considering the bid prices of PCC pavements in WYDOT. The last group will be set up for maintenance and preservation projects. These sections will include different types of pavements and will be distributed along 10 test sections. Each test section will be 225 feet long. When necessary, parts of the existing I-80 and previously designed sections will be used for studying the effectiveness of overlays on existing cracked pavements.

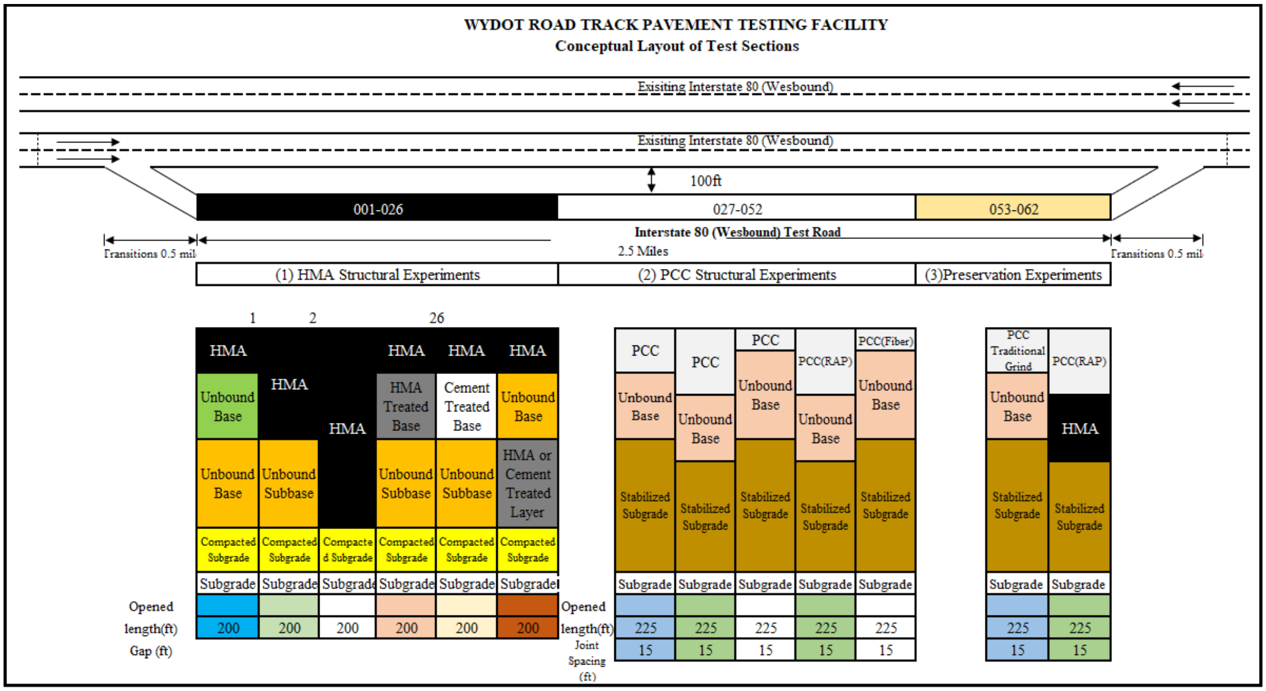


Figure 12. The conceptual layout of the testing sections on the mainline of I-80.

Limited Onsite Buildings

Although the second design layout will include the same testing section groups, the onsite buildings will be limited to reduce the overall costs of construction. The facility will be setup such that data can be monitored remotely from the offices. There will be no full-time staff at the test road. The reduced stage of the test track will also allow for remote operation, data collection, and monitoring. The conceptual layout of the limited-onsite-building strategy is shown in Figure 13. The descriptions of onsite facilities are listed in Table 5. In this strategy, the onsite buildings will include a small building for maintenance and inspection, a storage stockpile area for materials, and roadside data cabinets. Each of the 62 test sections will have a dedicated roadside cabinet equipped with sensors, recording units, and transmitting units to transfer the data collected automatically to a central database.

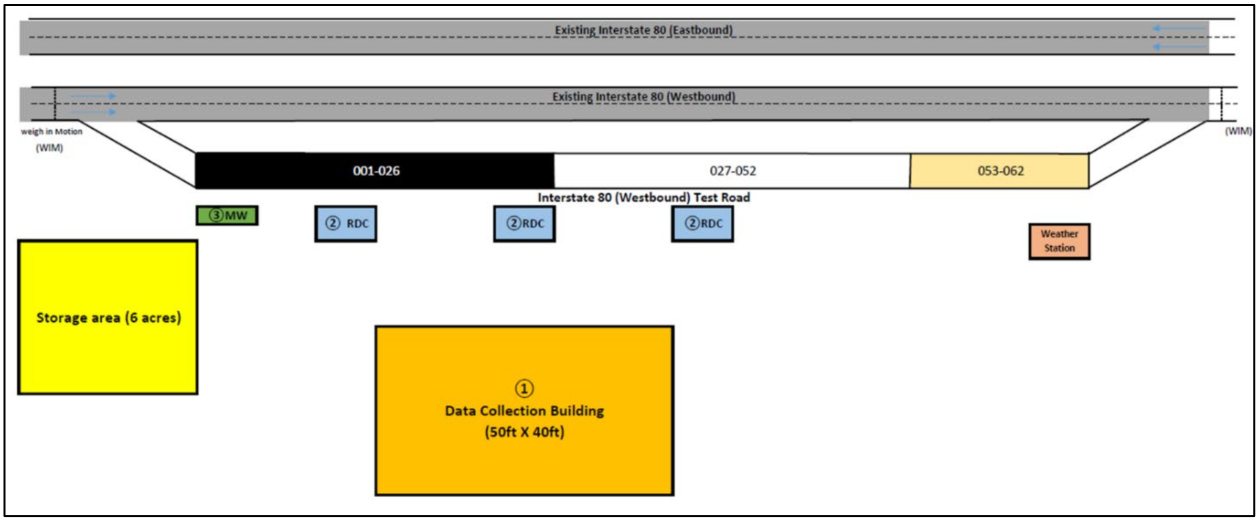


Figure 13. Limited onsite testing facility conceptual design on a westbound segment of I-80.

Figure 14 shows an example of the roadside data cabinet currently sponsored by the Florida DOT for the new concrete pavement test track in Clay County, Florida. A fiber connection will be used to link all the cabinets to the data building located on the south end of the conceptual westbound test road. In addition, a number of monitoring wells will be installed near the test sections where one monitoring well can be used for multiple sections. According to the practices of Florida DOT, the concrete test track is currently provided with four monitoring wells at test sections 1, 21, 27, and 52 to track all the changes in the water table, as demonstrated in Figure 15. The prosed test track can follow similar practices to collect the ground water table data as part of the data acquisition. The expected total area of the limited onsite testing facility will be 90 acres.

Table 5. Element descriptions of the limited onsite testing facility proposed in Wyoming.

Serial	Element	Description
1	Data collection building	• 12-feet by 14-feet communication room • Restrooms • Storage area
2	Roadside data cabinets (RD)	• House for instrumentations of data acquisition • 62 cabinets aligned with the testing section to automatically collect the pavement-related data.
3	Monitoring well	• To monitor the water table underneath the pavement layers of the testing sections.
4	Test track	• Typical I-80 sections of interstate roads (see test section layout)
5	Weather station	• Climate data collection and recording
6	Weight-in-motion (WIM)	• Two WIM stations allow continuous data collection if one of the stations is inoperative or needs calibration.

Figure 14. Florida Department of Transportation Roadside Cabinets (Greene, 2020).

Figure 15. Monitoring well (Greene, 2020).

Methodology: Suitability Analysis

Multi-criteria suitability analysis is used in this study to identify appropriate locations for the proposed facility based on a set of criteria. The overall methodology chart of the suitable location analysis is depicted in Figure 16. In this study, five criteria are considered for the spatial analysis which are slope, daily truck traffic, crash history, active oil wells, and proximity to Laramie and Cheyenne. The data of all criteria along I-80 are spatially analyzed and reclassified into suitability raster data set on a desirability scale from 0 to 5, 5 being the most suitable location. The spatial data is analyzed within a buffer zone of one mile along I-80. Then, all the layers of the different criteria are aggregated considering different weights to generate the overall suitability map. Once appropriate locations are recognized from the spatial analysis, the proposed zones are evaluated with the WYDOT's Right-of-Way (ROW) office to collect more information about the land acquisition and the suitability of the land use. Finally, the proposed locations are further evaluated in the field using Unmanned Aerial System applications.

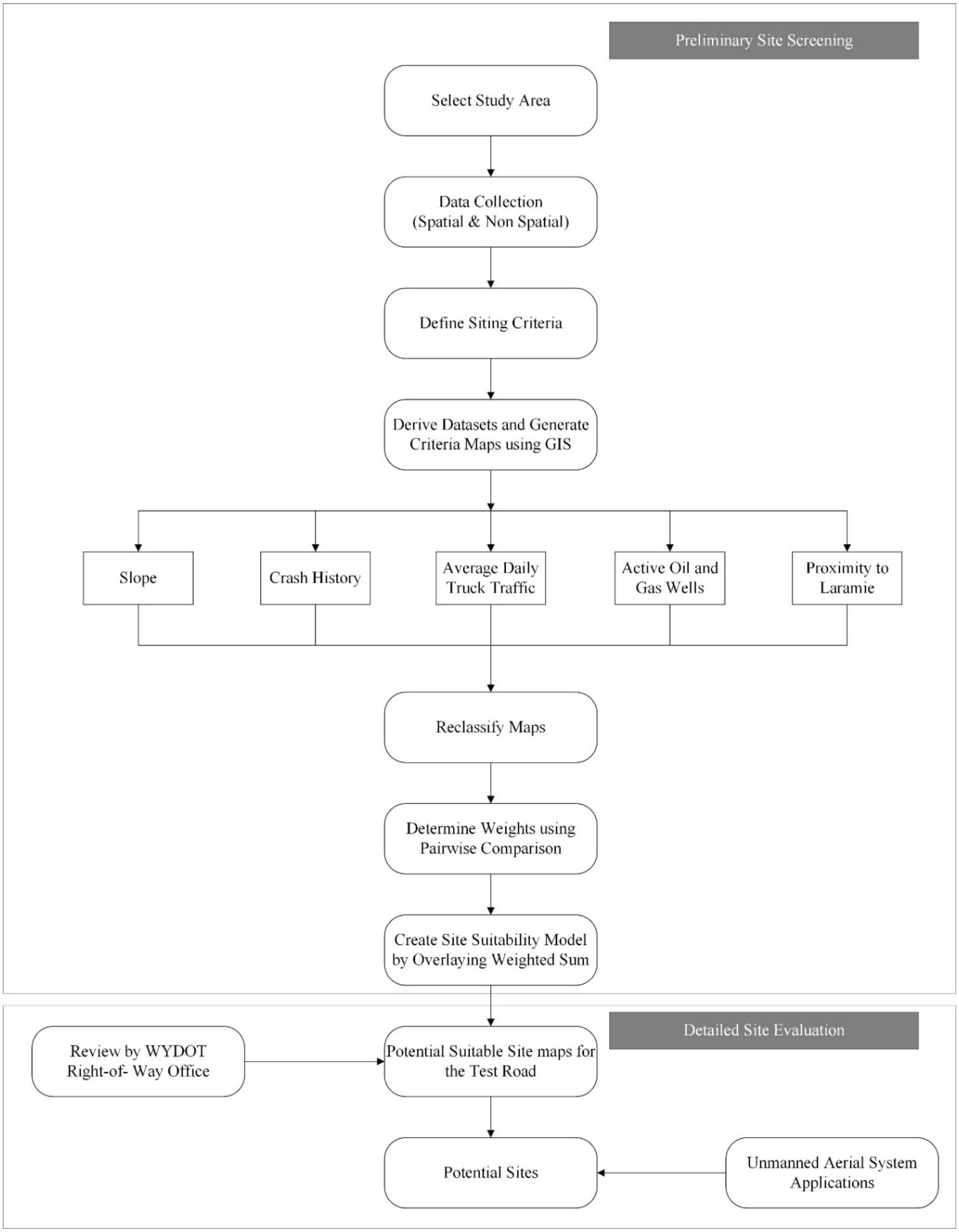


Figure 16. Schematic of the methodology for selecting the suitable locations of the test track.

Decision Making Criteria

The first step in the suitability analysis will be the definition of the problem. In this study, the objective was to find the most suitable roadway segment on I-80 that is almost a 3.5-mile length and characterized by the best combination of engineering and environmental properties. Then, a set of selection criteria will be defined for the proposed test track to maximize the benefits and reduce negative impacts on the roadway system. Five criteria were considered in the analysis. They are discussed in the subsections below.

Land Slope

The land slope is an important criterion in mountainous or hilly terrains. Steep slopes increase the cost of construction arising from cuts and fill. Therefore, the selection of a relatively flat area for the proposed facility is desired. As mentioned earlier in the report, Wyoming is characterized by mountains and high plains, and identifying a flat area is primarily necessary to minimize the volume of earth works for economic reasons. A high weight was placed on this criterion due to the challenging nature of Wyoming's topography. The slopes are generated from the Digital Elevation Model (DEM) of the study area using ArcGIS. Flat and level areas with slopes between 0 and 2 percent are classified with the highest desirability level. Higher slopes correspond to lower desirability levels.

Crash History

Wyoming records one of the highest truck crash rates in the U.S. due to high truck traffic on I-80, adverse weather conditions, and challenging road geometry (Mashhadi et al., 2017; Haq et al, 2020a, 2020b, 2021a, 2021b). Another important criterion was to consider locations without a cluster of crashes to ensure continuous collection of data on the test section without frequent closures due to crash incidents. In this study, five-year crash history data was analyzed from 2015 to 2019. The results are presented using the hotspot analysis in ArcGIS.

Traffic Data

An important component of accelerated pavement testing is the traffic that should provide adequate truck traffic loading to accelerate the damage of the test sections within the study period. The suitable sites for the proposed test track are spatially analyzed using the data of average daily traffic and truck traffic for 2019. The following describes the five levels of desirability for traffic volumes.

- Desirability Level 5: AADT of more than 6500 vehicles per day
- Desirability Level 4: AADT of 6000-6500 vehicles per day
- Desirability Level 3: AADT of 5500-6000 vehicles per day
- Desirability Level 2: AADT of 4000-5500 vehicles per day
- Desirability Level 1: AADT of less than 4000 vehicles per day

Proximity to Laramie or Cheyenne

The desired locations should be within a close distance to either Laramie, where the UW is, or Cheyenne, where the WYDOT office is. This will provide better mobilization to the test track. The location also will be efficient for data monitoring and technology transfer. Both the UW and WYDOT offices will play significant roles in the periodic condition monitoring, sensor measurements, building test sections, and quality control and assurance. To minimize the impact form distant location, the spatial analysis will only be conducted in Laramie and Albany counties.

Active Oil Well

This criterion is mainly considered to reduce the environmental impact of building the test track near active oil well areas. The reason for avoiding active oil wells is that there are high activities of drilling and building the test track could limit the activities of producing oil and natural gas. Hence, the high desirability of the potential location is specified for road segments that are distant from active oil wells. The spatial locations of the active oil wells are inserted in ArcGIS. Then, the desirability raster data are developed using the hotspot analysis.

Multi-Criteria Analysis in ArcGIS

Multi-Criteria Analysis (MCA) is a well-known method to handle land suitability evaluation. In GIS, there are two main methods used. They are briefly described in the following subsections.

Boolean Overlay

The first method is called Boolean overlay that includes only binary codes for the input maps. Then, common Boolean operators are applied to the input maps to define the output. For example, the ‘AND’ operator includes the intersection process. It combines the conditions from input maps that both values must be ‘true’. Other operators can be included in the mathematical formulation such as ‘OR’ for the union process (Gorsevski et al., 2012).

Weighted Linear Combination

In this method, the decision-making criteria are combined with different weights depending on the importance of each criterion. Then, the overall value of suitability is shown on the map with the predefined desirability scale. This method allows a full tradeoff among criteria and provides more flexibility than the Boolean overlay approach (Gorsevski et al., 2012). For the proposed test track, it is impractical to consider the Boolean overlay approach because all segments are expected to have different features. It is very unlikely to find a segment that shows the highest desirability for all criteria. Hence, the input maps of the criteria are weighted to trade off the best location. To come up with an appropriate weighting score for the five criteria, a pairwise comparison method is implemented. In this method, each pair of criteria is ranked where the more suitable (preferable) criterion receives a score of one while the less suitable criterion receives a score of zero. When the two criteria are equally important, a score of 0.5 is assigned to each one. Accordingly, the pairwise comparison is summarized, as shown in Table 6. It is clear that the land slope is the most important criterion (weight = 40 percent) since it has a direct impact on the cost of construction. Traffic safety and traffic volumes are equally important with a corresponding weight of 25 percent in the linear combination of the spatial analysis. Then, proximity and active oil wells are ranked to display the least affecting factors of the proposed locations (weight = 5 percent).

Table 6. Pairwise comparison and corresponding weights for the suitable location criteria.

Criterion	C1	C2	C3	C4	C5	Score	Weight (%)
Land Slope (C1)	-	C1	C1	C1	C1	4	40
Crash History (C2)	-	-	C2C3	C2	C2	2.5	25
Traffic Data (C3)	-	-	-	C3	C3	2.5	25
Proximity (C4)	-	-	-	-	C4C5	0.5	5
Active wells (C5)	-	-	-	-	-	0.5	5
Total						10	100%

Spatial Analysis Results

The weighted linear combination of the predefined criteria is analyzed using the spatial analyst tool on ArcGIS. The results are presented in a cartographic representation. First, the heat map of the crash history on I-80 is shown in Figure 17. The results present the high-risk crash locations that are represented by the Z-score of the statistical significance. Hence, a higher Z-core is an indication of a higher probability of crash occurrence (Manap et al., 2021). The results show that crash hotspots are located in the summit area and near Cheyenne. The majority of segments display low z-scores.

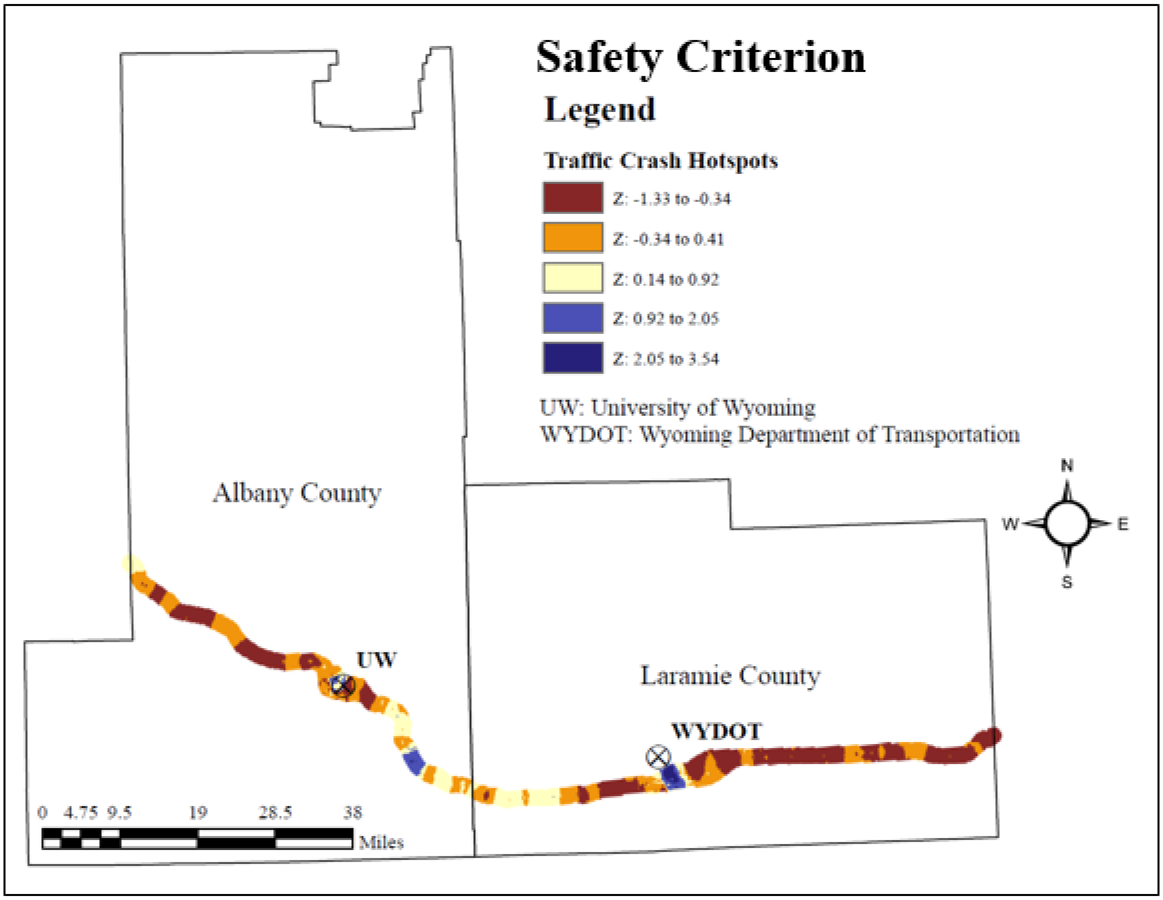


Figure 17. Suitability map of crash hotspots from 2015 to 2019.

Figure 18 shows the suitability data for traffic volumes. The AADT on some segments is missing showing incomplete objects on the map. The results show that the traffic criterion is more favorable in the segments between Laramie and Cheyenne where higher traffic volumes are accommodated by I-80. This can provide more efficient traffic loading for accelerating the damage on the proposed test track.

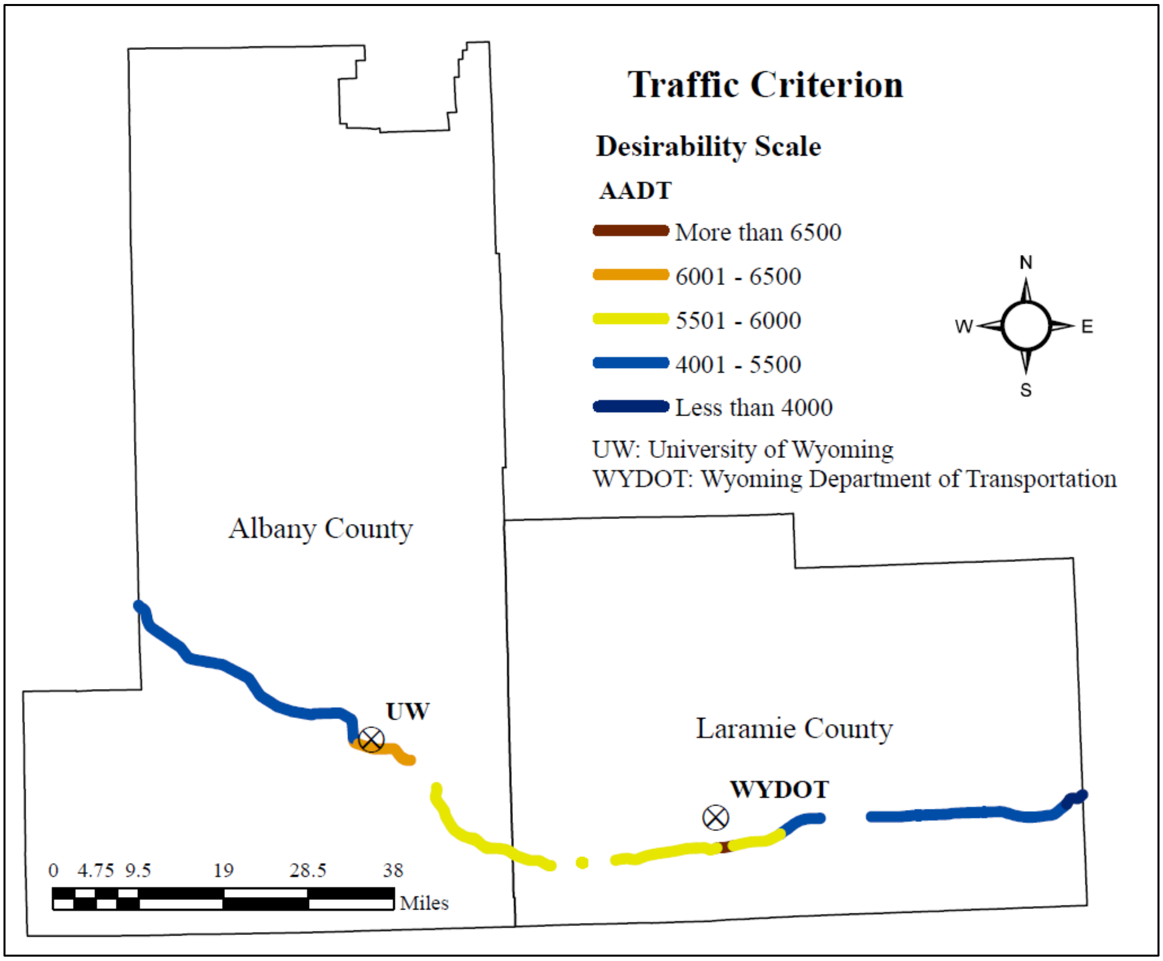


Figure 18. Suitability map of traffic volumes of 2019 Annual Average Daily Traffic.

Figure 19 shows the suitability map for the land topography and corresponding slopes. The least desirable areas are located west of Laramie where the summit is formed with mountainous terrain. The land is almost flat in the western area of Laramie and the eastern area of Cheyenne. Along the corridor between Laramie and Cheyenne, locations show different suitability with different slopes.

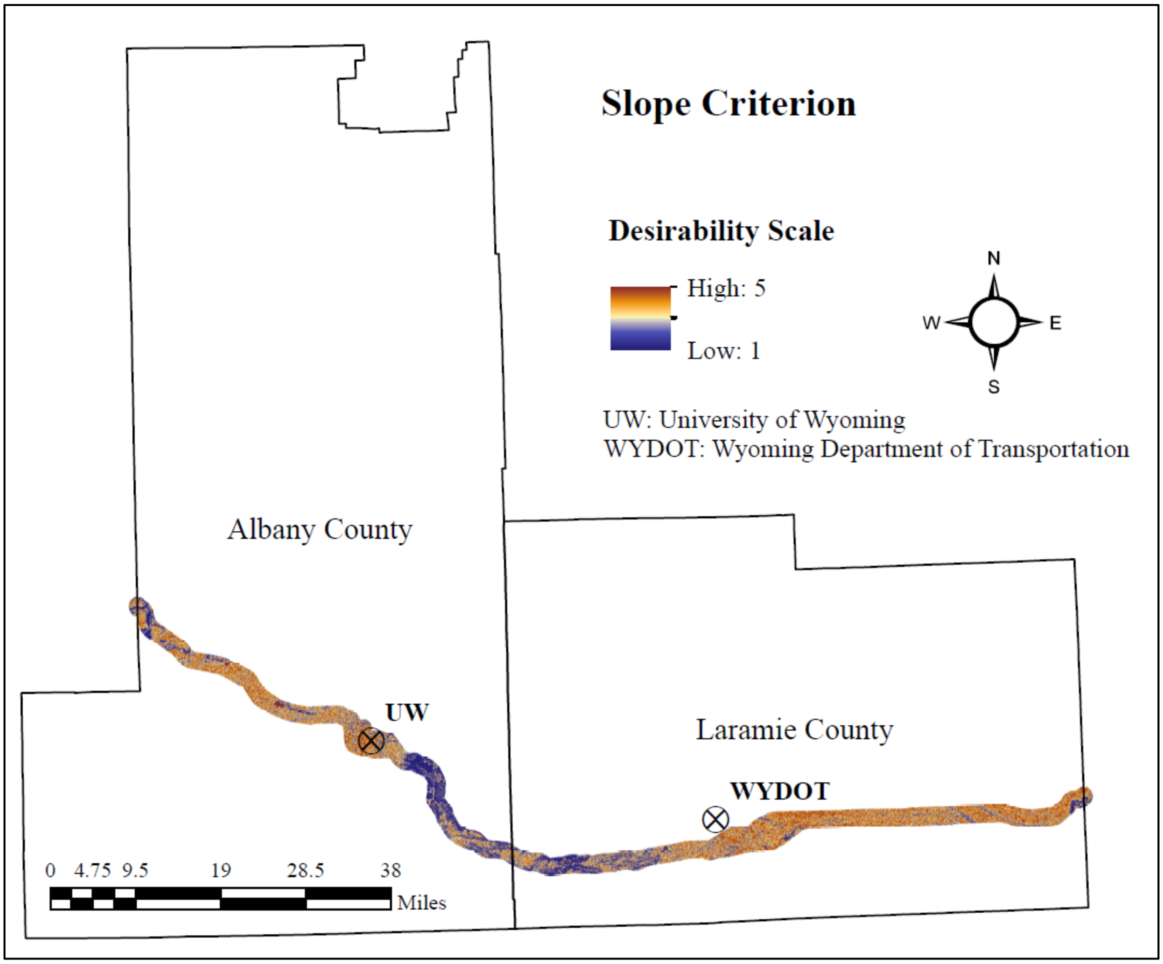


Figure 19. Suitability map of slope criterion.

Figure 20 displays the suitability for the active well sites criterion. Although this criterion is weighted with only 5 percent of the total decision, most locations display high desirability. Few road segments with active oil and drilling activities are found along Cheyenne and its eastern area.

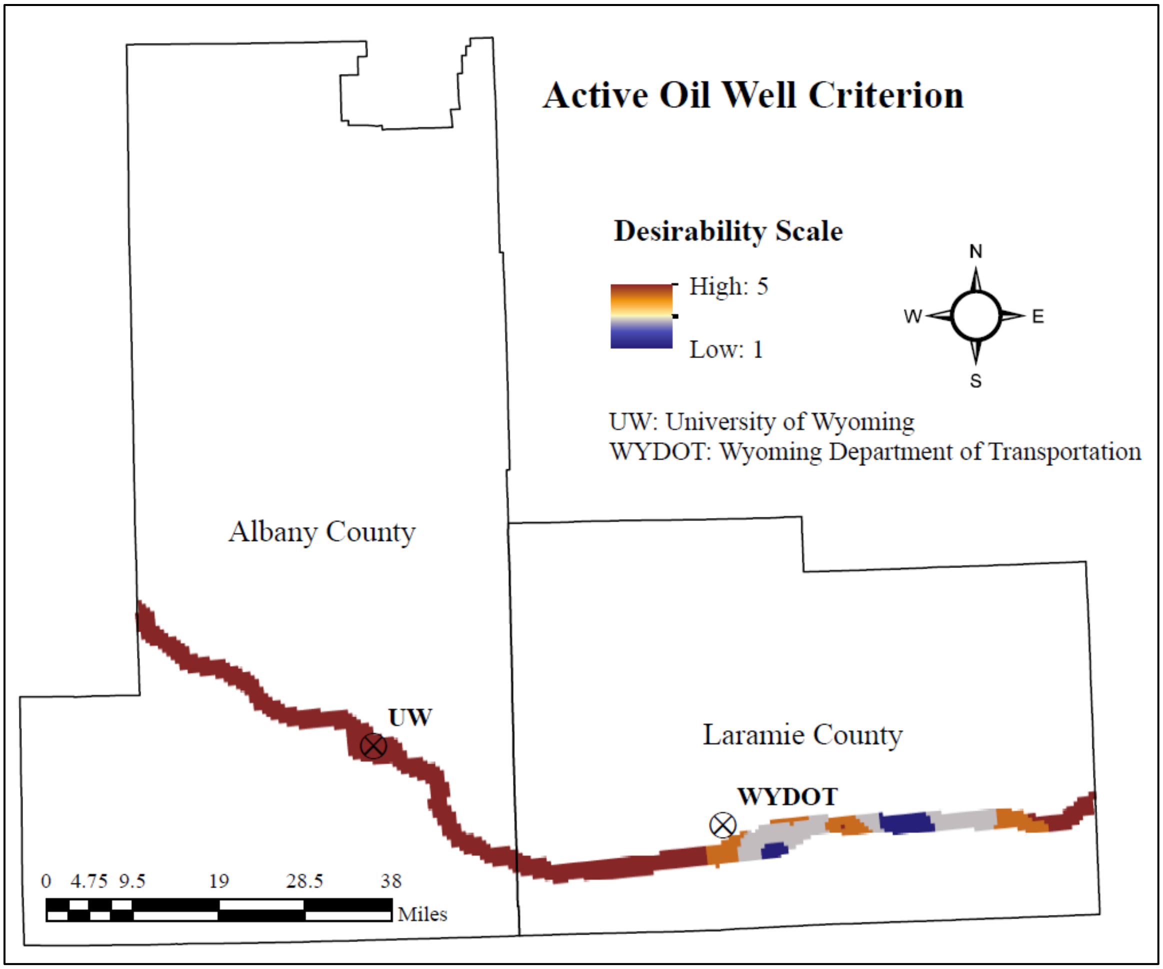


Figure 20. Suitability map of active oil well sites.

The total combined desirability of the proposed location for the test track is mapped in Figure 21. Some locations show a high desirability of optimum conditions for the decision-making criteria. It is almost certain that the proposed test track is not recommended to be constructed along the summit area and in the Cheyenne vicinity. As a result, four main zones are proposed from the spatial analysis of I-80 transportation data. These zones include the highest weighted desirability obtained from the combined decision-making. Other candidates can be obtained from the map; however, it may not be suitable to be proximate to both UW and WYDOT.

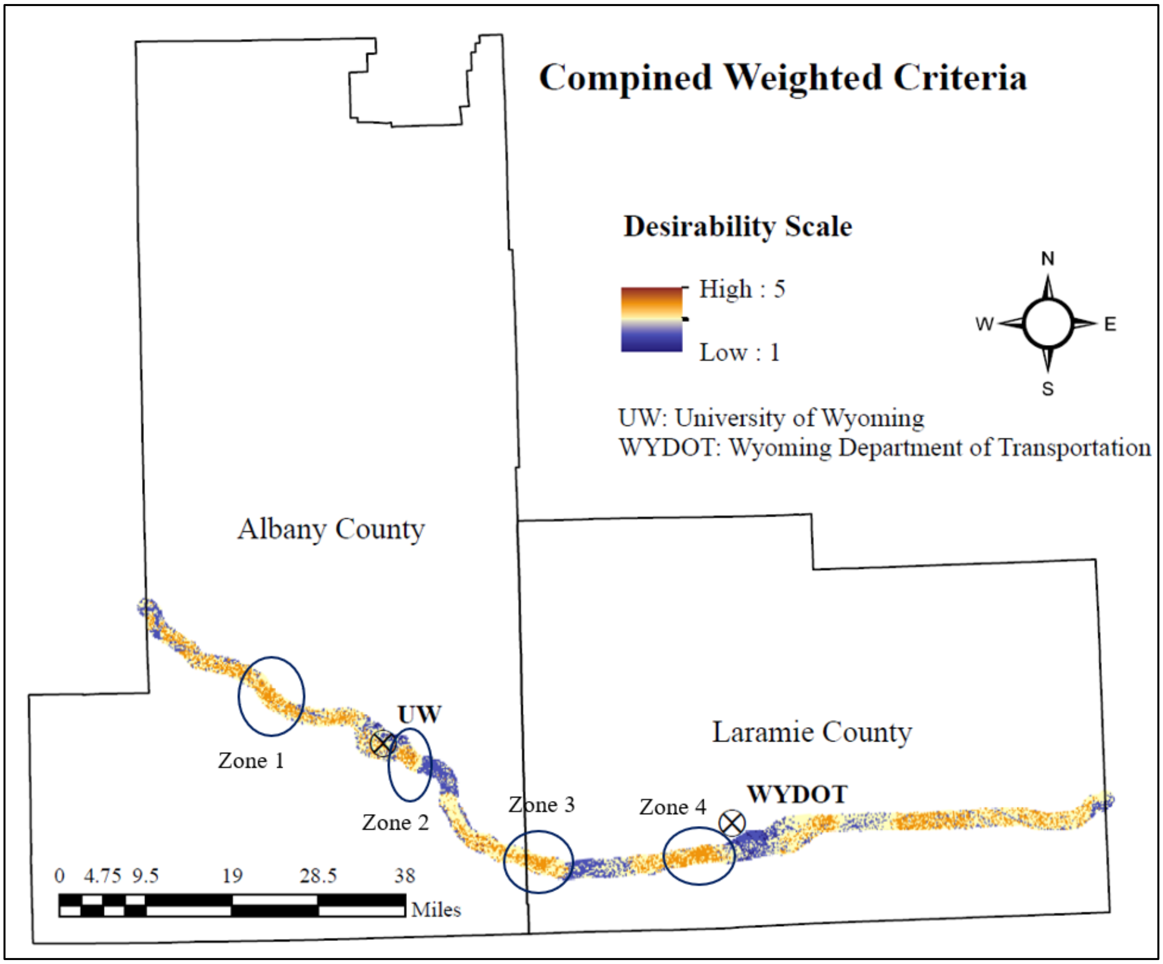
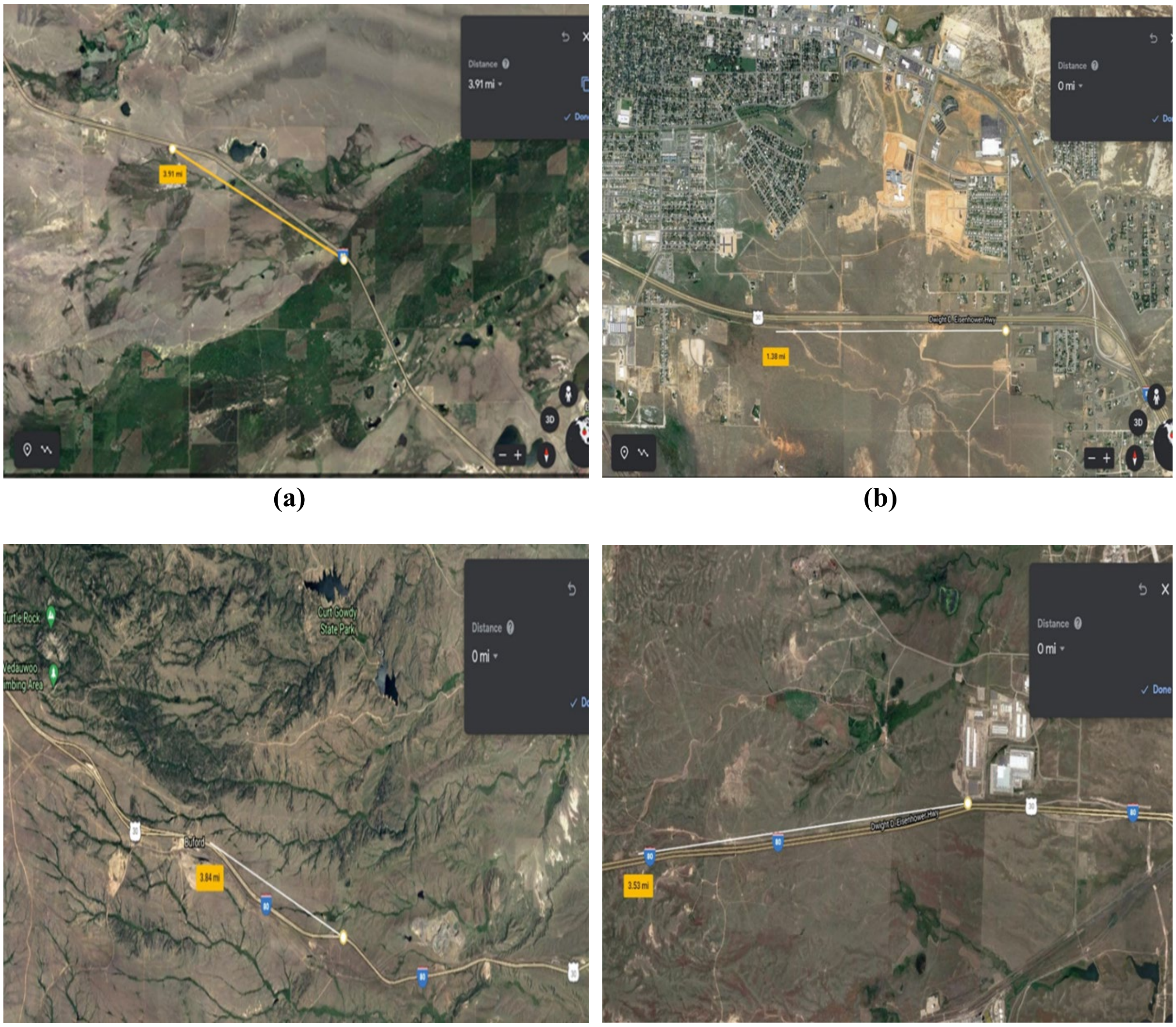


Figure 21. Map of the combined desirability weighted by the decision-making criteria.

The identified zones are verified on the ground with high-resolution satellite images from Google Maps for site reconnaissance, see Figure 22. Using the measuring tool in Google Earth, the 3.5-mile of the main line is simply placed with the current alignment of I-80 to check the suitability of constructing an adjacent mainline test track. It is found that Zone 2 cannot provide a suitable location for the proposed test track since most of the adjacent land uses are residential. The other proposed zones are further investigated to define the pros and cons of each site as listed in Table 7.



(a) (b)

(c) (d)

Figure 22. Google Images of proposed construction zones for the test track: (a) Zone 1; (b) Zone 2; (c) Zone 3; and (d) Zone 4.

(Source: Google Earth modified)

Table 7. Site Characteristics of the proposed construction zones of the test track.

Suitable Zone	Mile Post	Pros	Cons
Zone 1	291.46 to 296.0	• Low amount of earthwork • No cost for bridges or expropriation • No rerouting expected for adjacent roads • Possibility to address culverts • Near to low volume roads (paved and gravel roads) • Close to Laramie (20 min drive from Laramie) • Land value	• Moderate right of way • Pond and seasonal creek • Pipeline
Zone 2	314.6 to 316.11		• Does not provide enough length for the mainline.
Zone 3	335.68 to 339.03	• Low amount of earthwork • Possibility of having two short-span bridges • Close to Laramie (25 min drive from Laramie) • Existence of low volume roads near to the mainline • The land goes through the Bureau of Land Management (BLM) Land and State Land.	• High right of way • Possibility to expropriate • Higher costs for bridges and expropriation • Higher land values • Crosses South Fork Crow Greek • Landowner Willadsen eminent domain history
Zone 4	352.45 to 365.16	• Low amount of earthwork. • Low right of way. • Possibility of having one short span bridge. • No expropriation expected	• Far from Laramie (41 min drive from Laramie) • Higher costs for one bridge • Possibility to reroute some gravel roads • No existence of low volume paved roads near to the mainline • Slightly hilly to some parts

WYDOT's ROW office provided feedback about the current land use, landowners, and value ranges of the locations proposed. Table 8 lists summaries of the feedback received about the expected values of the ROW land acquisition for the proposed test track along I-80. The WYDOT's ROW office proposes an alternative site located almost 7 miles west of Zone 4 (Mile Post: 341-346). This area encompasses an almost 8,800-acre parcel size with agricultural land use. The alternative location displays the city and private ownership with a land value ranging from $254 to $1,530 per acre. This location also shows the pros and cons. Although the cost of land acquisition could be low, the location is hilly and can cost more for the earthwork. Overall, Zone 4 is found to be the most recommended location considering the spatial analysis and the WYDOT's ROW feedback. This zone is further investigated using field evaluation.

Table 8. The Feedback about the land value from the WYDOT's ROW office.

Zone	Current Land Use	Parcel Size	Est. # of Landowners	Notes	Value Range
1	Ag - Pasture	68 - 3920 acre	2-4	Pipeline on topo map south of I-80	•$475-$936/acre on the 3920-acre parcel •$3k-$5k/acre on the 68 acres •commercial/industrial land at exit 290
3	Rural residential, Ag	20 - 3341 acre	8-10	Union Pacific Railroad (UPRR) south of interstate	•$1150 - $2000/acre
4	Ag - Pasture	1,7360+ acres and 5,688 acres	1 (King Ranch)	Multiple oil sites	•$257.00- 1,529.6 per acre

Field Evaluation Using Unmanned Aerial Systems (UAS)

The implementation of UAS has become a viable alternative to the traditional method of surveying sites. The Unmanned Aerial Vehicle (UAV), commonly known as a drone, is applied in this study to provide high-quality survey and aerial photography allowing for a better-informed bird's eye view of the project area speedily. The UAS also provides access to hard-to-reach areas of the project location. Moreover, it allows large areas to be surveyed and mapped quickly compared to the traditional method of surveying (Albeaino and Gheisari, 2021). UAVs are lightweight and easy to transport from site to site. Consequently, the approach saves time, energy, and cost involved in surveying a large area. The 3-D model of the surveyed area is developed using the main techniques of photogrammetry. Photogrammetry combines images that contain the same point on the ground from multiple views to yield detailed 2D (dimensional) and 3D maps. These maps can also be used to extract information, such as highly accurate distances or volumetric measurements.

In this study, a demonstration of using drone surveying was conducted in the proposed location of Zone 4. The first step was to define the grid required for the data points. The grid was set along a strip with a 500-foot wide and one-mile long adjacent to the westbound segment on I-80 (approximately Mile Post 354.2 to 355.2). The number of photos taken for photogrammetry depended on the level of detail required. These images were "georeferenced," which means that the drone tags each picture it takes with location data based on the GPS position of the drone. Also, the photo points need to be set to achieve at least 75 percent vertical overlap and 60 percent horizontal overlap. All of these recommendations were set in the drone before taking off as shown in Figure 23.

Figure 23. A licensed operator controlling the drone remotely in the proposed location on I-80.

The points cloud was stored and then processed using Pix4D software. The processing engine uses the overlapping part of adjacent photos to estimate the third dimension and create the 3D model. In addition, aerial photos and videos were obtained from the demonstration to have a preliminary overview of the surveyed location and define potential obstacles. Figure 24 shows the aerial photos taken at an observation point along the westbound segment of I-80 in Zone 4. The topography of the terrain looks relatively flat with slightly hilly locations. Also, the power poles are found to be aligned with I-80 making the ROW relatively short. This indicates that relocating the power lines can be considered if Zone 4 was selected for constructing the test track.

The results from Pix4D are shown in Figure 25. The point cloud was processed to render the 3D digital map of the proposed location. Several benefits can be achieved from the developed model. First, the 3D model provides a useful 3D reference to monitor and inspect the potential location in great detail. Also, the accuracy of the 3D model developed considering referenced points can help planners calculate distances, areas, and volume of the different parts along the I-80 for better decision-making. The 3D data from Pix4D mapper outputs can then be used in GIS, AutoCAD Civil 3D, or Google Earth for vertical alignment of the mainline and earthwork calculations.

(a)

(b)

Figure 24. Aerial photos of the surveyed location in Zone 4: (a) the east side of observation point; (b) the west side of observation point.

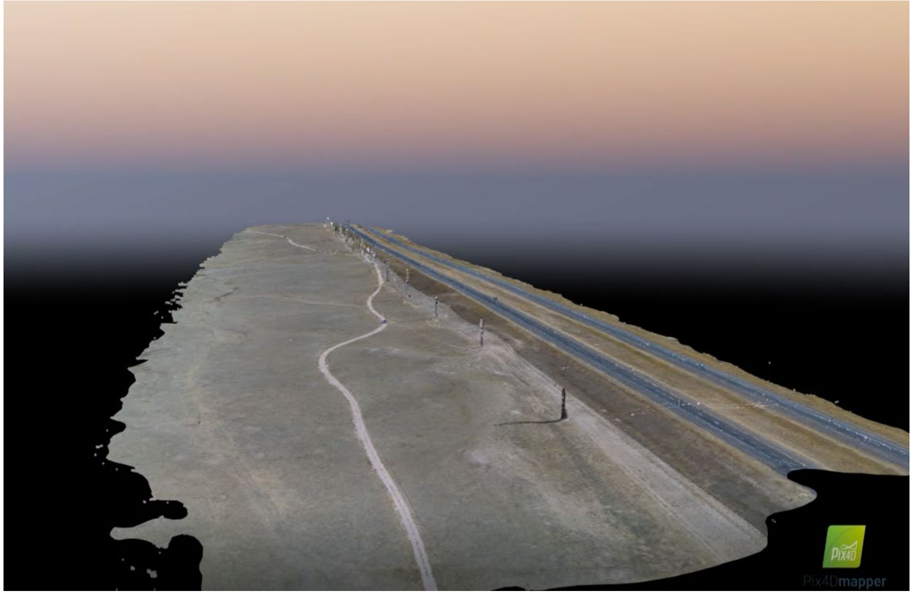


Figure 25. The 3D digital map created on PIX4D software of the proposed test track location in Zone 4.

CHAPTER 4: BENEFIT-COST ANALYSIS

Background

The economic assessment of the APT program is necessary to address funding issues, increase accountability, and encourage partnership. The economic benefits to potential partners are presented in the form of a benefit-cost ratio (B/C). The B/C is a key indicator of the overall return on investment in the proposed test track in Wyoming. The economic evaluation of APT programs has become a major topic for the past decade and was made the theme of discussion during the Third APT conference (Jones et al., 2012; Steyn, 2012). The attempts at performing the economic assessment of APT programs are attributed to the need to justify the benefits of APT research in the midst of general international economic constraints. Often, it takes years for the implementing agencies to realize the actual benefits (Choubane and Greene, 2019).

The benefit of the APT program involves identifying, analyzing, and quantifying the direct and indirect benefits of the program. However, assessing the economic benefits of any research program can be a difficult task (Choubane and Greene, 2019). The assessment involves uncertainties and subjectivities as the benefits associated with the research development need to be compared with the "do-nothing" scenario (Rose and Bennett, 1994). Additionally, not all projects run as intended in the initial years. To address these issues, some authors used deterministic and probabilistic life-cycle cost analysis (LCCA) with sensitivity analysis to assess the benefits of research programs. Several authors have used the fuzzy logic-based LCCA to make engineering decisions and proved effective (Chen et al., 2004; Bagdatli, 2018; Chen and Flintsch, 2007). During the feasibility stage of the proposed test track in Wyoming, both deterministic and fuzzy approaches with sensitivity analysis are conducted to provide a comprehensive framework to determine the economic benefit-cost impacts considering the LCCA of the test track (Fosu-Saah et al., 2022).

Methodology: Benefit-Cost Analysis

The economic evaluation begins with identifying the objectives of pavement research programs. It is assumed that the objectives of the pooled fund studies for the first phase will focus basically on the following items:

- Calibrate pavement design (e.g., mechanistic-empirical pavement design)
- Improve pavement material specifications (e.g., base, subbase, and surface layers)
- Improve pavement performance
- Improve maintenance and rehabilitation practices

Based on the experiment deliverables of the test track, several benefits are expected to be achieve, including the following:

- Savings in asphalt binder grade
- Refinement of MEPDG for flexible asphalt pavements

- Refinement of MEPDG for rigid concrete pavements
- Improvement in crack performance of pavements
- Improvement in overlay performance
- Increased service life of pavements

The two approaches to economic evaluation are described below.

Deterministic Approach

The method involved in the determination of the B/C using the deterministic LCA is introduced in Figure 26. Despite the uncertainty of some information under the deterministic approach, the economic evaluation of the proposed APT program assumed benefits and cost values considering literature assumptions, conservative, and subjective judgements. In addition, a sensitivity analysis is conducted to minimize the uncertainty in funding availability by conducting different scenarios of Federal and state funding.

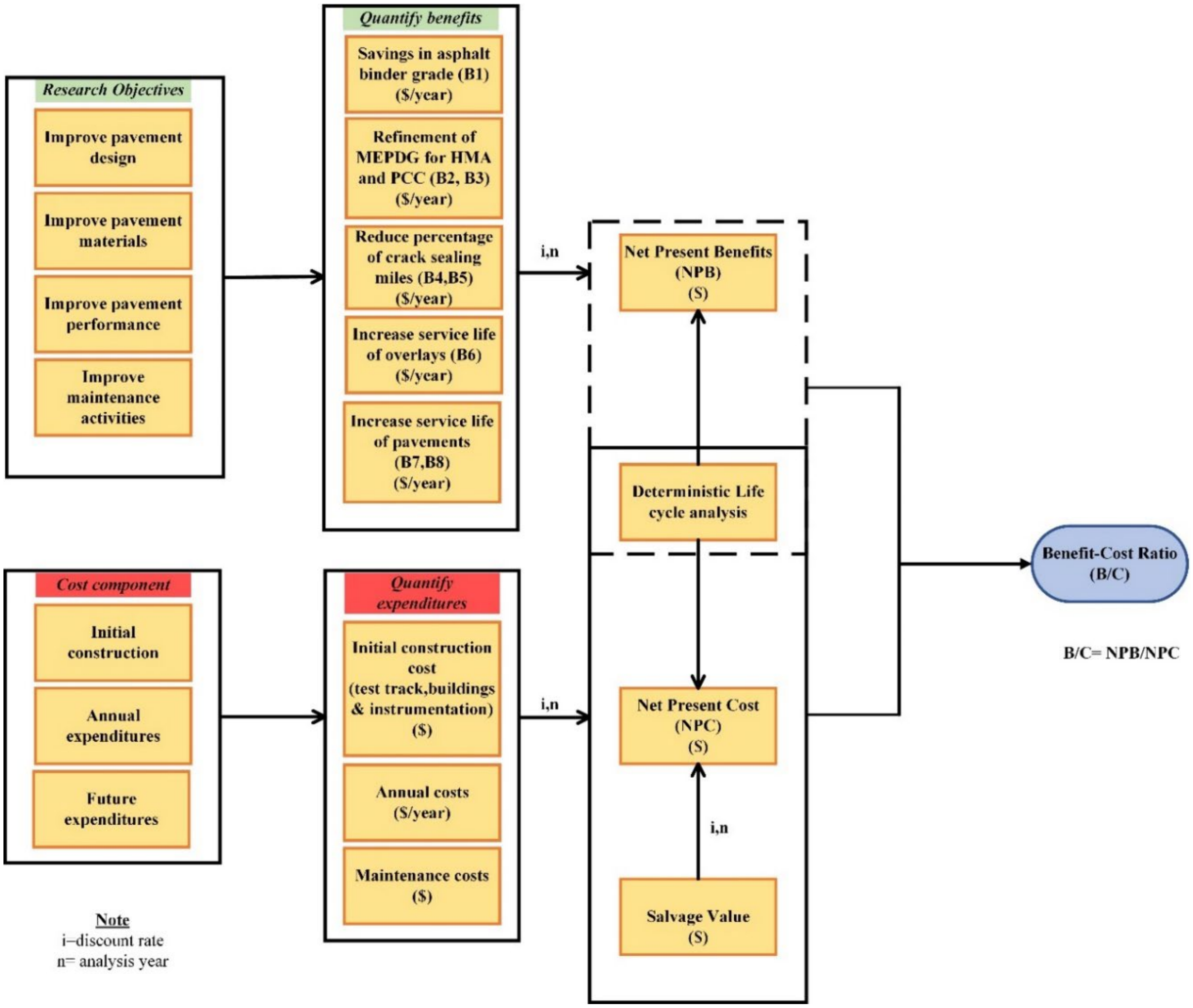


Figure 26. Schematic diagram of deterministic benefit-cost analysis.

The individual benefits listed in Figure 26 are explained in the following subsections.

Savings in Asphalt Binder Grade (B1):

Research findings can result in savings in the selection of performance grading (PG) binder products. A study on the performance of asphalt binder grades in wearing and binder courses in-service is likely to result in cost-effective asphalt selection and design. In other words, findings from the test track are expected to calibrate the performance of the binder under representative climate conditions. This will lead to the selection of more precise products of PG grade and reduce the overestimated PG products due to uncertainty in pavement performance. The expected direct benefit from binder selection is calculated using the relationship in Equation 1.

$$\boldsymbol{B_1 = Benefits\ (B_{PG}) = \nabla C_1 * Q} \tag{1}$$

where, B_{PG}= benefits in PG grading, $\Delta \mathrm{C}_1$ = differences in binder cost (\$), and Q = Average quantity of asphalt consumption (ton/year).

Refinement of MEPDG for flexible asphalt pavements (B2):

MnROAD found that pavements in Minnesota were more conservative, over-designed, and costly. Subsequently, the MnPAVE software developed from MnROAD findings saved the state almost \$2.2 million annually due to reducing pavement thicknesses by 1-1.5 inches (Worel et al., 2008). Similar benefits are expected from the test track in Wyoming. Research findings from the regional facility are expected to calibrate the pavement performance with layer design inputs that would lead to more precise and reduced thicknesses. The savings in asphalt thickness are calculated using Equation 2.

$$\boldsymbol{B_2 = HMA\ Benefits = L_{HMA} * Q_{saving} * C_2} \tag{2}$$

where, L_{HMA} =average mileage of new HMA construction per year (miles), Q_{saving} = quantity of HMA saving in (ton/mile), and C_2 = HMA unit cost per ton in dollars.

Refinement of MEPDG for rigid concrete pavements (B3):

Benefits like those obtained from flexible pavement are expected from the refinement of MEPDG for rigid pavements from the pooled fund studies. The cost savings can be calculated using Equation 3.

$$\boldsymbol{B_3 = PCC\ Benefits = L_{PCC} * A * C_3} \tag{3}$$

where, L_{PCC} = average mileage of new PCC construction per year, A = area (square yard/mile), and C_3 = differences in thickness cost per square yard per mile.

Improvement in crack performance (B4 and B5):

Research findings from pavement testing can reduce low-temperature cracking by 10 percent (Worel et al., 2008). Low-temperature cracking is a major distress of pavements in the dry-freeze region. It is expected that findings from the proposed test track on low-temperature cracking would result in pavements with improved resistance to low-temperature cracks. Consequently, budgets used for crack sealing will be reduced and savings will be realized for the agencies. The expected benefits for both HMA and PCC pavements are determined using equations 4 and 5, respectively.

$$\boldsymbol{B_4 = HMA\ Benefits\ =\ L_{HMA}^{S} * (10\%\ reduction\ in\ crack\ mile) * C_4} \tag{4}$$

$$\boldsymbol{B_5 = HMA\ Benefits\ =\ L_{PCC}^{S} * (10\%\ reduction\ in\ crack\ mile) * C_5} \tag{5}$$

where, L_{HMA}^{S}, L_{PCC}^{S}= average mileage of crack sealed per year (percentage of road network size) for HMA and PCC respectively, and C_4, C_5= cost of crack seal per mile in dollars for HMA and PCC respectively.

Improvement in overlay performance (B6):

Findings from pavement preservation studies using APT can increase the service life of overlays by 10 percent due to the improved designs (Worel et al., 2008). It was assumed that part of the pooled fund studies will focus on the performance of overlays. Implementation of research findings can recognize savings in rehabilitation costs due to the extended service life of overlays. The net present benefits were calculated using the life cycle analysis of overlays using Equation 6.

$$\boldsymbol{B_6 = Equivalent\ Annual\ Benefits\ of\ HMA\ Overlay\ Savings\ =\ C_6 * L * \left(\frac{i*(1+i)^{N}}{(1+i)^{N}-1} - \frac{i*(1+i)^{1.1N}}{(1+i)^{1.1N}-1}\right)} \tag{6}$$

where, C_6 = cost of HMA overlay per lane mile per unit thickness, L = annual average length of overlays (miles), N = average service life of overlays (years), and i = discount rate.

Increased service life of new construction (B7 and B8):

Pooled fund research findings can increase the service life of pavements by 20 percent for new construction based on similar assumptions made at MnROAD (Worel et al., 2008). The APT findings will give a better understanding of pavement behavior and failure mechanisms in the region. It is anticipated that research on pavement performance will possibly lead to improved material selection, design, and construction. This will lead to building resilient flexible pavements with extended service life. The expected savings are determined using equations 7 and 8.

$$B_7 = HMA\ Savings\ =\ C_7 * L * \left(\frac{i * (1+i)^N}{(1+i)^N - 1} - \frac{i * (1+i)^{1.2N}}{(1+i)^{1.2N} - 1}\right) \quad (7)$$

$$B_8 = PCC\ Savings\ =\ C_8 * L * \left(\frac{i * (1+i)^N}{(1+i)^N - 1} - \frac{i * (1+i)^{1.2N}}{(1+i)^{1.2N} - 1}\right) \quad (8)$$

Where, C_7, C_8= average cost of pavement construction per lane mile per unit cost for HMA and PCC pavements respectively, L = annual average length of new construction (miles), N = average service life of new pavements (years), and i = discount rate.

Cost Estimates:

At this stage of the benefit-cost analysis, most of the cost estimates are derived from previous experiences, such as reported data from MnROAD. Then, values were adjusted considering inflation from the 1990s-dollar amounts. The cost components are described as follows:

- Initial construction costs include building the test track facility and installation of sensors and other devices. The construction cost of the test track is estimated to be $46.5 million, and it covers design, ROW acquisition (ROW), environmental impact assessment, and construction of buildings and test sections. This amount was estimated from the construction costs of MnROAD in the 1990s adjusted by inflation.
- Annual costs include labor, operating (overheads), and research. Additionally, operating costs (overheads) that include office administrative charges, utilities, and maintenance of sensors are estimated. The estimated cost of research studies per year and the future cost of rehabilitation of the test tracks are also determined.
- Lastly, the salvage value of the test track is determined as a ratio of the remaining service life of the test track.

Fuzzy Logic Approach

Fuzzy systems provide knowledge-based models to solve logical problems using fuzzy set rules. The methodology utilized in this study is based on the components and general architecture of the fuzzy logic system shown in Figure 27. First, the crisp input variables include the annual costs of operations, initial construction costs, maintenance costs, etc. The input variables are based on the results of the deterministic approach. Second, fuzzification involves converting crisp quantities to fuzzy sets. The conversion to fuzzy sets is done using fuzzy linguistic variables, fuzzy linguistic terms, and membership functions. The imprecision of the data comes from several sources, including the expected level of regional states' participation and implementation, cash flow, discount rates, etc. These imprecisions can be represented by the membership function. The membership value was assigned using the intuition approach. The inference process converts the fuzzy input values to fuzzy output values. The set of rules is defined on linguistic terms based on the linguistic variables of the crisp inputs and outputs. Finally, defuzzification involves the conversion of fuzzy sets back to a crisp single value. This is necessary because the fuzzy set output cannot be used for further processing and applications without relevant conversions to single and meaningful values. There are various defuzzification methods followed.

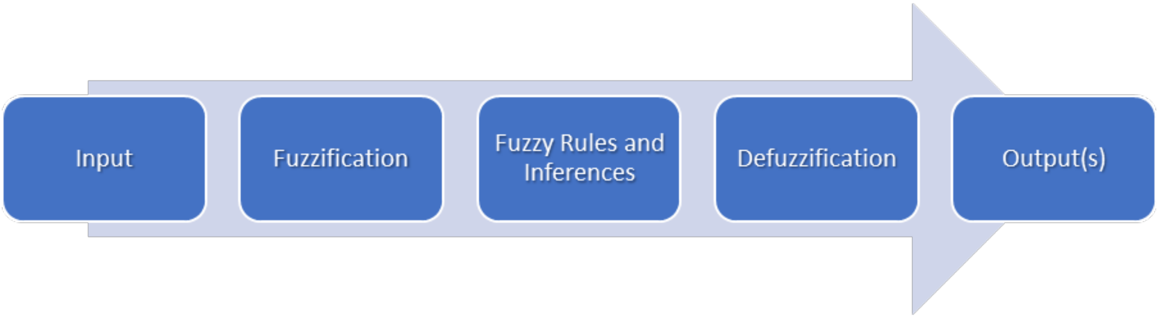


Figure 27. General architecture of fuzzy logic.

This study uses the trapezoidal fuzzy number to characterize fuzzy measures of linguistic value because the trapezoidal fuzzy number (TpFN) is easy to use and interpret during economic analysis (Wang and Liang, 2007). The trapezoidal membership function is denoted by A = (c, a, b, d). The interval [a, b] has the maximal grade of fA(x), i.e. fA(x) =l, x ϵ [a, b] and it represents the most possible value of the assessment data. The “c” and “d” are the lower and upper bounds of the assessment data, and they can be used to represent the fuzziness of the data. If c=a and b=d, [a, b] becomes the tolerance interval of the measurement. More information about trapezoidal function is published elsewhere (Wang and Liang, 2007).

For example, in this study, the fuzzy discount rate ($\tilde{i}$) is “approximately four percent” and can be represented by the fuzzy soft set of (3.6, 4, 4, 4.3). In this situation, it becomes a triangular fuzzy number, which is a special case of a trapezoidal fuzzy number. Further, the analysis period of 10 years is represented by a fuzzy soft set of (9, 10, 10, 11). Testing on the proposed APT facility is projected to begin two years after the facility has been built and represented as (1.5, 2, 2, 2.5) in the fuzzy environment. For a non-fuzzy number “a”, it can be represented by (a, a, a, a).

Benefit Cost Ratio

The overall benefit/cost ratio of the estimated economic benefits is presented in both deterministic and fuzzy formats.

For the deterministic approach, the net present (NB) values of benefits and costs are shown in equations 9 and 10, respectively.

$$\text{NPB} = \sum_{t=1}^{N} B_t * \frac{(1+i)^{n_t} - 1}{i * (1+i)^{n_t}} * \frac{1}{(1+i)^y} \tag{9}$$

$$\text{NPC} = \sum_{t=1}^{N} C_t * \frac{(1+i)^{n_t} - 1}{i * (1+i)^{n_t}} * \frac{1}{(1+i)^{y}} \qquad (10)$$

where, B_t= annual benefits (\$), C_t= annual cost (\$), n_t= time of each annual benefit and cost (year), i =discount rate, N = analysis period (assumed to be 10 years for this study), and y = time period to the start of experiments (assumed to be 2 years for this study).

For the fuzzy logic approach, the fuzzy B/C ratio is based on equivalent uniform annual benefits and the associated costs. A tilde "~" is placed above a symbol if the symbol represents a fuzzy set.

Dry-Freeze States Statistics

The size and pavement type of the national highway system (NHS) and the material prices of states were considered in valuing the expected benefits. Figure 28 shows the mileage of the national highway system (NHS) in terms of pavement types in the region. The results show that flexible pavement is the most common pavement in the dry-freeze region. This proposes that most of the potential pooled fund studies may focus on flexible pavements. However, composite pavement recorded the least among the states.

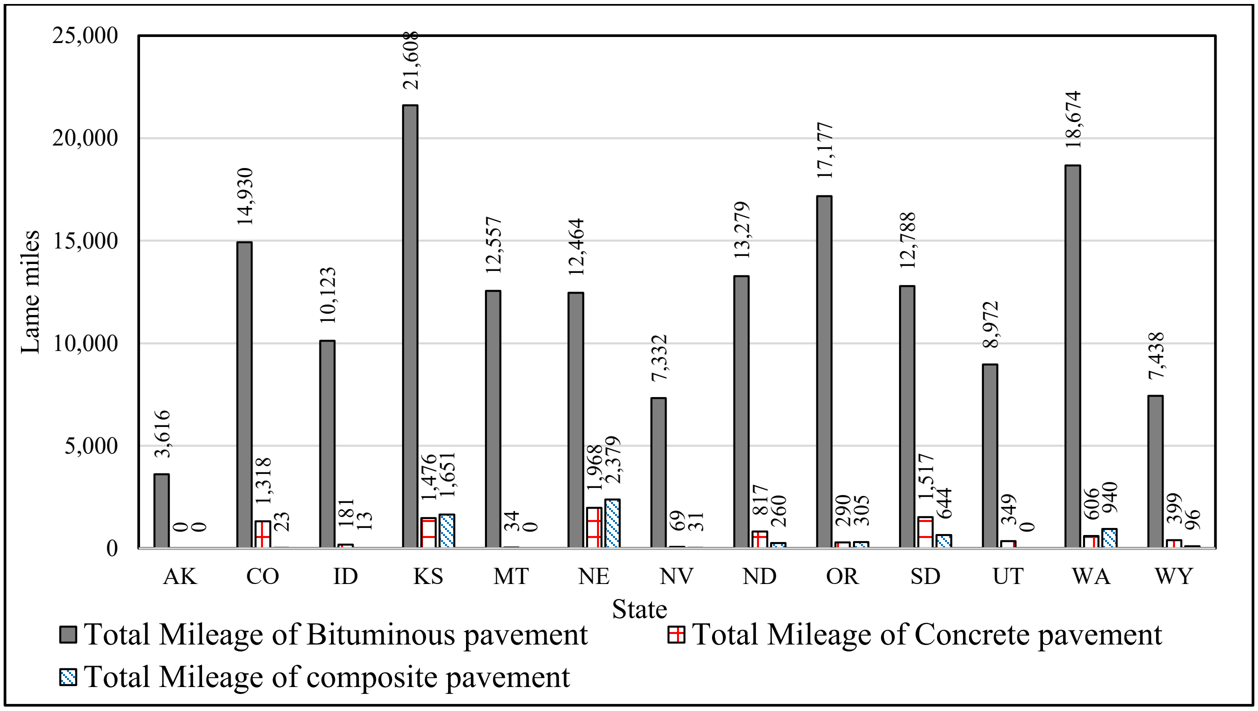


Figure 28. Total reported mileage of NHS (FHWA, 2018).

The consumption of HMA by the states in 2017 is shown in Figure 29. It was used as a benchmark to calculate potential savings in the PG binder. The expected binder savings would be made due to improved cost-effective binder selection. Washington state (WA) recorded the highest estimated consumption of HMA while South Dakota (SD) recorded the least. Thus, WA has the potential to make the highest savings in binder usage if this consumption trend remains the same during implementation. On the other hand, SD may make the least savings though significant in dollars.

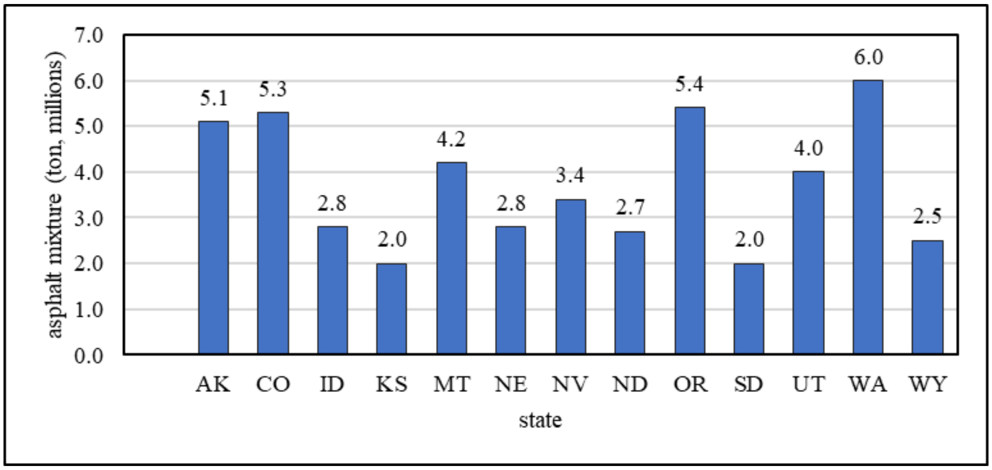


Figure 29. Summary of HMA consumption (NAPA, 2020).

The estimated discount rates are also reported and used for each individual state in the dry-freeze zone, as shown in Figure 30.

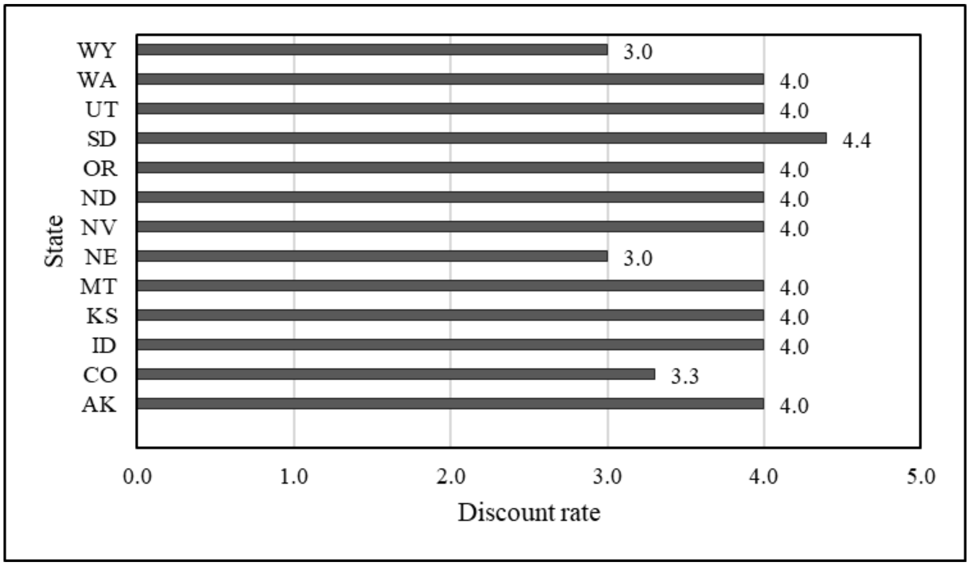


Figure 30. Discount rate of states (West et al., 2013).

Funding Scenarios

Since APT facilities require a significant investment in infrastructure and management, the collaboration between different partners is essential to ensure the cost-effectiveness of operating the regional pavement research. Consequently, FHWA and industry have sponsored several research funding operations of test tracks in the U.S. It is anticipated that FHWA and industry will contribute to the proposed test track of the dry-freeze region. In order to reduce the level of uncertainty and subjectivity in sponsorship, a sensitivity analysis was undertaken in B/C determination with different volumes of contribution from partners. Details of such scenarios are highlighted in Table 9.

Table 9. The funding scenarios used for the sensitivity analysis.

Funding Scenario	Percentage of funding (%)		
	FHWA	Industry	Dry-freeze States
1	30%	10%	60%
2	20%	10%	70%
3	10%	10%	80%
4	0%	10%	90%
5	0%	0%	100%

Benefit-Cost Results

Details of expected benefits to the states are shown in

Table 10. The expected benefits represent savings in road agency costs because of improved design, construction, and maintenance of pavements. Though conservative, the results corroborate earlier findings that small improvements in pavement performance and service life can potentially save road agencies hundreds to millions of dollars annually (Worel et al., 2008), as shown in the Table below.

Table 10. Expected benefits from pooled fund studies implementation.

State	Benefits in (PG) binder (B1) ($)	Refinement of MEPDG ($)		Reduce low-temperature cracking by 10%.		Increase service life of overlays (B6)	Extend service life by 20%	
		HMA (B2)	PCC (B3)	HMA (B4)	PCC (B5)		HMA (B7)	PCC (B8)
AK	$2,341,155	$1,068,448	N/A	$85,916	N/A	$2,255,741	$1,505,319	N/A
CO	$2,432,965	$1,942,632	$3,548,160	$354,737	$309,598	$1,882,100	$2,757,352	$215,296
ID	$1,285,340	$1,845,501	$2,956,800	$240,522	$42,517	$1,275,878	$2,600,096	$100,285
KS	$918,100	$2,039,764	$3,548,160	$513,406	$346,712	$1,368,587	$2,873,790	$200,571
MT	$1,928,010	$1,942,632	$2,956,800	$298,354	$7,987	$1,582,653	$2,736,943	$100,285
NE	$1,285,340	$1,942,632	$3,991,680	$296,145	$462,283	$1,571,037	$2,764,471	$221,076
NV	$1,560,770	$1,424,338	$1,478,400	$174,208	$16,208	$1,848,215	$2,006,727	$100,285
ND	$1,239,435	$1,942,632	$3,843,840	$315,509	$191,913	$1,673,653	$2,736,943	$200,571
OR	$2,478,870	$2,002,116	$1,774,080	$408,126	$68,121	$2,173,694	$2,820,748	$100,285
SD	$918,100	$1,942,632	$4,139,520	$303,843	$356,343	$1,614,368	$2,722,974	$191,572
UT	$1,836,200	$1,418,122	$2,069,760	$213,175	$81,980	$2,261,618	$1,997,968	$150,428
WA	$2,754,300	$2,000,911	$3,548,160	$443,694	$142,349	$2,363,135	$2,819,051	$150,428
WY	$1,147,625	$1,418,122	$2,365,440	$176,727	$93,725	$1,875,059	$2,018,064	$165,807

NOTE: N/A = not applicable.

The total expected benefits and costs are presented in the net present values, as shown in Table 11. The values were determined for the first phase along a 10-year period. It should be noted that the initial construction costs are assumed to be distributed among the states to allow for determining the overall B/C ratio of the test track. The investments, needed to be made by the states for the initial construction of the test track, range from $1.4 million to $4.6 million. The total expected benefits to the states range from $54 million to $107 million in all funding scenarios. However, the estimated total cost of investment by state ranges from $7 million to $10 million.

Table 11. Present value of estimated benefits and costs for all funding scenarios.

State	Total expected benefits (NPB) ($)	Total Estimated cost (NPC) ($)				
		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
AK	$54,416,931	$7,075,086	$7,307,487	$7,539,888	$7,772,289	$8,004,690
CO	$100,807,574	$8,263,822	$8,694,346	$9,124,869	$9,555,393	$9,985,916
ID	$77,591,481	$7,668,922	$8,000,296	$8,331,669	$8,663,043	$8,994,416
KS	$88,556,119	$7,949,885	$8,328,086	$8,706,287	$9,084,487	$9,462,688
MT	$86,640,692	$7,900,803	$8,270,824	$8,640,844	$9,010,865	$9,380,885
NE	$93,997,184	$8,089,310	$8,490,748	$8,892,186	$9,293,624	$9,695,062
NV	$64,559,842	$7,334,993	$7,610,712	$7,886,430	$8,162,149	$8,437,868
ND	$91,071,320	$8,014,336	$8,403,278	$8,792,221	$9,181,163	$9,570,106
OR	$88,683,226	$7,953,142	$8,331,886	$8,710,629	$9,089,373	$9,468,116
SD	$91,407,692	$8,022,955	$8,413,334	$8,803,713	$9,194,092	$9,584,471
UT	$75,209,139	$7,607,876	$7,929,075	$8,250,274	$8,571,473	$8,892,672
WA	$106,650,697	$8,413,549	$8,869,027	$9,324,505	$9,779,983	$10,235,461
WY	$69,444,814	$7,460,168	$7,756,749	$8,053,330	$8,349,911	$8,646,493

The anticipated B/C ratio for each state is determined for each funding scenario. The sensitivity analysis using the scenarios shows the effect of cooperation on the B/C ratio of individual states as shown in Figure 31. The study found that the expected B/C ratio for Scenario 1 ranges from 7.9 to 12.9. Scenario 2 presents a B/C, which ranges from 7.6 to 12.3. Additionally, investment returns for participating states range from 7.4 to 11.6 in scenario 3 while in scenario 4, the calculated B/C ranges from 7.2 to 11.1. In Scenario 5, the states in the region are expected to financially sponsor the entire (100 percent) construction and research studies costs at the facility. The resulting B/C ranges from 6.9 to 10.6. Apart from the road network size, pavement types, and other parameters, the discount rate of states appears to influence the expected B/C ratio. This shows that the benefits realized by states depend on the level of implementation of research findings and discount rate.

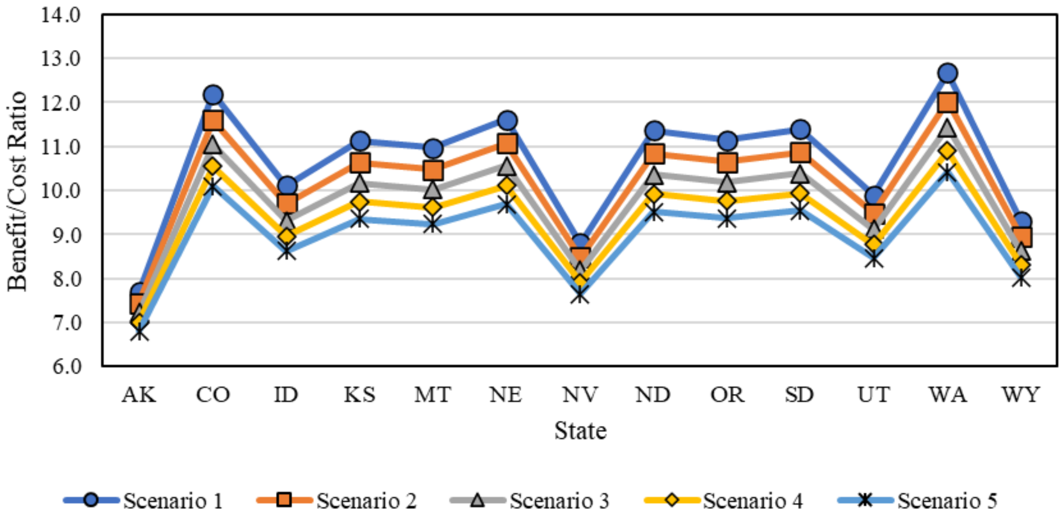


Figure 31. Benefit/Cost ratios of the dry-freeze states for the five funding scenarios.

The fuzzy initial investment cost, annual fuzzy expenses, annual fuzzy benefits, fuzzy maintenance costs, fuzzy instrumentation costs, and fuzzy salvage value used for the analysis are presented in Table 12. The input values are based on the deterministic approach but represented with fuzzy sets.

Table 12. Fuzzy Data of the Economic Analysis.

Component	Fuzzy Set ($ million)	Estimated Value
Initial Investment Cost	(60,62,62,64)	Approximately $62 million
Instrumentation Cost	(0.60,0.65,1.0,1.02)	Approximately between $650,000 and $1.0 million
Annual Operations Cost	(8,9,10,10.4)	Approximately between $9 and $10 million
Maintenance Cost	(0.35,0.4,0.55,0.6)	Approximately between $400,000 and $550,000
Salvage Value	(24,25,25,26)	Approximately $25 million
Annual Benefits	(148,150,150,152)	Approximately $150 million

Overall B/C Ratio

According to the previous results, the expected B/C ratios of participating states would provide different benefit-cost impacts depending on the contribution of each state in funding the proposed test track. Considering the defined benefits and total costs, the estimated overall B/C of the proposed facility is found to be 9.2 for the overall benefit-cost impact of the testing facility. This value is comparable to the values calculated by other testing facilities. The overall B/C ratio of the proposed facility also indicates a healthy return on investment in the regional pavement research projects. However, the overall B/C is likely to increase with funding participation from both FHWA and the private sector. Despite the high return of the proposed testing facility, there is an opportunity to expand the benefits by considering different partnerships from FHWA and the private sector. The literature shows that large-scale pavement testing facilities are operated by collaborating partners. FHWA as well as industrial entities for both flexible and rigid pavements have shown remarkable participation in relevant research programs. Hence, the potential participation of FHWA and the pavement industry are evaluated. The overall B/C of the proposed test track ranges from 9.2 to a range of 10.9 at different sponsorship levels as shown in Figure 32. In addition, scenario 1 resulted in a B/C ratio ranging from 10.9 to 13.6 in the most optimistic situations. This scenario represents the most cost-effective scenario. On the other hand, scenario 5 produced a B/C ratio ranging from 9.2 to 11, representing the most expensive option for participating states. B/C decreased gradually with a decrease in support from FHWA and the industry. The overall B/C of 9.2 is likely to increase by 19 percent in Scenario 1.

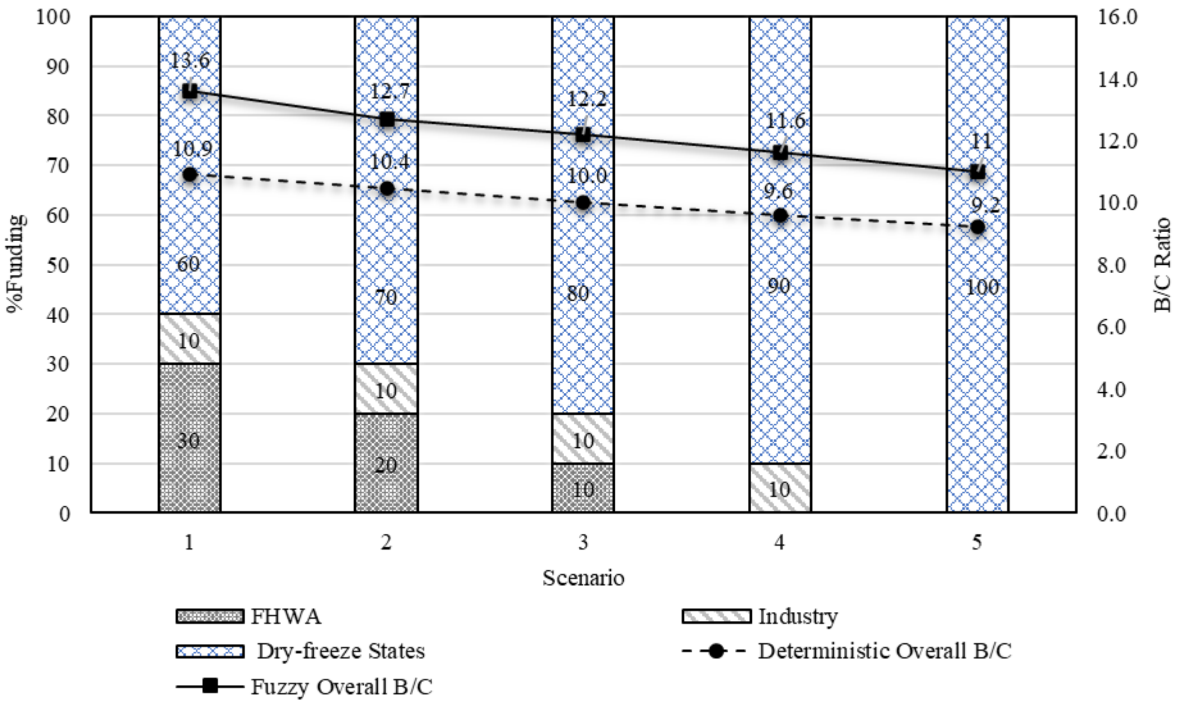


Figure 32. Fuzzy and deterministic B/C ratios sensitivity results.

Sensitivity Analysis

The sensitivity analysis of LCCA deals with uncertainties. The sensitivity analysis was applied in this study to examine the impact of external participation on the B/C ratio. The sensitivity analysis was applied in both approaches to encourage participation and deal with uncertainty in the external support of the program. Figure 8 shows the results of sensitivity analysis for both the deterministic and fuzzy B/C ratios. Low external support from the federal and industry has a negative impact on the potential B/C ratio realized.

A pairwise t-test comparison of means of the B/C ratio of deterministic and fuzzy concepts at a 5 percent significant level (α) show significant differences in means [t-value= -14.58, p-value<0.01]. The results of the two approaches are significantly different. Lower participation from Federal and industry leads to less variability in the B/C ratios depending on state participation. Participation from numerous external sources tends to increase the variability in B/C ratios between the deterministic and fuzzy approaches. Sensitivity analysis has been used by other authors to deal with uncertainties associated with future events.

CHAPTER 5: CONSTRUCTION COST ESTIMATES

Background

Another major aspect of studying the feasibility of the proposed test track is to come up with preliminary construction cost estimates. The cost estimation of construction projects on highways has become a significant concern because it impacts decision-making. Estimating the costs during the planning/programming phases is usually conceptual and considers mainly historical bid prices and common quantities to determine the overall cost values (FHWA, 2007). In this study, previous work scopes with similar characteristics are addressed to develop reliable unit costs of the different test track components, including materials unit costs, lane-mile unit costs, typical quantities, and square-foot cost averages. These contracts are addressed within WYDOT and other roadway construction contracts across the U.S. Then, the mainline components and their quantity and cost estimates are introduced to define the dollar value of the test track even prior to the design phase of the project.

There are three main elements in a highway project cost estimate are (Turochy et al., 2001):

- Preliminary engineering (PE)
- ROW and utilities
- Construction costs

Preliminary Engineering Costs

This cost component relates to the expenses of designing the project and preparing the construction plans by the design engineers. These costs exclude the ROW and construction costs. The preliminary engineering costs are normally estimated in the planning stage as a percentage applied to the estimated construction cost. In this study, a representative percentage of 15 percent of the total construction costs will be considered for the additional costs listed for the test track.

Right of Way

The cost for the ROW will be considered an estimate for purchasing the land from the landowner. This cost component is significantly affected by the available space needed to properly utilize the proposed test track in Wyoming. Also, the parcel land use and land value significantly affect the ROW cost estimates. The expected total area in acres will differ for the proposed test track depending on the conceptual layout. The following sections provide expected values for the total area of the proposed test track on I-80 in Wyoming.

In addition, to estimate the costs for the ROW, the PIs worked closely with the ROW office in WYDOT to define the expected unit cost, per acre, for the previously selected construction zones during selecting the potential location. As mentioned previously, four suitable construction zones were determined considering the spatial desirability of the traffic, geometric, and safety criteria. The ROW cost estimates consider the recommended Zone 4 for the land value.

Construction Costs

This is the main construction component that is directly affected by the quantities of the materials. The unit bid prices include a unit cost for both labor and purchasing the materials. These expenses are a function of project features, including pavement width, lengths, thicknesses, earthwork, and drainage, among other bid items.

Mainline Cost Components and Quantities

In order to come up with a representative cost estimate for the test track. Initial information must be received for the proposed design of the pavement structure. Then, these elements are selected and defined in the WYDOT bid price report to select the appropriate unit price. At this stage, only general information about the expected quantities of the project bid items is available. For the mainline of the test track, it is assumed that typical I-80 sections will be defined for the test sections which include the following:

1. I-80 typical sections on the Interstate test track:
    - For HMA sections: 12-inch HMA surface layer and 12-inch crushed base layer
    - For concrete sections: 11-inch PCC slab and 6-inch crushed base layer
    - 2-lane one-direction highway with a 12-inch lane width
    - 10-feet HMA shoulder width on both sides
    - 25-feet clear zone
2. Low-volume Road typical sections on the low-volume road segment:
    - For HMA sections only: 5-inch HMA surface layer and 6-inch crushed base layer
    - 2-lane roadway with a 12-inch lane width
    - 10-feet gravel shoulder width on both sides
    - 15-feet clear zone

The assumptions for the material unit weights are 150 and 135 pounds per square inch for HMA and aggregates, respectively. For the PCC slabs, a unit bid price (per square yard) is secured for the 11-inch slab from the WYDOT's bid price reports.

Considering the defined components on the mainline, Table 13 lists the summary of the material quantities expected on all the test sections on both the I-80 and the low-volume road test tracks. The total area of the mainline for the I-80 is determined to be almost 86 acres.

Table 13. Summary of the material quantities expected for the mainline on I-80 and the low-volume road.

Mainline Group	Element	Description	Unit	Quantity	N	Total Quantity
I-80 Track	Length:	Unit length of HMA test section	FT	200	26	5200
		Unit length of PCC test section	FT	225	26	5850
		Unit length of preservation test section	FT	225	10	2250
		Length of HMA transitions	MI	0.5	2	1.0
		Total Length	MI			3.52
	Width:	Buffer from existing I-80	FT	100	1	100
		Mainline ROW	FT	100	1	100
		Total Width	MI			0.038
Low-Volume Road Track	Length	Unit length of test section	FT	200	26	5200
		Unit length of preservation test section	FT	200	10	2000
		Total Length	MI			1.4
	Width:	Buffer from existing LVRs	FT	50	1	50
		LVR ROW	FT	75	1	75
		Total width	MI			0.02

As far as the unit bid prices, WYDOT annually posts the bid price history of all the projects conducted. The unit costs are found to vary among the different projects depending on the quantity, scope, and contracts specified. Hence, pre-selected bid items in the 2020 and 2021 weighted average bid prices are considered in the cost estimate analysis. As shown in Table 14, some of the bid prices are adjusted to account for the uncertainty of the sponsored contractors. The values are increased since the quantities of constructing the test sections are relatively low compared to regular highway construction projects. Moreover, the costs of pavement maintenance and preservation along the third test section groups will differ depending on the type of each surface treatment. Hence, the costs for cold-in-place recycling projects are considered reference costs for pavement preservation experiments.

Table 14. Unit costs and bid items considered for the test track mainline.

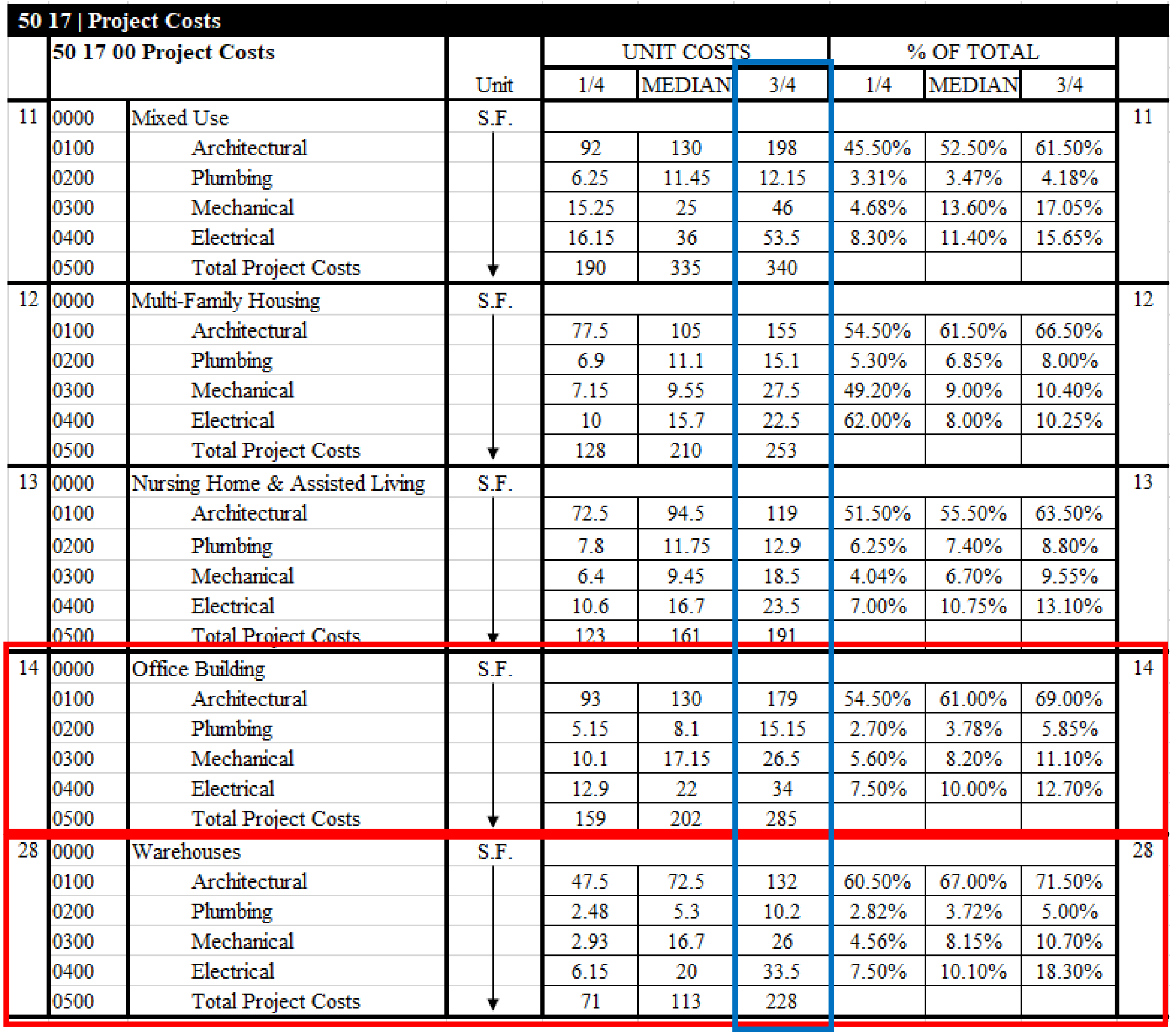
Item	Item Description	Units	Average Price	Adjusted Price
401.0200	Hot plant mix	Ton	$51.31	$75.00
301.01080	Crushed base	Ton	$23.31	$23.22
414.01060	Concrete pavement (11 in)	SY	$75.00	$100.00
499.03330	Cold in-place recycling	SY	$4.57	$10.00

Onsite Buildings Cost Components and Quantities

The construction of the onsite buildings includes several items that are limited to the WYDOT's bid prices. A reliable and effective reference is considered in this study to estimate the construction cost of buildings at the feasibility stage. The RSMeans data is one of the leading construction cost estimating databases that provides a variety of formats for determining the expected construction costs (RSMeans, 2021). RSMeans data includes thousands of previous construction projects to estimate the unit costs of the different building elements considering various detail levels. The analysis can be conducted using the RSMeans online tools (RSMeans, 2022) which provide users the ability to automatically determine the costs. For the purpose of simplification, the 2021 reference of the square foot unit costs (RSMeans, 2021) is used to simply estimate the construction costs of the onsite facilities considering the overall area and type of buildings. As shown in the proposed layout in Chapter 3, the future testing facility in Wyoming will include buildings that can be categorized as:

- Office buildings
- Parking lot
- Warehouse for the pole barn
- Service roads

Taking a thorough review of the project costs in the square-foot-costs reference book, the costs for these components are recognized. Figure 33 shows the data obtained from the reference book for the office building and the warehouse. The estimates of the cost components are available in three statistical formats: 25-percentile, median, and 75-percentile values. Considering the maximum case of uncertainty, the 75-percentile values are considered in the analysis of the cost estimates for the proposed test track. For service roads on site, the cost estimates are consistent with those for an HMA low-volume road. For the parking lot, a unit cost of \$10 per square foot is considered. The results for quantities of the onsite buildings are listed in Table 15 for the full-stage conceptual layout. The expected area for the onsite facilities is determined to be almost 21 acres. The total area for the land acquisition of the full-stage layout is determined to be 117 acres considering the area of the mainline and onsite facilities, as well as an additional 10 percent approximation marginal error.



50 17 | Project Costs										
	50 17 00 Project Costs			UNIT COSTS			% OF TOTAL			
			Unit	1/4	MEDIAN	3/4	1/4	MEDIAN	3/4	
11	0000	Mixed Use	S.F.							11
	0100	Architectural		92	130	198	45.50%	52.50%	61.50%	
	0200	Plumbing		6.25	11.45	12.15	3.31%	3.47%	4.18%	
	0300	Mechanical		15.25	25	46	4.68%	13.60%	17.05%	
	0400	Electrical		16.15	36	53.5	8.30%	11.40%	15.65%	
	0500	Total Project Costs	↓	190	335	340				
12	0000	Multi-Family Housing	S.F.							12
	0100	Architectural		77.5	105	155	54.50%	61.50%	66.50%	
	0200	Plumbing		6.9	11.1	15.1	5.30%	6.85%	8.00%	
	0300	Mechanical		7.15	9.55	27.5	49.20%	9.00%	10.40%	
	0400	Electrical		10	15.7	22.5	62.00%	8.00%	10.25%	
	0500	Total Project Costs	↓	128	210	253				
13	0000	Nursing Home & Assisted Living	S.F.							13
	0100	Architectural		72.5	94.5	119	51.50%	55.50%	63.50%	
	0200	Plumbing		7.8	11.75	12.9	6.25%	7.40%	8.80%	
	0300	Mechanical		6.4	9.45	18.5	4.04%	6.70%	9.55%	
	0400	Electrical		10.6	16.7	23.5	7.00%	10.75%	13.10%	
	0500	Total Project Costs	↓	123	161	191				
14	0000	Office Building	S.F.							14
	0100	Architectural		93	130	179	54.50%	61.00%	69.00%	
	0200	Plumbing		5.15	8.1	15.15	2.70%	3.78%	5.85%	
	0300	Mechanical		10.1	17.15	26.5	5.60%	8.20%	11.10%	
	0400	Electrical		12.9	22	34	7.50%	10.00%	12.70%	
	0500	Total Project Costs	↓	159	202	285				
28	0000	Warehouses	S.F.							28
	0100	Architectural		47.5	72.5	132	60.50%	67.00%	71.50%	
	0200	Plumbing		2.48	5.3	10.2	2.82%	3.72%	5.00%	
	0300	Mechanical		2.93	16.7	26	4.56%	8.15%	10.70%	
	0400	Electrical		6.15	20	33.5	7.50%	10.10%	18.30%	
	0500	Total Project Costs	↓	71	113	228				

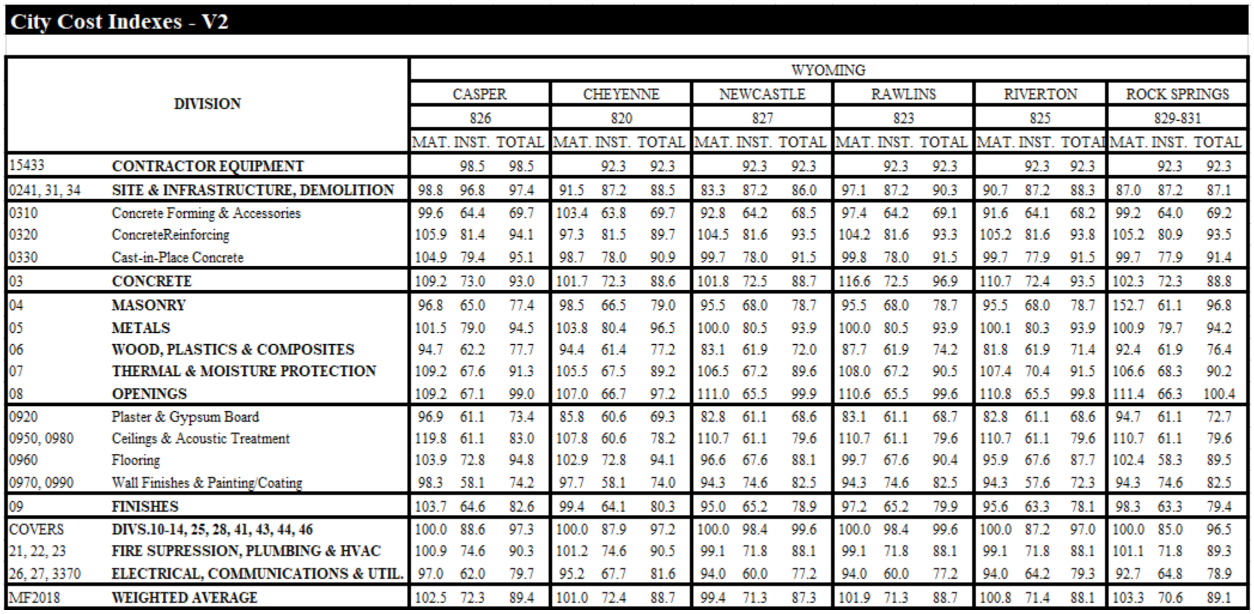
Figure 33. The project unit costs used for estimating the costs of the onsite buildings for the proposed test track (RSMeans, 2021).

Table 15. Summary of the quantities for the onsite buildings of the full-stage conceptual layout.

Group	Element	Description	Unit	Quantity	N	Total Quantity
Onsite Facilities	Office building	90ft × 70ft one-story building	SFT	6300	1	6300
	Pole barn	80ft × 80ft storage garage	SFT	6400	1	6400
	Parking lot	Capacity of 50 cars	SFT	22400	1	22400
	Stockpile area	construction materials storage area	Acre	10	1	10
	Other	Service roads, weather station, etc.	Acre	10	1	10

Note: SFT = Square foot.

It should be noted that the estimated unit costs of the onsite buildings are provided considering the national average costs. However, the regional costs are expected to vary significantly due to the varied costs for labor and materials. Therefore, the RSMeans data provide adjustment location factors to reflect the local market. Figure 34 shows the city cost indices for the local market in the major cities of Wyoming. The cost estimate analysis of this study considers the city of Cheyenne as the reference to adjust the costs. With this, an overall adjustment factor of 88.7 percent was applied to the unit cost of the 75-percentile values defined in the previous step.



City Cost Indexes - V2

DIVISION		WYOMING																	
		CASPER			CHEYENNE			NEWCASTLE			RAWLINS			RIVERTON			ROCK SPRINGS		
		826			820			827			823			825			829-831		
		MAT.	INST.	TOTAL	MAT.	INST.	TOTAL	MAT.	INST.	TOTAL	MAT.	INST.	TOTAL	MAT.	INST.	TOTAL	MAT.	INST.	TOTAL
15433	**CONTRACTOR EQUIPMENT**		98.5	98.5		92.3	92.3		92.3	92.3		92.3	92.3		92.3	92.3		92.3	92.3
0241, 31, 34	**SITE & INFRASTRUCTURE, DEMOLITION**	98.8	96.8	97.4	91.5	87.2	88.5	83.3	87.2	86.0	97.1	87.2	90.3	90.7	87.2	88.3	87.0	87.2	87.1
0310	Concrete Forming & Accessories	99.6	64.4	69.7	103.4	63.8	69.7	92.8	64.2	68.5	97.4	64.2	69.1	91.6	64.1	68.2	99.2	64.0	69.2
0320	ConcreteReinforcing	105.9	81.4	94.1	97.3	81.5	89.7	104.5	81.6	93.5	104.2	81.6	93.3	105.2	81.6	93.8	105.2	80.9	93.5
0330	Cast-in-Place Concrete	104.9	79.4	95.1	98.7	78.0	90.9	99.7	78.0	91.5	99.8	78.0	91.5	99.7	77.9	91.5	99.7	77.9	91.4
03	**CONCRETE**	109.2	73.0	93.0	101.7	72.3	88.6	101.8	72.5	88.7	116.6	72.5	96.9	110.7	72.4	93.5	102.3	72.3	88.8
04	**MASONRY**	96.8	65.0	77.4	98.5	66.5	79.0	95.5	68.0	78.7	95.5	68.0	78.7	95.5	68.0	78.7	152.7	61.1	96.8
05	**METALS**	101.5	79.0	94.5	103.8	80.4	96.5	100.0	80.5	93.9	100.0	80.5	93.9	100.1	80.3	93.9	100.9	79.7	94.2
06	**WOOD, PLASTICS & COMPOSITES**	94.7	62.2	77.7	94.4	61.4	77.2	83.1	61.9	72.0	87.7	61.9	74.2	81.8	61.9	71.4	92.4	61.9	76.4
07	**THERMAL & MOISTURE PROTECTION**	109.2	67.6	91.3	105.5	67.5	89.2	106.5	67.2	89.6	108.0	67.2	90.5	107.4	70.4	91.5	106.6	68.3	90.2
08	**OPENINGS**	109.2	67.1	99.0	107.0	66.7	97.2	111.0	65.5	99.9	110.6	65.5	99.6	110.8	65.5	99.8	111.4	66.3	100.4
0920	Plaster & Gypsum Board	96.9	61.1	73.4	85.8	60.6	69.3	82.8	61.1	68.6	83.1	61.1	68.7	82.8	61.1	68.6	94.7	61.1	72.7
0950, 0980	Ceilings & Acoustic Treatment	119.8	61.1	83.0	107.8	60.6	78.2	110.7	61.1	79.6	110.7	61.1	79.6	110.7	61.1	79.6	110.7	61.1	79.6
0960	Flooring	103.9	72.8	94.8	102.9	72.8	94.1	96.6	67.6	88.1	99.7	67.6	90.4	95.9	67.6	87.7	102.4	58.3	89.5
0970, 0990	Wall Finishes & Painting/Coating	98.3	58.1	74.2	97.7	58.1	74.0	94.3	74.6	82.5	94.3	74.6	82.5	94.3	57.6	72.3	94.3	74.6	82.5
09	**FINISHES**	103.7	64.6	82.6	99.4	64.1	80.3	95.0	65.2	78.9	97.2	65.2	79.9	95.6	63.3	78.1	98.3	63.3	79.4
COVERS	**DIVS.10-14, 25, 28, 41, 43, 44, 46**	100.0	88.6	97.3	100.0	87.9	97.2	100.0	98.4	99.6	100.0	98.4	99.6	100.0	87.2	97.0	100.0	85.0	96.5
21, 22, 23	**FIRE SUPRESSION, PLUMBING & HVAC**	100.9	74.6	90.3	101.2	74.6	90.5	99.1	71.8	88.1	99.1	71.8	88.1	99.1	71.8	88.1	101.1	71.8	89.3
26, 27, 3370	**ELECTRICAL, COMMUNICATIONS & UTIL.**	97.0	62.0	79.7	95.2	67.7	81.6	94.0	60.0	77.2	94.0	60.0	77.2	94.0	64.2	79.3	92.7	64.8	78.9
MF2018	**WEIGHTED AVERAGE**	102.5	72.3	89.4	101.0	72.4	88.7	99.4	71.3	87.3	101.9	71.3	88.7	100.8	71.4	88.1	103.3	70.6	89.1

Figure 34. The RSMeans data city cost indices used for adjusting the national average unit costs.

Other Tangible Costs

Other cost components are found in several cost estimate references and similar contracts. They are normally represented as percentages of the total construction costs. They can be summarized as follows:

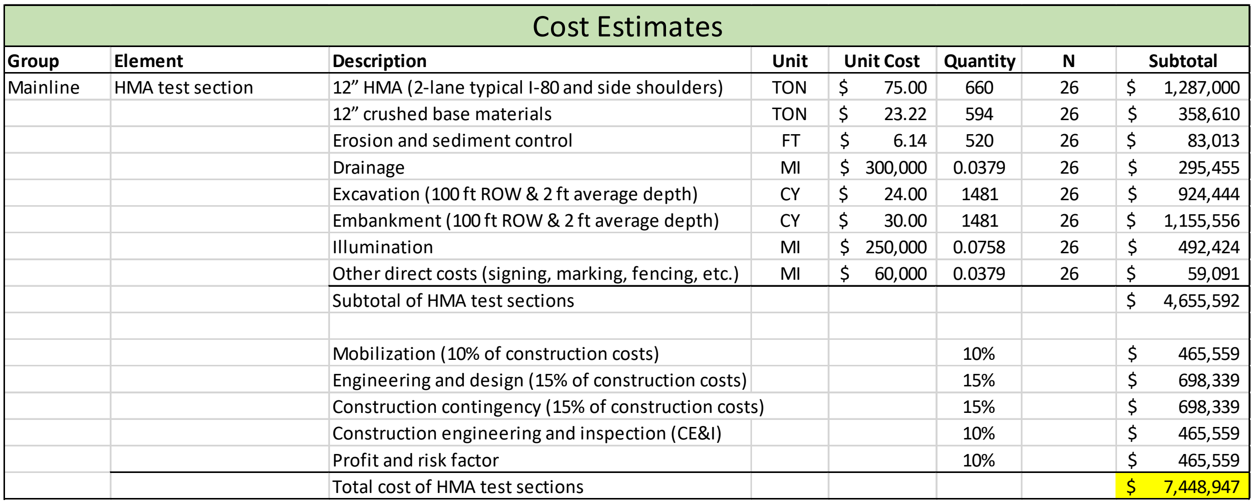
- Mobilization – These costs account for additional expenditures necessary for the movement of personnel, equipment, and supplies to the project site. This value can be estimated considering the historical costs of previous projects. The literature shows that mobilization costs normally range between 6 and 10 percent (Anderson et al., 2007). The proposed test track is expected to be out of the city. Hence, a representative mobilization cost of 10 percent of the total construction cost is considered in this study.
- Construction Contingencies – These overhead costs account for the likelihood that additional construction work may be included or the contingency for cost growth during construction. The construction contingencies normally range from 5 to 25 percent of the total construction cost (FHWA, 2007). For the test track, the contingency costs are estimated at 15 percent.

- Profit and Risk Factor – Potential risks and profit should be identified and quantified. During the feasibility stage, such information may not be available. With a probability of 90 percent, the risk of construction costs ranges between 2.71 percent and 8.67 percent of the total costs (Brokbals et al., 2019). In addition, the combined profit margins for both highway and building construction are estimated at 5 percent. Hence, the profit and risk factors are used in this feasibility study as 10 percent of the construction cost.

Results of Cost Estimates

In this section, the cost results are presented for only the full-stage conceptual layout considering the mainline on I-80. All predefined unit costs are linked with the determined quantities to develop the final cost model for the proposed test track facility in Wyoming.

Figure 35 shows the costs estimate summary for the HMA test sections on the mainline. For the purpose of simplification, all sections have similar systems for drainage, erosion and sediment control, earthwork, illumination, and traffic control. The total estimated cost for these sections is determined to be almost $7.5 million.

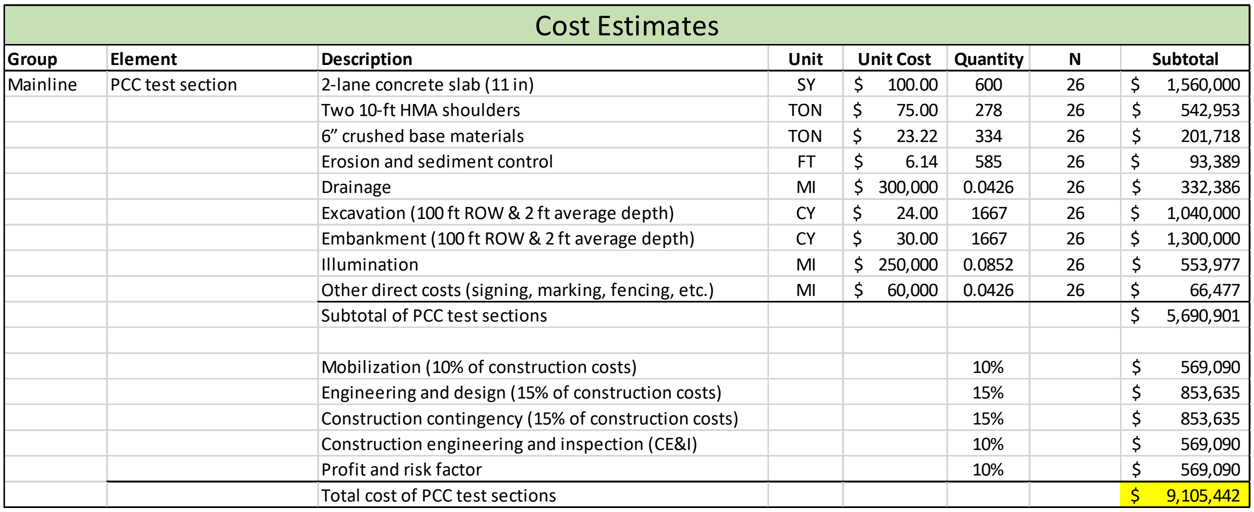


Cost Estimates

Group	Element	Description	Unit	Unit Cost	Quantity	N	Subtotal
Mainline	HMA test section	12” HMA (2-lane typical I-80 and side shoulders)	TON	$ 75.00	660	26	$ 1,287,000
		12” crushed base materials	TON	$ 23.22	594	26	$ 358,610
		Erosion and sediment control	FT	$ 6.14	520	26	$ 83,013
		Drainage	MI	$ 300,000	0.0379	26	$ 295,455
		Excavation (100 ft ROW & 2 ft average depth)	CY	$ 24.00	1481	26	$ 924,444
		Embankment (100 ft ROW & 2 ft average depth)	CY	$ 30.00	1481	26	$ 1,155,556
		Illumination	MI	$ 250,000	0.0758	26	$ 492,424
		Other direct costs (signing, marking, fencing, etc.)	MI	$ 60,000	0.0379	26	$ 59,091
		Subtotal of HMA test sections					$ 4,655,592
		Mobilization (10% of construction costs)			10%		$ 465,559
		Engineering and design (15% of construction costs)			15%		$ 698,339
		Construction contingency (15% of construction costs)			15%		$ 698,339
		Construction engineering and inspection (CE&I)			10%		$ 465,559
		Profit and risk factor			10%		$ 465,559
		Total cost of HMA test sections					$ 7,448,947

Figure 35. The cost estimate model for the HMA test sections on the mainline.

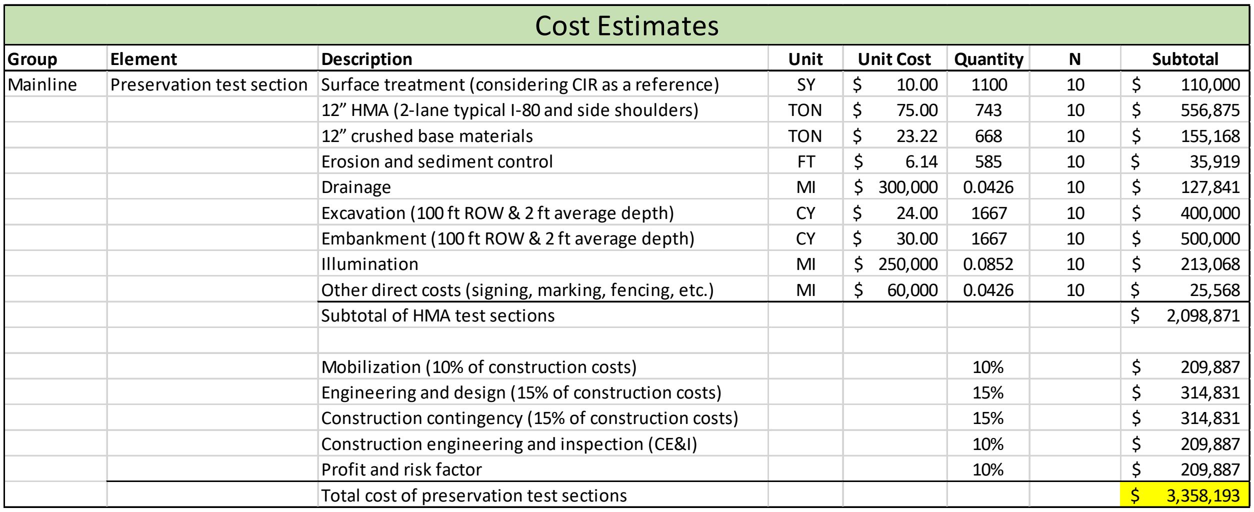
Figure 36 shows the cost estimates determined for the PCC test sections. The total estimated costs are almost $9.1 million. Figure 37 shows the cost summary for the test sections used for pavement maintenance preservations. The developed models for the three elements on the mainline can provide a unit cost per section by simply dividing the total costs by the number of sections. Accordingly, the average cost of construction per 200-foot HMA test section is $37,500 while the cost for a 225-foot PCC test section is almost $40,500.



Cost Estimates

Group	Element	Description	Unit	Unit Cost	Quantity	N	Subtotal
Mainline	PCC test section	2-lane concrete slab (11 in)	SY	$ 100.00	600	26	$ 1,560,000
		Two 10-ft HMA shoulders	TON	$ 75.00	278	26	$ 542,953
		6” crushed base materials	TON	$ 23.22	334	26	$ 201,718
		Erosion and sediment control	FT	$ 6.14	585	26	$ 93,389
		Drainage	MI	$ 300,000	0.0426	26	$ 332,386
		Excavation (100 ft ROW & 2 ft average depth)	CY	$ 24.00	1667	26	$ 1,040,000
		Embankment (100 ft ROW & 2 ft average depth)	CY	$ 30.00	1667	26	$ 1,300,000
		Illumination	MI	$ 250,000	0.0852	26	$ 553,977
		Other direct costs (signing, marking, fencing, etc.)	MI	$ 60,000	0.0426	26	$ 66,477
		Subtotal of PCC test sections					$ 5,690,901
		Mobilization (10% of construction costs)			10%		$ 569,090
		Engineering and design (15% of construction costs)			15%		$ 853,635
		Construction contingency (15% of construction costs)			15%		$ 853,635
		Construction engineering and inspection (CE&I)			10%		$ 569,090
		Profit and risk factor			10%		$ 569,090
		Total cost of PCC test sections					$ 9,105,442

Figure 36. The cost estimate model for the PCC test sections on the mainline.

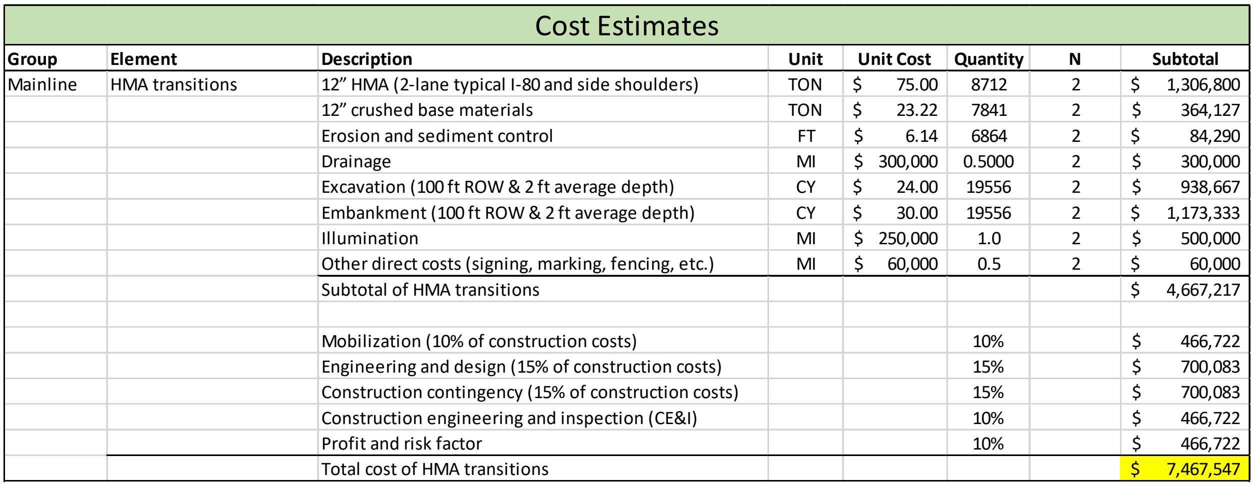


Cost Estimates

Group	Element	Description	Unit	Unit Cost	Quantity	N	Subtotal
Mainline	Preservation test section	Surface treatment (considering CIR as a reference)	SY	$ 10.00	1100	10	$ 110,000
		12” HMA (2-lane typical I-80 and side shoulders)	TON	$ 75.00	743	10	$ 556,875
		12” crushed base materials	TON	$ 23.22	668	10	$ 155,168
		Erosion and sediment control	FT	$ 6.14	585	10	$ 35,919
		Drainage	MI	$ 300,000	0.0426	10	$ 127,841
		Excavation (100 ft ROW & 2 ft average depth)	CY	$ 24.00	1667	10	$ 400,000
		Embankment (100 ft ROW & 2 ft average depth)	CY	$ 30.00	1667	10	$ 500,000
		Illumination	MI	$ 250,000	0.0852	10	$ 213,068
		Other direct costs (signing, marking, fencing, etc.)	MI	$ 60,000	0.0426	10	$ 25,568
		Subtotal of HMA test sections					$ 2,098,871
		Mobilization (10% of construction costs)			10%		$ 209,887
		Engineering and design (15% of construction costs)			15%		$ 314,831
		Construction contingency (15% of construction costs)			15%		$ 314,831
		Construction engineering and inspection (CE&I)			10%		$ 209,887
		Profit and risk factor			10%		$ 209,887
		Total cost of preservation test sections					$ 3,358,193

Figure 37. The cost estimate model for the preservation test sections on the mainline.

Additional costs are determined for the mainline considering the HMA segments used for transitions. Typical sections of HMA I-80 are quantified and the cost estimate results are shown in Figure 38. The quantity is determined for the total 0.5-mile length of the transition. Then, the amount is doubled to consider the two ends of the mainline test track (a total of one mile of transition).

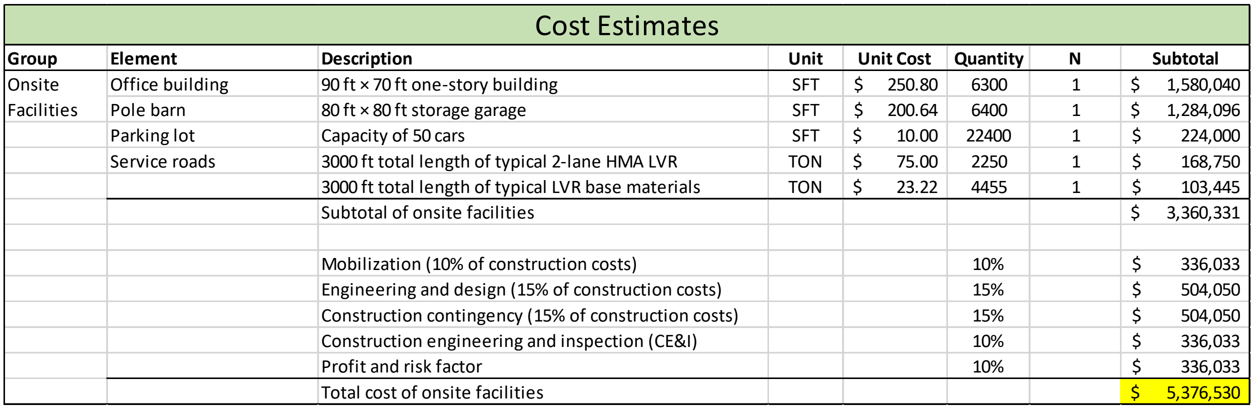


Cost Estimates

Group	Element	Description	Unit	Unit Cost	Quantity	N	Subtotal
Mainline	HMA transitions	12” HMA (2-lane typical I-80 and side shoulders)	TON	$ 75.00	8712	2	$ 1,306,800
		12” crushed base materials	TON	$ 23.22	7841	2	$ 364,127
		Erosion and sediment control	FT	$ 6.14	6864	2	$ 84,290
		Drainage	MI	$ 300,000	0.5000	2	$ 300,000
		Excavation (100 ft ROW & 2 ft average depth)	CY	$ 24.00	19556	2	$ 938,667
		Embankment (100 ft ROW & 2 ft average depth)	CY	$ 30.00	19556	2	$ 1,173,333
		Illumination	MI	$ 250,000	1.0	2	$ 500,000
		Other direct costs (signing, marking, fencing, etc.)	MI	$ 60,000	0.5	2	$ 60,000
		Subtotal of HMA transitions					$ 4,667,217
		Mobilization (10% of construction costs)			10%		$ 466,722
		Engineering and design (15% of construction costs)			15%		$ 700,083
		Construction contingency (15% of construction costs)			15%		$ 700,083
		Construction engineering and inspection (CE&I)			10%		$ 466,722
		Profit and risk factor			10%		$ 466,722
		Total cost of HMA transitions					$ 7,467,547

Figure 38. The cost estimate model for the HMA transition segments on the mainline.

For the full-stage conceptual layout, the onsite buildings are quantified in square footage to determine the total costs using RSMeans data. According to the feedback received about the best practices, the cost estimates are determined and summarized in Figure 39. A total cost of almost $5.4 is expected for the construction of the onsite facilitates. Additional costs may be considered for supporting the technical laboratory and onsite asphalt mixing plant. However, this study does not include these items during the planning phase.

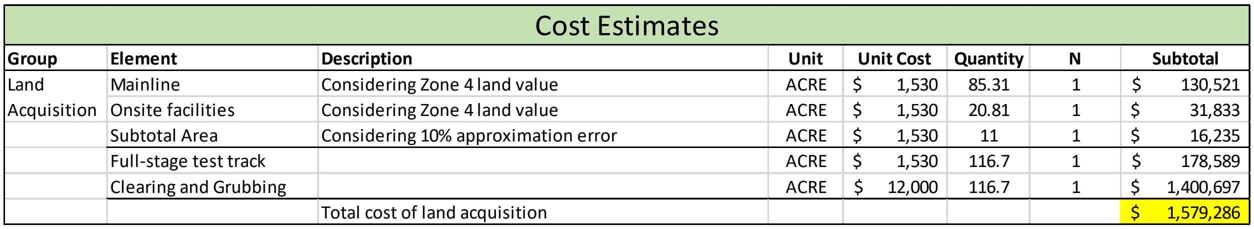


Cost Estimates

Group	Element	Description	Unit	Unit Cost	Quantity	N	Subtotal
Onsite Facilities	Office building	90 ft × 70 ft one-story building	SFT	$ 250.80	6300	1	$ 1,580,040
	Pole barn	80 ft × 80 ft storage garage	SFT	$ 200.64	6400	1	$ 1,284,096
	Parking lot	Capacity of 50 cars	SFT	$ 10.00	22400	1	$ 224,000
	Service roads	3000 ft total length of typical 2-lane HMA LVR	TON	$ 75.00	2250	1	$ 168,750
		3000 ft total length of typical LVR base materials	TON	$ 23.22	4455	1	$ 103,445
		Subtotal of onsite facilities					$ 3,360,331
		Mobilization (10% of construction costs)			10%		$ 336,033
		Engineering and design (15% of construction costs)			15%		$ 504,050
		Construction contingency (15% of construction costs)			15%		$ 504,050
		Construction engineering and inspection (CE&I)			10%		$ 336,033
		Profit and risk factor			10%		$ 336,033
		Total cost of onsite facilities					$ 5,376,530

Figure 39. The cost estimate model for the onsite facilities of the full-stage layout.

When it comes to the cost estimates for ROW and land acquisition, two main items are considered, including the cost of purchasing and the costs of site preparation (i.e., clearing and grubbing), as shown in Figure 40. The land value of the potential Zone 4 is used as a reference location in the cost model. The unit cost is estimated as $1,530 per acre considering the feedback received from WYDOT’s ROW office. The total area is quantified from the standard dimensions and lengths of the mainline, and onsite buildings, as well as an additional 10 percent for approximation errors. The unit cost of clearing and grubbing is secured from WYDOT average bid prices. Accordingly, the total cost of land acquisition for the construction of the full-stage test track is determined to be almost $1.6 million. Additional costs can be considered specifically for Zone 4 where some utility poles are expected to be relocated.



Cost Estimates

Group	Element	Description	Unit	Unit Cost	Quantity	N	Subtotal
Land	Mainline	Considering Zone 4 land value	ACRE	$ 1,530	85.31	1	$ 130,521
Acquisition	Onsite facilities	Considering Zone 4 land value	ACRE	$ 1,530	20.81	1	$ 31,833
	Subtotal Area	Considering 10% approximation error	ACRE	$ 1,530	11	1	$ 16,235
	Full-stage test track		ACRE	$ 1,530	116.7	1	$ 178,589
	Clearing and Grubbing		ACRE	$ 12,000	116.7	1	$ 1,400,697
		Total cost of land acquisition					$ 1,579,286

Figure 40. The cost estimate model for the land acquisition of the full-stage layout.

Another major component of the test track construction cost estimate includes the costs for instrumentation. Although specific instrumentations will be defined according to the research needs of the test sections and experiments, an estimate of instrumentation costs can be determined using historical values and previous experiences. The MnROAD test track, for example, determined the instrumentation costs in Phase II research to be almost 4 percent of the total costs (Worel and Deuse, 2015). Since this study estimates the costs in the planning phase, the percentage of instrumentation is raised to 6 percent of construction costs, totaling almost $2.1 million. Figure 41 shows the cost breakdown of the different components for the proposed test track considering the mainline and full-stage options. It is expected that the total cost of constructing the test track will be $36.4 million.

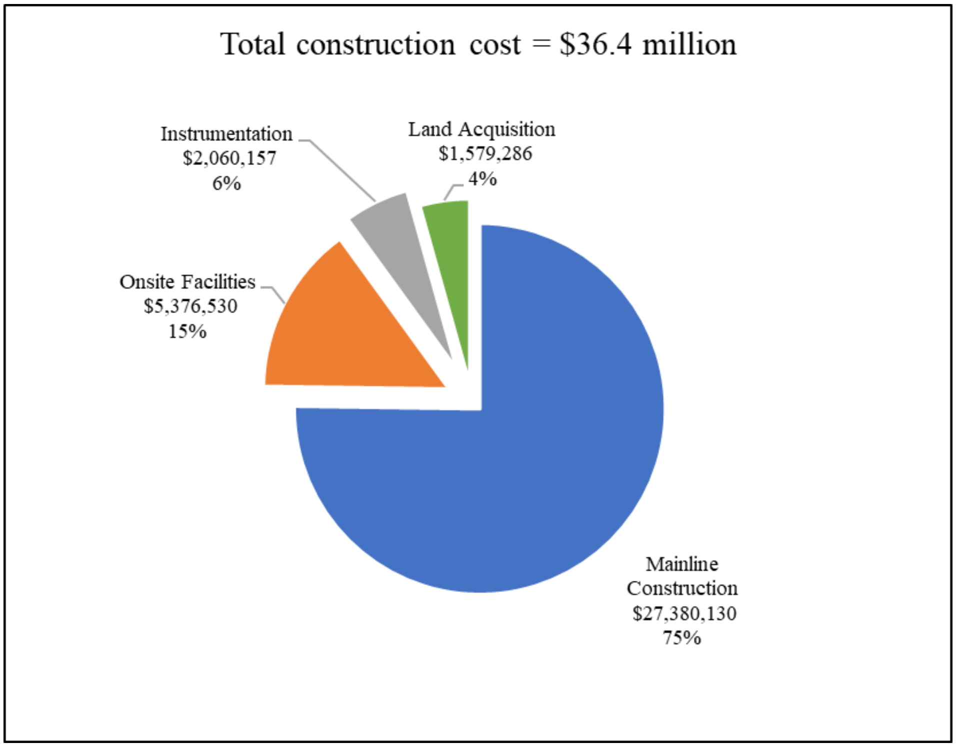


Figure 41. Cost summary of the proposed test track in Wyoming.

Validation of Cost Estimates

During the benefit-cost study presented in Chapter 4, the total construction costs are estimated considering the MnROAD construction in the 1990s adjusted by inflation. The total amount is estimated to be \$46.5 million. This amount indicates a percentage of difference of 20 percent compared to the total costs determined in the current chapter. However, the highway construction cost in Minnesota ranks the 30th while the cost in Wyoming ranks 39th nationally (Craighead, 2018). This implies that the costs can be discounted to reflect the local cost estimates in Wyoming. Considering the 2015 cost dollars for the cost per lane-mile developed by Craighead (2018), the discount percentage can be up to 27 percent.

Another validation shows that, in 2002, the Washington DOT (WSDOT) conducted a national highway construction survey for a "representative project that would be universal in all states" (Kishore and Abraham, 2009). In Wyoming, the average construction cost per lane-mile was found to be almost \$1.26 million. According to the National Highway Construction Cost Index (NHCCI), the costs are almost doubled in 2022 compared to the 2002-dollar values (Bureau of Transportation Statistics, 2022). Hence, the estimated construction cost per lane-mile for the interstate is expected to be almost \$2.5 million. For the total 3.5-mile two-lane test track, the total estimated costs will be \$17.5 million excluding other tangible costs. The tangible cost estimates conducted in this study show that the total additional costs are up to 60 percent of the construction costs that accumulate a total cost of \$28 million for the mainline. This amount is representative of the mainline cost estimate developed in this study as shown in Figure 41. From the mentioned validation processes, the total estimated cost can be a representative value for decision-making in the feasibility stage. In addition, the cost estimates for the benefit-cost analysis are within the expected range of the cost model so that relevant B/C ratios are developed for decision-making.

CHAPTER 6: COLLABORATION FOR WYOMING'S TEST TRACK FACILITY

Background

The collaboration between WYDOT and UW is vital for the success of operating the proposed test track on I-80. The proposed testing facility will be funded and operated through efficient cooperation between local, state, industrial, Federal, academia, and international entities. Hence, UW can serve as a key partner for the test track to facilitate the research program activities, including technology transfer, training, and more. This chapter outlines the main outcomes of the strategic partnership between WYDOT and UW to benefit the State of Wyoming and participating states in the dry-freeze climatic zone.

Research Program Overview

The research center at WYDOT provides funding to help improve the existing transportation system and its safety measures so that maximum benefits can be achieved for the economic well-being and quality of life in Wyoming. The collaboration with different entities can be implemented through the following funding categories.

State Planning and Research (SP&R)

Of the Federal highway funds received by each DOT, 2 percent is earmarked for the State Planning and Research (SP&R) funding programs. The SP&R funds are used for planning future highway programs, development and implementation of management systems, research, technology transfer, training on engineering standards, and monitoring real-time conditions and elements. According to the state planning and research code found at Title 23, U.S. Code § 505 (b) (1), not less than 25 percent of the SP&R funds must be allocated for research, development, and technology transfer activities related to highway and public transportation systems. SP&R funding is the main source of funding for the WYDOT research program (WYDOT, 2022). The collaboration between UW and WYDOT for the proposed test track could be sponsored through the Research Center since the main objective of the partnership would be to facilitate academic research, education, workforce development, and technology transfer with WYDOT. In addition, matching state funds would need to be secured for full-scale experiments on the low-volume road test track. The outcomes of such local projects can enhance the training and technology transfer for local practitioners. Hence, the Wyoming Technology Transfer Center (WYT2/LTAP) could contribute to these projects through different forms of support, including research activities, training programs, and technology transfer. The WYT2/LTAP center will consider the recommended research activities highlighted from the previous efforts, as summarized in appendices D and E for pavement and non-pavement research, respectively. The center will also strengthen the skills of managing and monitoring pavement performance through sponsored workshops and certification programs. Such programs will provide state and local practitioners with the tools to effectively address the challenges of pavement design, materials, and maintenance.

Transportation Pooled Fund (TPF) Program

The Federal Highway Administration (FHWA) facilitates the management of the Transportation Pooled Fund (TPF) program for research projects with widespread, regional, or national interest. The proposed test track is expected to sponsor research projects for HMA and PCC pavements with regional interests for participating states in the dry-freeze zone. Hence, most of the experiments on the test track could be conducted on a cooperative basis with regional states, FHWA, third parties, contractors, and/or universities. UW could contribute to such a strategic partnership to facilitate and define the research needs currently urgent for the several partners. Planning the implementation of different experiments could be organized by UW for the participating states, depending on several factors, including the scope of each experiment, the timeline of the experiment, and the availability of the test sections on each pavement type group. Also, UW is equipped with technological capabilities for software development and management. The proposed online tools for data sharing and management could be hosted and operated by UW. This will allow UW to share the findings and results of the different experiments with participating states and globally. Moreover, UW couldinitiate a strategic partnership with MnROAD and NCAT, as recommended previously in this study to share the expertise and knowledge of the full-scale testing. This can be done through sponsored conferences and annual meetings where practitioners and researchers share their visions, disseminate findings, construct ideas, and set research agendas together.

National Cooperative Highway Research Program (NCHRP)

WYDOT’s Research Center participates in the National Cooperative Highway Research Program, which is jointly managed by the Transportation Research Board (TRB), the American Association of State Highway and Transportation Officials (AASHTO), and FHWA. These funds do not require a state match because they are administered by the Federal government.. The proposed test track will address several national challenges for pavement and non-pavement research. The Civil & Architectural Engineering and Construction Management Department at UW has consistently contributed to the advanced knowledge of transportation engineering through several experimental research. Hence, the faculty and scholars of the department could serve in defining the research need for the test track and align it with national needs. UW could also share the responsibilities of delivering on federal investment.

WYDOT and the University of Wyoming Partnership Outcomes

Over decades, WYDOT has contracted with UW on research projects that resulted in the completion of more than 50 projects. The projects ranged from short-term to long-term endeavors resulting in multiple deliverables. UW’s graduate program enables graduate students and scholars to be an important element of this collaboration through fresh perspectives, innovative solutions, and dedicated qualities. In addition, the WYT2/LTAP Center has a record of accomplishment of success in assisting state and local Wyoming agencies to enhance the efficiency of transportation systems. This has been done through multiple research grants, reference materials, conducting T2/LTAP workshops throughout Wyoming, WYDOT certifications, training, technical assistance, and technology transfer. Therefore, the strategic partnership between WYDOT and UW could provide an immediate and positive impact on the success of managing and operating the proposed test track. The outcomes will provide in-depth knowledge and experience for graduate students and scholars at UW that will maximize the educational benefits of Civil Engineering. In addition, WYDOT is better positioned to provide these students and scholars with full-time programming positions.

Moreover, through WYDOT-supported projects, UW will be able to secure funding to help support its mission and staff. This funding provides paid work opportunities for students seeking real-world experience in transportation engineering. By having interesting real-world projects, UW can attract better student employees, and provide those students with more rewarding opportunities for internships and full-time positions. In addition, through high-profile partnerships with the proposed test track and major APT facilities in the country, UW, as well as the WYT2/LTAP Center can raise their profile and advertise their services to other clients.

As this partnership continues, the residents of Wyoming will continue to be beneficiaries through improved safety and efficiency of the transportation network in the state.

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

The significant benefits associated with APTs and the need for cost-effective and sustainable infrastructure have prompted the WYDOT to propose a regional APT test road for the U.S. dry-freeze states. The facility will be the foremost test road in the dry freeze climate. A feasibility study of building a state-of-the-art APT program was conducted to identify potential partners, research needs, suitable construction locations, benefit-cost impacts, quantity and cost estimates, and effective collaboration with the UW. The following conclusions are drawn from this study.

Conclusions from Partnership Surveys and Virtual Meetings

A comprehensive discussion about the proposed APT facility is introduced, including the results of two online surveys sent to state DOTs and industrial entities in the dry-freeze climatic zone. In addition, several virtual meetings were held with the major APT officials in the U.S., including MnROAD, NCAT, and FDOT test tracks. The information obtained from both surveys and virtual meetings leads to several lessons learned and conclusions as follows:

- Most of the participants in both surveys and virtual meetings consider the building of the proposed test track in Wyoming to be significantly important for the study of pavements in the dry-freeze region.
- General guidelines are provided for the different components of the proposed test track facility, including recommended lengths for the test tracks, supporting onsite buildings, and data collection and sharing.
- Conventional flexible pavements using HMA asphalt are the most common pavement type recommended to be tested at the proposed test track facility. Other types may be included according to the specific needs of partners.
- Although monitoring bridges through full-scale tests provides several benefits, most state DOTs in the dry-freeze region show low interest in testing bridges on the proposed test track in Wyoming.
- Respondents in both surveys show different interests in participating in pooled fund studies, taking a seat on an advisory board, and joining technical subcommittees intended for the program.
- The initial feedback shows a high interest in state DOTs to participate in regional research studies on the proposed test track. This increases the importance of accelerating the coordination and implementation of the proposed facility in Wyoming.
- Some state DOTs are willing to fund the construction of the testing facility, sponsor research, and provide technical and instrumentation support and take part in pooled fund studies.
- Contractors and associations intend to undertake commercial evaluations as well as financial, training, materials, technical, and operations support. Additionally, they intend to promote the needs and interests of the regional test track facility at the national level.

- International roughness index (IRI) and rut depth are the recommended condition indices for the proposed test track research program. Moreover, data on research programs and all relevant information would be available on a dedicated facility website.
- The NCAT, MnROAD, and FDOT's testing facilities have several experiences with full-scale pavement testing techniques, including construction, funding, operation, data collection and management, and maintenance. The proposed testing track in Wyoming can consider this expertise and the lessons learned to increase the successfulness of the proposed facility for the dry-freeze region. All the officials of the major testing facilities showed a willingness to support WYDOT with technical expertise to develop the proposed testing facility.

Conclusions from Potential Locations

A suitability analysis is conducted with multi-criteria decision-making to select the most appropriate location for constructing the proposed test track in Wyoming. A spatial analyst tool in ArcGIS is employed with the Linear Weighted Combination method to aggregate five affecting decision-making criteria. These factors are considered to minimize the engineering, economic, and environmental impacts on the existing corridor of I-80. The following are drawn from this analysis:

- The proposed locations for constructing the test track display several challenges of mountainous and hilly terrains, traffic safety concerns, representative traffic volumes, mobilization concerns, and active oil wells activities. The decision-making includes ranked criteria with different scores to provide an overall recommendation about the suitable location using raster data with a suitability scale.
- The spatial analysis reveals that four construction zones are recommended to maximize the benefits of the proposed test track. Further investigations was conducted for the proposed construction zones showing several pros and cons of each site.
- Zone 4 is found to be the most recommended location considering the spatial analysis and the WYDOT's ROW feedback. In this Zone, the location of the proposed test track will be on the western side of Cheyenne with close distances for mobilization. This zone was further investigated using field evaluation.
- The demonstration of the Unmanned Aerial System (UAS) showed the importance of using innovative technology as a viable alternative to the traditional method of surveying sites.
- The UAS, or drone, was employed in the study to provide high-quality survey and aerial photography allowing for a better-informed bird's eye view of the project area.
- The aerial photogrammetry revealed the presence of about 20 high-tension electricity poles within the ROW of zone 4. This will require the relocation of the lines to allow for the construction of the test road and other ancillary facilities.

Conclusions from Benefit-Cost Analysis

The LCCA is an important decision–making tool in transportation projects of all kinds. The proposed test track facility is economically advantageous and worth investing in, and it has the potential to provide several benefits through pavement research and technology. This study proved the applicability of the deterministic life cycle cost analysis and the fuzzy concept incorporating sensitivity analysis to develop a framework for evaluating the economic benefits of the proposed APT facility at the planning stage. The economic evaluation of the APT facility at the project feasibility stage leads to the following conclusions:

- The overall B/C of the proposed test track facility for the dry-freeze region is found to be 9.2. Such a high ratio indicates that the benefits of operating the test track have the potential to pay off the investment and, therefore, be financially feasible for implementation. Securing funding from FHWA and the private sector can increase the overall B/C for the participating states to values between 9.4 and 10.7.
- The individual B/C of states was greater than 1. This implies a healthy return on investments to the participating states. Nonetheless, the benefits depend on the scale of implementation of research findings.
- Improvement in pavement design, construction, maintenance, and cost-effective material selection based on research findings can make significant savings in agency costs.
- Sensitivity analysis is important in the economic evaluation to determine ranges of B/C to minimize the uncertainties in sponsorship.
- The study reinforces the cost-effectiveness of operating the test track facilities through partnerships and cooperative research. The results show that sponsorship from FHWA and the industry influenced the overall B/C. Scenario 1 represents the optimum cost-effective funding option for the APT program of participating states.
- The economic evaluation of the APT facility at the feasibility stage has some complexity that involves degrees of uncertainty. The example shown in this study helped establish the feasibility of using the fuzzy approach in assessing the economic benefits of the APT program at the planning stage. The economic evaluation of the testing facility has been examined under both the deterministic and fuzzy methods with sensitivity analysis.
- Partnerships in APTs are highly recommended for cost-effective research programs. The sensitivity analysis showed significant maximization of benefits through external participation though the overall B/C of the program did not change significantly. The study also found a significant reduction in the initial cost of building due to external support from FHWA and the industry.

Conclusions from Construction Cost Estimates

The quantity and cost estimates of construction projects on highways is an important factors affecting decision-making. Estimating the costs of the proposed test track during the planning/programming phases is usually conceptual and considers mainly historical bid prices and common quantities to determine the overall cost values. The cost model for the full-stage conceptual layout is developed and the following are found:

- The total construction cost estimate of the proposed test track is found to be $36.4 million. The total cost encompasses 75 percent for the mainline construction, 15 percent for the onsite facilities, 6 percent for instrumentation, and 4 percent for land acquisition.
- Although WYDOT will mainly sponsor the construction of the test track, the construction of the test sections can be conducted by the participating states and industries. The cost estimates reveal that the average cost of construction per 200-foot HMA test section is $37,500 while the cost for a 225-foot PCC test section is almost $40,500.
- The RSMeans data is found to serve as a good reference for the construction cost estimates of the onsite buildings. Additional costs for laboratories and an onsite mixing plant can be considered if needed.
- The historical evaluation of the construction costs using national references provides relevant cost estimates for the mainline of the test track. In addition, the construction cost data of the MnROAD testing facility validates the current estimates of the proposed test track in Wyoming. The mentioned validation processes recommend the current estimates be representative.
- The cost estimates for the benefit-cost analysis are found to be within the expected range of the cost model so that the obtained B/C ratios are relevant for decision-making.

Conclusions from Collaboration for Wyoming's Test Track

The strategic partnership between WYDOT and the UW is vital for the success of operating and managing the proposed test track. The UW WYT2/LTAP Center can significantly contribute to the advancement of the test track program through several forms of sponsorship, including research grants, education, advisory board, technological partnership, training, workforce development, and technology transfer.

Recommendations

Based on the results of this study, constructing a new test track on I-80 in Wyoming is found to be feasible. It is highly recommended that WYDOT and other state DOTs realize that partnerships in the APT are the way forward, looking at the global economic situation. It has become necessary to encourage cooperation and constant need for testing facilities based on the technical and financial benefits to the public and private sectors. This study provides the following recommendations while addressing the feasibility of the proposed test track in Wyoming:

- Partnerships are key to avoiding duplication of research topics. WYDOT needs to establish and nurture relationships with MnROAD, NCAT, other APTs, industry, and state DOTs. Through these relationships, WYDOT can discover pavement research areas and share ideas and resources for a successful program. In this context, NCAT has a unique partnership with MnROAD for the national survey. It will also leverage available resources and ideas for research needs.

- It is recommended that WYDOT identify the operation costs of the proposed testing facility in a uniform shape. The funding must be secured from the involved agencies regardless of the expected partners. Having constant and stable funding for the operation would be very beneficial for long-term monitoring and for avoiding delays in operations.
- The need for innovation funding calls can bring multiple partners from academia, industry, private companies, and associates. It is recommended WYDOT find an appropriate means to call associate partners to engage in the proposed test track facility based on their needs (whether research or marketing objectives). This increases the level of research activities on the testing tracks and consequently increases the corresponding benefits.
- A well-structured organization for the proposed test track can save a lot of processing time for funding and operations. It is recommended WYDOT define the state agency expected to participate and their representatives. Also, it is recommended that the office of materials in WYDOT define a staff dedicated to the research program on the proposed test track on I-80.
- Owning the data collection equipment may increase the flexibility of data collection activities and provide higher frequency data. This would contribute to increasing the accuracy of data collected on the road tracks.
- WYDOT will be the joint owner of the data and the data will be made open access for all. The proposed facility can also incorporate the LTPP-Info Pave database system to provide consistent data with the MnROAD program. That will integrate the results from the different climatic zones and provide a better understanding of pavement performance.
- WYDOT should consider joining the NRRA so that relevant projects can be sponsored in Wyoming to address regional and national needs.
- Selecting a suitable location for the test track is a significant task in the planning process. Proximity to a major airport when selecting the site of the test track is important. This makes it easier and more convenient for sponsors to visit the test track at different times. The proximity to the airport makes it easier for sponsors anywhere in the world to visit the facility.
- It is recommended WYDOT consider hiring a construction management expert as part of the staff at the facility. This helps achieve savings while WYDOT is taking the responsibility of building the test sections. Building the test sections in-house helps to achieve quality targets readily. Being the prime contractor allows flexibility to make changes at any time without financial consequences and contractual breaches.

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APPENDIX A: LITERATURE REVIEW

Introduction

Different pavement evaluation techniques have been used over the years to understand and predict the performance of pavement systems. The pavement evaluation methods include computer simulation, laboratory testing, APT and long-term monitoring like the long-term pavement performance (LTPP) studies. Figure A1 shows the relative cost and time and the associated level of reliability of the different pavement evaluation methods with the broad basis of pavement engineering. The figure shows that computer simulation and analysis is an inexpensive, fast but less reliable evaluation procedure. Laboratory testing may take several weeks to complete with a relative increase in reliable knowledge and costs. Accelerated Pavement Testing also provides a reliable cost-effective way to evaluate the long-term performance of pavement within a few months. However, long-term performance monitoring takes so many years to produce reliable results at a high cost.

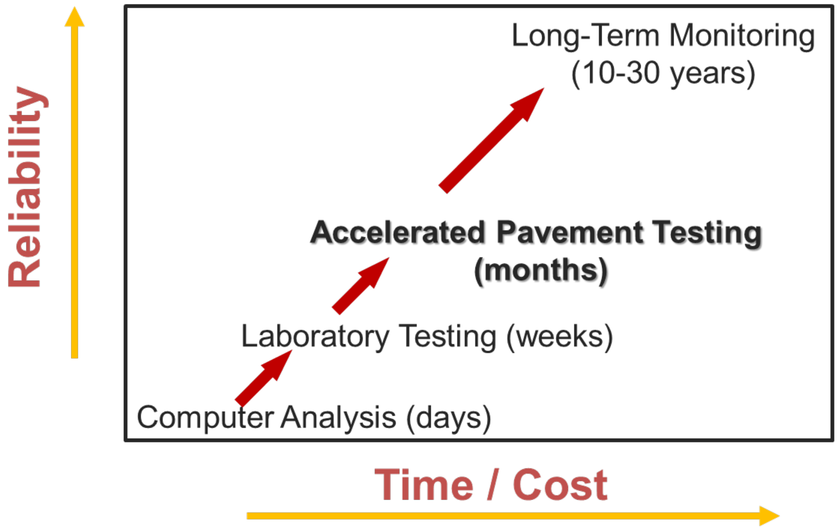


Figure A1. The different pavement testing methodologies.

Accelerated Pavement Testing (APT)

Accelerated Pavement Testing (APT) is the "controlled application of wheel loading to pavement structures for the purpose of simulating the effects of long-term, in-service loading conditions in a compressed time period" (Hugo and Martin, 2004). APTs allow pavement performance of test sections to be monitored continually to evaluate rutting, cracking, roughness, friction, etc. under long-term loading and environmental effects. The acceleration of damage to the pavement is achieved by increased load repetitions and or loads, the use of thinner pavement sections with decreased structural capacity, or a combination of these factors.

Types of Accelerated Pavement Testing in the U.S.

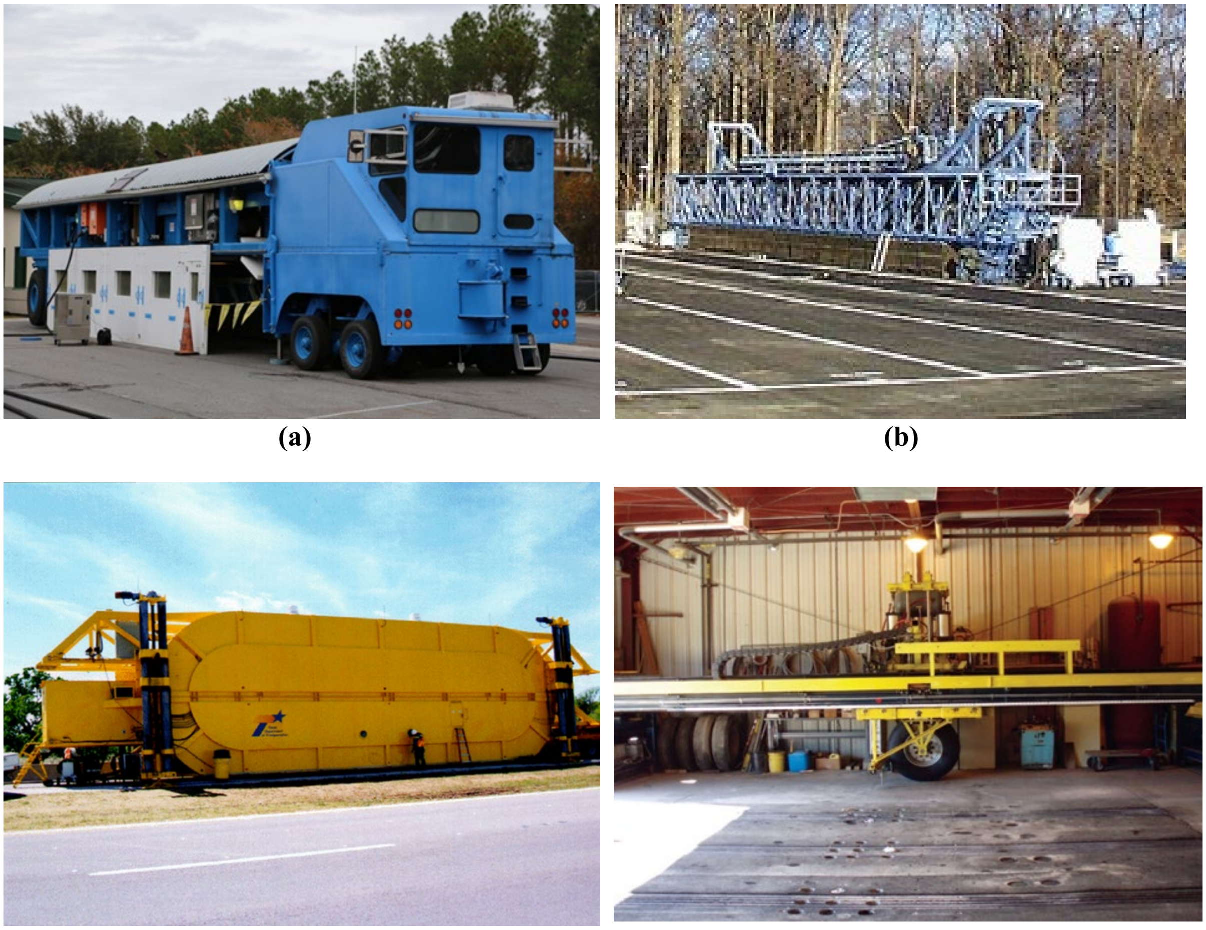
There are two main types of APTs. These are the load simulation machines and test roads. These APT types are described below.

Load Simulation Machines

The Load simulation machines are mechanical devices that rapidly apply a given load to the test sections. They can be classified into linear and circular pavement test facilities. Figure A2 shows examples of load simulation machines employed. Examples of linear testing devices are the Heavy Vehicle Simulator (HVS), Accelerated Loading Facility (ALF), Accelerated Transportation Loading System (ATLAS), Mobile Load Simulator (MLS), etc. Besides, the circular devices include the Canterbury Accelerated Pavement Testing Indoor Facility (CAPTIF), and the fatigue carrousel. These devices are movable and can be transported to different sites. The test sections are constructed by conventional plants and processes to simulate real-world conditions. However, the loads are applied at relatively slow speeds between 2 mph to 15 mph. The load simulation devices offer the ability to vary load and overload, and control temperature and moisture. Moreover, it is difficult to measure roughness due to the short test sections. Accelerated loading with load simulation devices can allow 20 years of loading in-service pavements to be simulated within about 3 months. They can investigate flexible, rigid, and composite pavements within a short time.

Test Roads

Full-scale test roads are test tracks with several instrumented test sections that are subjected to actual or real-world truck traffic. This method is regarded as probably the most realistic way to test pavements as pavements are subjected to long-term in-service loading and environment effects. Examples of test roads are the Minnesota Road Research Project (MnRoad), and the National Center for Asphalt Technology (NCAT) test track, as shown in Figure A3. The AASHO Road test is also one of the leading test tracks conducted back in the 1960s. The test roads are more representative of what happens on our roads in terms of speeds (typically 50-70 mph), axle load limits (realistic loads), and vehicle wander. Longer test sections typically between 200ft-500ft allow for the meaningful measurement of roughness. The test roads consider realistic suspension interaction, braking and acceleration effects, and long-term aging effects of pavements. Overall, the test sections are constructed by conventional plants and processes so that real-world conditions are modeled. The following sections describe in detail the three major test track facilities currently operated in the U.S.



(a) (b)

(c) (d)

Figure A2. Different Types of Load Simulation Devices: (a) FDOT's HVS Mk IV (TRB-AFD40, 2021); (b) FHWA's ALFs (FHWA, 2021); (c) Texas Mobile Load Simulator (Abdallah et al. 1999); (d) The APT Linear Loading Machine (Nantung et al. 2018).

(a) (b)

Figure A3. Aerial Photograph of Test Roads: (a) MnROAD Pavement Test Facility (Minnesota Department of Transportation, 2021); (b) NCAT Test Track Facility (West et al., 20218).

The Minnesota Road Research Project (MnROAD)

The Minnesota Road Research project known as MnROAD was constructed in 1991 by the Minnesota Department of Transportation (MnDOT) at Albertville, Minnesota. It is regarded as the first full-scale pavement testing facility since the American Association of State Highway Officials (AASHO) Road Test in the 1960s (Tompkins and Khazanovich, 2007). The early construction of MnROAD started with a budget of $25 million in early 1990 (Worel et al., 2008). As discussed in the meeting, this funding was mainly contributed by the MnDOT. The budget included buying the land, sensors, construction, staffing, buildings, and initial research efforts.

General Layout

The MnROAD is located on the westbound of interstate-94 (I-94) and is operated mainly by the MnDOT and Local Road Research Board (Van Deusen et al., 2018). Two distinct road test segments are located on MnROAD along the I-94 corridor (Worel et al., 2008):

- A 3.5-mile mainline interstate roadway that carries existing traffic on the interstate
- A 2.5-mile closed-loop low-volume road (LVR) trafficked by an 18-wheel, 5-axle, 80,000 lbs tractor-semi-trailer to simulate conditions of local roads.

According to Van Deusen et al. (2018) “Report on 2017 MnROAD construction activities”, MnROAD now has four unique road segments:

- A 2.7-mile, two-lane mainline interstate roadway that carries existing traffic with an average daily traffic (ADT) of 26,500 vehicles per day on the westbound I-94. The traffic composes of about 13 percent trucks.
- A 2.5-mile, two-lane closed-loop LVR segment carrying a MnROAD operated 80 kips, 5-axle, tractor/trailer combinations doing about 70 laps per day only to the inside lane.

The outer lane of the test segment is reserved for studying environmental effects on pavements.

- A 1000-feet, two-lane road segment located at the MnROAD stockpile area for evaluating the effects of implements of husbandry on LVR. The segment is occasionally used as a trial section paving before paving the experimental test section on the mainline or LVR.
- A 2.7-mile segment was constructed in 2017 and consists of a series of asphalt overlay and partial-depth spall repair test segments of concrete pavement originally built in 1973. This segment carries the existing traffic on the westbound of I-94 for an average of 7 days per month representing about one-third of the cumulative ESALs on the mainline test sections. The loads are applied during traffic diversion when the mainline is closed to traffic for monitoring or construction.

The overall layout of the MnROAD test tracks is shown in Figure A4. The roadway segments have over 50 unique experimental test sections with over 9500 sensors installed over the last 23 years on both asphalt flexible and concrete rigid pavements (MnROAD, 2021).

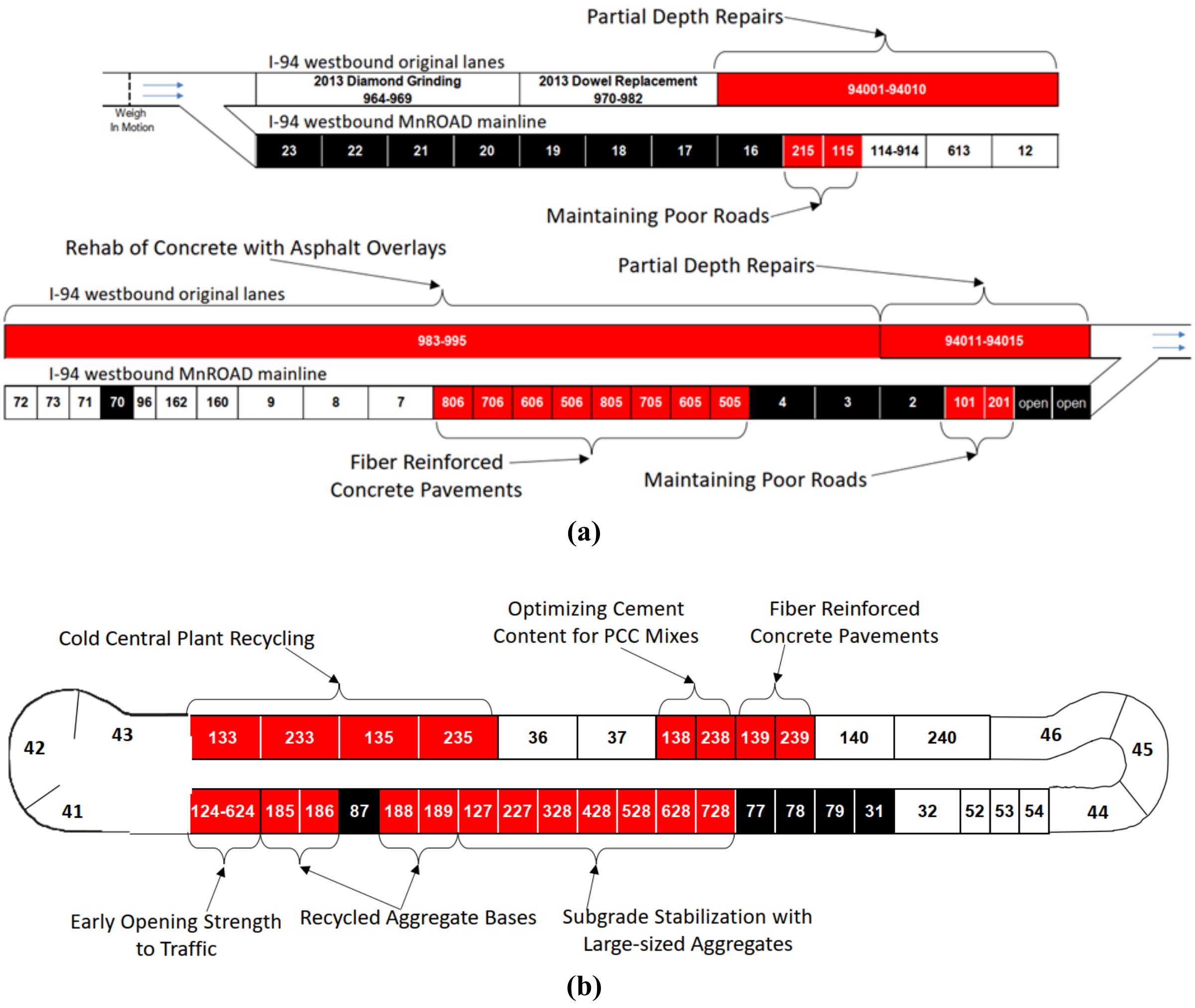
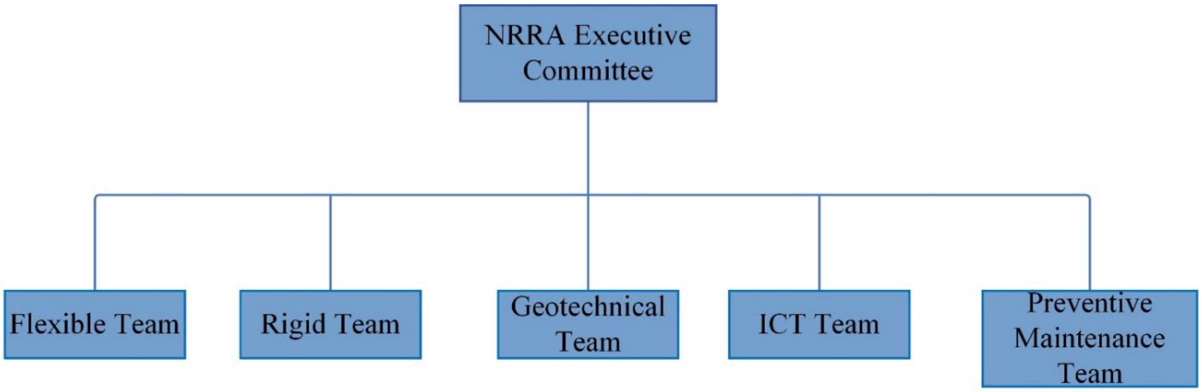


Figure A4. Layout of test sections: (a) MnROAD I-94 WB (Mainline and original I-94); (b) LVR (Van Deusen et al. 2018).

The Organizational Structure of MnROAD

MnROAD funding is a product of the cooperation between local, state, industry, federal agencies, academia, and international sources. In fact, one of the first goals was to establish partner relationships (Tompkins and Khazanovich, 2007). The majority of funds for research operations for the first ten years were provided through a partnership between the MnDOT and the Minnesota Local Road Research Board (LRRB) during the first research phase (Minnesota Department of Transportation, 2021). As discussed in the meeting, the LRRB is responsible for setting counties and local agencies on the research board of MnROAD for low-volume road research activities. Starting in 2017, federal pooled-fund programs are secured through the National Road Research Alliance (NRRA). The NRRA partners represent nine states and about 50 associate members (MnROAD, 2021; Van Deusen et al. 2018). The NRRA is made up of an executive committee and five research teams each chaired by agency members as shown in

Figure A5. The structure of the NRRA is intended to promote innovation and develop feasible products for the pavement industry. The objective of NRRA is to build resilient pavements through research and promote the cooperative implementation of research findings. The following sections provide additional information on the organizational structure of the NRRA.



Note: ICT=Intelligent Compaction technologies

Figure A5. The structure of the NRRA Research Teams (MnDOT)

NRRA Executive Committee

The executive committee is a decision-making body with membership from state DOTs. The executive committee sets the objectives and goals, selects projects for research, and determines the budget based on the recommendations of the five teams. Generally, the committee makes the decision for research programs that needs funding. The team is currently chaired by Glenn Engstrom, Minnesota Department of Transportation. As shown in Figure A6, representatives from North Dakota, Michigan, Iowa, Missouri, California, Wisconsin, Minnesota, Illinois DOTs, and Federal Highway Administration make up the committee.

Figure A6. Current NRRA membership in the U.S. (MnDOT, 2020)

NRRA Research Team

There are five research teams, namely, flexible, rigid, geotechnical, intelligent construction, and preventive maintenance. The following subsections briefly describe the five research teams.

- Flexible Team – This team focuses on new and rehabilitated flexible pavements. Members have expertise in asphalt pavements. The teams prioritize long and short-term research programs and develop long-term research test sections at MnROAD.
- Rigid Team – Members utilize their expertise to prioritize long and short-term research programs and develop long-term research test sections related to new and rehabilitated concrete pavements at MnROAD.
- Geotechnical Team – The team of experts develops long-term research test sections at MnRoad and prioritizes both short and long-term research projects related to bound and unbound used for pavement construction. The area of research includes grading and base, full-depth reclamation, and cold-in-place recycling for new and rehabilitated pavements. The team is involved in technology transfer to partners.
- Intelligent construction technologies (ICT) team – The ICT team is responsible for the planning, design, construction, real-time quality control, and monitoring and management of infrastructure construction using innovative technologies. The team undertakes short and long-term research and field evaluation of current and burgeoning technologies. Moreover, ICT collaborates with the industry to develop tools, technologies, and resources for implementation. The team is instrumental in the training of NRRA partners.
- Preventive Maintenance Team – It includes personnel with expertise in the maintenance of concrete and asphalt pavements. The team prioritizes research in the long and short term. Moreover, the team undertakes long-term research programs for the test section at MnROAD.

NRRA Membership

The NRRA has two levels of memberships: Agency and associate memberships.

- Agency Membership – This level of membership plays a central role in defining the objectives, goals, and the selection of research projects. The agency's annual membership fees depend on the size of State Planning and Research (SPR) funding of each state, where states with SPR dollars more than Minnesota are required to pay $150,000 otherwise $75,000. The state of Wyoming falls under the $75,000 funding level according to the 2018 SRR. The first phase of NRRA studies is expected to end by February 2021. A second pooled fund is expected to be created after the expiration of that phase.
- Associate membership – This membership consists of academic institutions, private companies, and associations interested in the development of research projects. Members provide input on research areas, advisory, and assistance roles to the project team on the

selection and planning of research programs. The annual membership fee for this category is $2,000.

Research Phases of MnROAD

Since its opening to traffic in 1994, the MnROAD research has gone through three main phases as follows:

- Phase I (1994 – 2007): Concrete and asphalt design thicknesses.
- Phase II (2008 – 2015): Partnerships with government, academia, and industry.
- Phase III (2017-present): NRRA teams.

Phase I

Phase I was implemented from 1994 to 2007 focusing on the structural performance of concrete and asphalt designs. This phase was funded mainly by the MnDOT and LRRB for construction and operation. The first research phase has helped MnDOT enhance design policies which result in increased pavement life. Under these main objectives, several studies were considered including seasonal load policies (winter and spring), mechanistic-empirical design (asphalt and concrete), asphalt binder grading, low-temperature cracking reduction, and improved pavement maintenance operations. It was found that the total benefits gained at MnROAD have led to annual savings for MnDOT of at least $33 Million representing a benefit-cost (B/C) ratio of 8.9 (Worel et al., 2008).

Phase II

The efforts in this phase centered on building partnerships with government, academia, and industry through the MnDOT and Transportation Engineering and Road Research Alliance (TERRA) to develop the needed support for building test cells, research projects, and implementation of findings (Van Deusen et al., 2018; Worel and Van Deusen, 2015). The priority of research and implementation activities was given to the development and calibration of a mechanistic-empirical design guide; implementation of innovative construction technology; improved preventive maintenance techniques; effective use of recycled materials; development and refinement of techniques for cost-effective pavement rehabilitation; understanding of pavement surface characteristics; and continued support of many non-pavement research areas. The annual benefits of the second phase were estimated to be more than $10 million representing a B/C ratio of 3.8 (Worel and Deusen, 2015).

Phase III

The reconstruction of the third phase began in 2016 with a unique partnership with the National Center for Asphalt Technology (NCAT) test track. Eight test sections were constructed of flexible pavements as part of the national cracking performance test experiment (Van Deusen et al. 2018). The partnership also advances national pavement preservation technology through the savings made from extended service life.

MnROAD has been a site for significant breakthroughs in pavement engineering (Choubane and Greene, 2019). Implementation of MnROAD research findings has led to reduced cost and sustainable transportation infrastructure for state DOTs. (Powell and Worel, 2016). Research findings lead to an increase in pavement performance, a reduction in maintenance cost, and repairs and delays (Worel and Van Deuse, 2015). Overall, MnROAD benefits have outweighed the costs (Worel and Van Deuse, 2015).

The National Center for Asphalt Technology (NCAT) Test Track

The National Center for Asphalt Technology (NCAT) test track was constructed in 2000 at Opelika, Alabama (Timm et al., 2006). The NCAT test track is a unique accelerated pavement testing facility that employs full-scale pavement construction with heavy traffic loadings traveling at highway speed for a comprehensive evaluation of asphalt pavements. It is sponsored and managed as a cooperative program (West et al., 2018). The facility was constructed at an estimated cost of $7.5 million in 2000 (Mucha, 2002). The track is located about 20 miles from Auburn University. The facility is operated and managed by the NCAT (Timm et al., 2006). However, many states, academic, and industrial parties are among the sponsors of the research programs. The test track was built to develop and evaluate better ways to design and construct hot mix asphalt (HMA) pavements (Brown et al., 2005).

General Layout

As shown in Figure A7, the NCAT test track is a 1.7-mile oval test track located on a 309-acre site in Lee County, Alabama. The test track consists of 46 test sections with an average length of 200 feet for each section, see Figure 2. The test sections are set up with different materials and experimental conditions (Brown and Powell, 2001). The track consists of a curve section with a speed limit of 45 mph (Brown and Powell, 2001). There are 26 test sections on the two straight segments of the track while the two curve sections have 10 experimental sections each. According to West et al. (2018), the test sections are sponsored on three-year cycles.

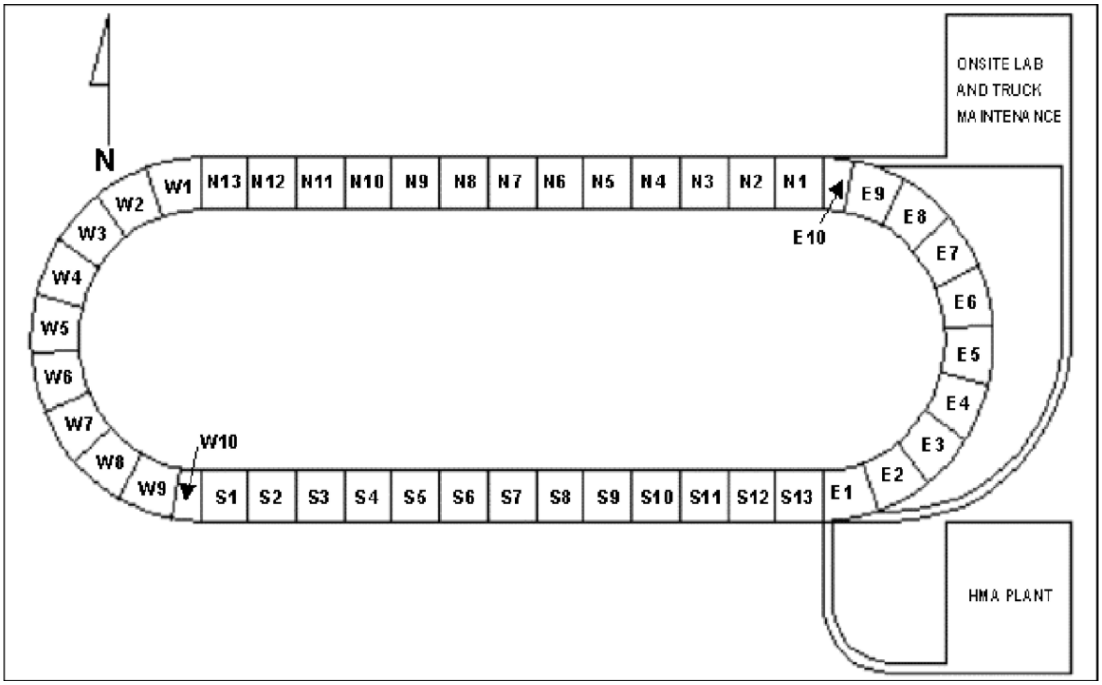


Figure A7. Layout of the test track (Brown et al. 2005).

Test Sections

The experimental sections are a product of cooperative research funding by FHWA and State DOTs such as Alabama, Florida, Georgia, Indiana, Missouri, Mississippi, North Carolina, Oklahoma, South Carolina, and Tennessee (Timm et al., 2006)

Research is conducted in a closed loop for every mix under similar environmental conditions and axle loadings. According to Brown et al. (2002), the accelerated test track was developed to allow the testing of several sections concurrently and rapidly. As discussed in the meeting, the experimental test sections are constructed with local materials hauled from sponsors to maximize the applicability of results to the sponsors. In specific situations, the test section may be divided into two subsections.

Test Cycles of NCAT

According to West et al. (2018), test sections are sponsored on three-year cycles. Test cycles consist of three (3) main parts:

- First part deals with building or replacing test sections which takes almost six months.
- The second part involves loading the section, collecting field performance and response data, and laboratory testing of construction materials. The test section is loaded with a fleet of a heavily loaded tractor-trailers to provide approximately 10 million 18,000-pound equivalent single-axle loads (ESALs) within a two-year period.
- Finally, a forensic analysis of the damaged sections is undertaken to investigate the factors affecting the existence of distress.

The facility has gone through a number of test cycles (West et al. 2018).

- First cycle – The inaugural cycle began in 2000 and focused on surface mix performance with 46 test sections.
- Second cycle – The second cycle started in 2003 with 26 original test sections built in 2000. The objective was to continue monitoring the pavement performance through the second cycle. Fourteen test sections had new surface overlays while eight sections had new pavement structures for evaluating the entire structure and not only the surface overlays. Strain gauges, pressure plates, and temperature probes were installed into the structural test sections to monitor pavement responses to the traffic and environment.
- Third cycle – The third cycle began in 2006 with 22 new test sections. The sections included 15 new surface mix performance sections, five new structural study sections, and two reconstructed sections.
- Fourth cycle – In 2009, the fourth cycle started and ended in 2012 with 25 new sections consisting of 12 mixed performance and 13 structural sections. It also included continued evaluation of existing test sections.
- Fifth cycle – The 2012 fifth cycle included new sections which focused on the use of recycled materials in pavements. The cycle also featured a study on pavement preservation.

State highway agencies (SHAs) used the research findings to improve material pavement designs, refined specifications, and cost-effective mixes. West et al. (2018) state that key findings of the research cycles are broadly classified into six areas: (1) mix design, (2) aggregate characteristics, (3) binder characteristics, (4) structural pavement design and analysis, (5) relationships between laboratory results and field performance, and (6) tire-pavement interaction.

Performance Monitoring

The NCAT testing track has a state-of-the-art laboratory and field-testing equipment for material testing, field testing, asphalt testing, and pavement forensic analysis as discussed during the meeting. Rutting and cracking are monitored weekly (Powell and Brown, 2004). Performance measurements such as friction, roughness, falling weight deflectometer, and densification are undertaken monthly (Brown et al., 2002).

The Organizational Structure of NCAT

The NCAT organizational structure consists of a director board, steering committee, research faculty and engineers, and staff of the NCAT test track research. These organizations are further described in the following subsections.

Board of Directors

NCAT has a board of directors that includes members from the NAPA research and education foundation, Auburn University, and the asphalt pavement industry. The board guides strategic plans and policies.

Applications Steering Committee

It consists of state DOTs, industry, and universities. Members meet twice a year to review the scientific and technical quality of research programs of NCAT and reports findings to the Board of Directors.

Research Faculty and Engineers

The team comprises the following:

- NCAT director
- Director Emeritus
- 5 Assistant Research professor
- 4 Assistant research engineers
- Laboratory manager
- Senior Engineer
- Test track manager
- Associate director and research professor
- Associate research professor, lead researcher
- Mechanical engineer
- Assistant director and research professor
- Training manager

Staff

The staff of the NCAT facility is located either in the main building or the test track. The staff includes:

- A business manager
- A communications specialist
- 2 administrative associates
- A financial assistant
- An office assistant
- A contracts and grants specialist
- 3 Laboratory technicians (2 are at the NCAT main facility)
- Trucking coordinator
- Trucking supervisor
- 6 drivers

Accelerated Pavement Testing (APT) Program at the Florida Department of Transportation (FDOT)

The Accelerated Pavement Testing (APT) program in Florida commenced in October 2000. The accelerated loading is provided with the Heavy Vehicle Simulator (HVS) Mark 4 model purchased in 1999. Subsequently, the HVS Mark 6 was also procured in 2017 for pavement research purposes. "The primary objective of FDOT's APT program is to continuously improve the performance of Florida's pavements" (Greene et al., 2013). The two facilities are owned and operated by FDOT and are sited within the State Materials Research (SMO) Park in Gainesville, Florida.

The HVS Program

The HVS program was used to investigate both hot mix asphalt (HMA) and Portland cement concrete (PCC) pavements. The construction of the test section employed field construction practices. The APT assets include:

- Dedicated test track
- Dedicated test pits designed with water table control capabilities within the base layers.
- State-of-the-art Laboratory (asphalt and concrete)
- 2 Heavy vehicle simulators
    - HVS Mark 4 purchased in 1999
    - HVS Mark 6 purchased in 2017

The HVS test tracks consist of 8 linear test sections built to simulate field construction practices. Five of the test tracks measure 450 feet × 12 feet while the remaining 3 test tracks measure approximately 150 feet × 12 feet.

The APT program has become a critical component of FDOT's pavement research program and provided useful information for policy-making (Choubane and Greene, 2019). The State of Florida has saved over $35 million due to changes in pavement design methods and construction practices based on the findings of the APT program (Greene and Choubane, 2012).

The Concrete Test Road

The concrete test road is a two-lane 2.5-mile experimental concrete road test that would be loaded with real-world traffic. The test road is constructed adjacent to the northbound (NB) section of the US -301 in Clay County, Florida. Traffic will be diverted occasionally to the concrete test road and directed back to the existing asphalt surface US-301 for pavement performance monitoring. Construction and earthworks began in 2016 and it is expected to open the test track to traffic in 2023. The test road is about a 45-minute drive from the SMO in Gainesville, Florida. The site location was selected based on the following:

- Adequate truck volume (significant truck route connecting NE and SW Florida) similar to interstate traffic.

- Proximity to SMO (40 miles)
- Minimal driveways or side street

Consortium of APTs in the U.S

The Consortium of Accelerated Pavement Testing (CAPT) is a group of full-scale APT facility owners and operators in the U.S. It seeks to generate coordinated impacts through full-scale APT. The mission of CAPT is to share and develop best practices and collaborate in experimental design, data acquisition, data sharing, and validation of findings. CAPT's vision is that owners and operators will improve and economize their operations and accelerate the acceptance of pavement performance findings. Because the scopes and objectives of the various participants' programs vary significantly, ten key emphases were developed by CAPT to balance and focus efforts. CAPT focuses its future efforts on the overall coordination of full-scale APT research in the US, including the day-to-day activities outlined as needs and gaps by the participants. CAPT seeks to provide more continuous attention in the form of a forum to discuss and improve relevant APT issues. The Consortium is operated under the Transportation Pooled Fund Program (TPF) (www.pooledfund.org) and sponsored by FHWA, TRB, and AASHTO. It enables technology transfer activities between several federal, state, regional, and local transportation agencies, academic institutions, foundations, or private firms to fund research as a pooled fund study. Areas that affect participant APT programs include the needs and gaps in instrumentation, common installation methods, data collection methods, and equipment and analysis of the data files.

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APPENDIX B: REGIONAL STATE DOTS SURVEY

APPENDIX C: INDUSTRY AND ASSOCIATION SURVEY

APPENDIX D: PAVEMENT RESEARCH NEEDS AND TEXT DATA MINING

Introduction

Pavements are a significant infrastructure component of a nation's transportation system. However, many countries around the world are faced with aging highways and airport pavements. Due to global economic challenges, these assets have not been maintained at the optimum levels. For instance, in the U.S., there is a nationwide road maintenance backlog of $435 billion (American Society of Civil Engineers, 2017), which keeps rising. Highway agencies are confronted with an ever-increasing challenge to find cost-effective ways to maintain these infrastructures at optimum levels within their maintenance budget constraints. Engineers had to explore better ways to understand pavement mechanics and identify new types of pavement structures, innovative materials, and construction methods to improve the state of the practice. This issue led to the development of Accelerated Pavement Testing (APT) facilities to bridge the gap between laboratory test characterization and full-scale long-term performance monitoring (Jones et al., 2012). APTs have gained popularity in recent years due to several associated advantages, including better simulating of long-term and in-service conditions in a short period (Ali and Mehta, 2016) and the ability to monitor and measure pavement responses cost-effectively with minimum risks (Jones et al., 2012). According to Powell (Powell, 2012), APTs have been used to fill the gap when significant changes in either vehicle or pavement technology have exposed inadequacies in the current state of practice. It is a reliable method of studying pavements (Liu et al., 2016) and has produced findings that formed most theories about pavements and design methods (Steyn 2012). Hugo and Martin define APT as "… the controlled application of wheel loading to pavement structures for the purpose of simulating the effects of long-term in-service loading conditions in a compressed time period" (Hugo and Martin, 2004).

APTs include several forms of traffic loading. Some APTs facilities are developed along a predefined testing lane and with a fixed vehicle simulator, while other APTs can be established along existing highways where sufficient traffic loadings exist. APTs have been instrumental in advancing pavement technology for decades since the establishment of the AASHO Road test in the 1950s (Jones et al., 2012). The objective of this study is to review the contributions of APT applications to the advancement of the pavement industry. In addition, text mining is applied to identify research studies presented at APT conferences held between 1999 and 2021. This technique has previously been used for analyzing trends of the 6th APT conference proceedings (Boyer et al., 2017). This study identifies research trends over all the APT conferences using the title and abstract of the articles and offering a more detailed analysis.

Review of APT Applications in Pavement Engineering Research

There have been numerous studies assessing the performance of pavement structures using APT techniques over the years. They have been used to (i) monitor and record important information and analyze the different factors that interact with the pavement; (ii) investigate the quantitative effects of loadings and the environment on fatigue performance and layer deformations; (iii) establish a reliable database to calibrate pavement design methods (Sun, 2005). Past experiences with APT facilities across the world are categorized into the following groups: (i) specification development and policymaking, (ii) pavement design, (iii) pavement responses, (iv) pavement models, (v) preservation and rehabilitation, (vi) construction practices, (vii) material characterization and testing, and (viii) innovative materials and technologies. The subsequent subsections present an overview of the APT applications in terms of the categories mentioned above. The aim of this review is not to provide details of the research components for the implemented studies. Instead, the study summarizes the main features of such applications to provide a comprehensive literature review for readers who can refer to the references provided for more details of the findings.

Design Specification Development and Policy Making

State Highway Agencies have made informed policy decisions based on research findings on pavement design, materials, maintenance, and rehabilitation strategies using APT facilities. Such results have proven to be serviceable and cost-effective under real-world conditions. Thus, they play a significant role in supporting highway planning, policy, and decision-making (Steyn, 2012; West and Powell, 2012). APTs have equipped pavement engineers with a better understanding of the performance of novel asphalt mixtures like heavy polymer-modified asphalt binder (Greene et al., 2014); coarse and fine-graded asphalt mixtures (Choubane et al., 2006; West et al., 2018), stone-matrix asphalt (Timm et al., 2006; West and Powell, 2012), open-graded friction courses (OGFC) containing hard limestone (West and Powell, 2012), and crumb rubber and polymer modified asphalt (du Plessis et al., 2018) overlays. The APT findings have facilitated the revision of design manuals and specifications for many highway agencies. In addition, based on the excellent rutting performance of Superpave mixtures evaluated with APT, some agencies decided to implement the Superpave mix design method (West and Powell, 2012; du Plessis et al., 2018). A framework for the statewide implementation of warm mix asphalt (WMA) technology in California was developed based on the findings from a heavy vehicle simulator (HVS) set in the APT (Jones et al., 2012). Consequently, states realized savings from integrating the WMA technology (Timm et al., 2006; West and Powell, 2012; West et al., 2018). APT has also proven to be an effective way to develop and revise the specifications for aggregate requirements for asphalt mixes and the use of crushed concrete or recycled asphalt pavement (RAP) in base layers (Worel and Deusen, 2015). The pavement design with cement-treated crushed rock and slag bases was revised based on the Australian Accelerated Loading Facility (ALF) (Rose and Bennett, 1994). Similarly, other researchers used APT facilities to modify the asphalt layer coefficient for the AASHTO design method, including the West et al. study (West et al., 2018). Levenberg (Levenberg et al., 2012) used the Purdue APT facility to evaluate the risk associated with low-air voids in asphalt mixes and developed a decision-making tool for placing asphalt mixtures with low-air voids. The understanding of pavement deformation behavior and failure mechanism was gained through APT studies incorporated in enhancing design specifications of flexible pavement (Nagabhushana et al., 2016; du Plessis et al., 2018). Test cells were sponsored to support the development of design and construction guidelines for thermally insulated concrete (Worel and Deusen, 2015) and bonded concrete overlays of asphalt for rehabilitation (Paniagua et al., 2016). Another important application of APT is studying the freezing and thawing conditions in cold regions which affects pavement response to loading (El-youssoufy et al., 2016). The spring thaw period presents a drastic reduction in bearing capacity and an increase in permanent deformation and fatigue damage under traffic loading (Cary and Zapata, 2011). Consequently, highway agencies enforce load restrictions during spring thaw seasons to minimize the effects of thawing on the pavement. These load restrictions have an impact on operations and businesses of freight transportation. Therefore, the pressure from freight transporters to increase allowable load limits led to various studies using APTs to make informed decisions on applying load restrictions (Arnold et al., 2005; Worel et al., 2008; El-youssoufy et al., 2016). Reforms are made based on the APT findings to improve load restriction decisions and efficiencies in freight transportation operations (Arnold et al., 2005) and pavement life-cycle costs (Worel et al., 2008). The relevance of structural designs to pavement engineering became the primary focus of several APT programs (Hugo and Martin, 2004). All in all, several contributions were documented from APT research to refine the following:

- Mechanistic design procedures for unbounded concrete overlays (West and Powell, 2012),
- Fully permeable pavements (Leiva-Villacorta et al., 2016),
- Perpetual pavements design criteria (Cary et al., 2018),
- Improvement in the fatigue design of low-noise surfaces (Alabaster and Fussell, 2006), and
- Airport pavement design procedure (Gopalakrishnan and Thompson, 2007)

Pavement Structural Performance

APTs have been used to evaluate pavement performances by studying its responses (Khoury et al., 2016). Several researchers used an APT facility to conduct studies to monitor the performance of both cracking (Prowell et al., 2007; Worel and Deusen, 2015) and rutting (Wu et al., 2000; Bazi et al., 2019). Other applications include the analysis of the performance of perpetual pavements (Willis and Powell, 2009; Khoury et al., 2016), thin asphalt concrete wearing courses (Druta et al., 2014), thin jointed concrete pavements (Burnham and Izevbekhai, 2012), asphalt-rubber, and conventional overlays (Harvey and Popescu, 2000; Harvey et al., 2001). Through the design experiments of APTs, researchers have demonstrated the excellent performance and applicability of SUPERPAVE mixes (Wu et al., 2000), asphalt mixtures containing river sands (Melhem and Sheffield, 2000), higher asphalt contents (Timm et al., 2006), and asphalt mixes containing highly modified asphalt binders (Khoury et al., 2016). Moreover, numerous studies were initiated to study tire-pavement interactions using accelerated means, including the impact of wide-base tires (Greene et al., 2010), tire type effect (Dessouky et al., 2013), and flexible airfield pavements under heavy aircraft loading (HVS-Airfields Mark VI) with high tire pressures (Wang et al., 2016). Other APT studies focused on tire-pavement noise and pavement surface characteristics (Smit and Waller, 2007), frictional properties, texture configurations, durability, ride quality, acoustic impedance, and HMA and PCC surfaces (Worel and Deusen, 2015). The objectives of other APT studies were to: determine environmental effects on dowelled and undowelled Portland cement concrete slabs (Sargand and Khoury, 2012), increase the resistance of bitumen-stabilized materials to moisture damage (Twagira and Jenkins, 2012), monitor the effects of aging and healing on top- down cracking (Zou et al., 2012), determine the impact of moisture (Erlingsson, 2010) and thawing conditions (Bilodeau et al., 2020) on pavement response and performance. Some engineers used APTs to understand the failure mechanisms in rubblized concrete pavements with HMA (Garg et al., 2012), the high-temperature deformations (Liu et al., 2016), and the deterioration of PCC airfield pavements (Cunliffe et al., 2016). Accelerated testing was further used to establish the relationship between different levels of dynamic loading and pavement performance (Pont et al., 1999), such as the effects of various multiple axle combinations on bituminous pavements (Khoury et al., 2016) and multi-wheel loading gear configuration on loading-induced failure potential of flexible airfield pavements (Wang et al., 2020).

Pavement Models and Performance Prediction

APTs bridge the gap between laboratory-based mechanistic models and full-scale long-term performance evaluation. They provide validation and calibration of mechanistic models developed based on hypotheses and assumptions (Jones et al., 2012). Contributions of APTs in pavement modeling are provided in Figure D1. Details of the findings in pavement modeling are published elsewhere (Selvaraj, 2007; Tia et al., 2007; Erlingsson, 2007; Henning et al., 2007; Willis and Powell, 2009; Kruger et al., 2009; Oscarsson, 2011; Steven et al., 2012; Bendtsen et al., 2012; Blab et al., 2012; Caicedo et al., 2012; Ahmed and Erlingsson, 2013; Aguiar-Moya et al., 2016; Leiva-Villacorta et al., 2016; Pokharel et al., 2018; West et al., 2018; Cheng et al., 2020; Ghalesari et al., 2020).

Preservation and Rehabilitation

According to the literature, the benefit-cost ratio of timely pavement preservation to roads can be estimated as high as 10:1 (Ram and Peshkin, 2013). Considering the quantum of maintenance backlogs and a limited budget for maintenance, engineers are using the opportunities presented at APT facilities to evaluate pavement preservation treatments, especially on testing tracks. In

2015, for instance, the Minnesota Road Research Project (MnROAD) and the National Center for Asphalt Technology (NCAT) partnered to advance national pavement preservation studies (Worel et al., 2020a).

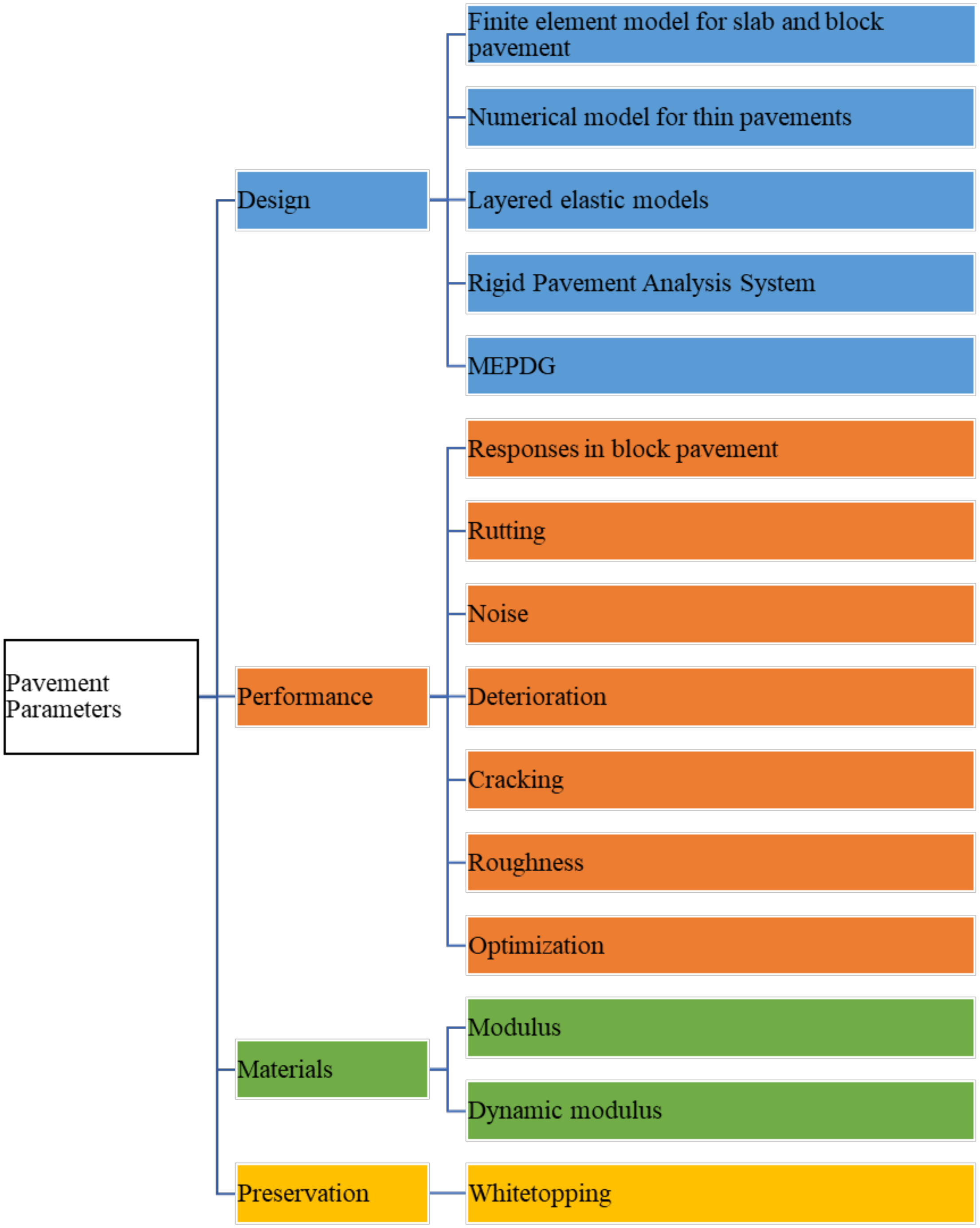


Figure D1. APT Contributions to Pavement Modeling.

Research in pavement preservation using APT includes chip sealing, micro-surfacing, crack sealing, thin overlays (West and Powell, 2012; Ali and Mehta, 2016), unbonded concrete overlays (Worel and Deusen, 2015), high polymer inlays (Powell, 2012; West and Powell 2012), high precision diamond grinding (Timm et al., 2006), slurry seals (Worel et al., 2009), overlays (Greene, 2016), full-depth reclamations strategies (Romanoschi et al., 2004) and whitetopping for rehabilitation (Tia et al., 2007). Other test sections in the Florida HVS facility featured studies on the early strength requirement of slab replacement concrete (Worel et al., 2009) and the effectiveness of using epoxy-coated steel and fiber-reinforced polymer dowels in PCCP joint repairs (Hossain et al., 2012).

Construction Practices

Several studies are underway at test track facilities like the MnROAD to promote intelligent compaction (IC). The findings have led to the development and implementation of pilot specifications of IC technology (Tompkins et al., 2007). Benefits of IC include improved construction quality, reduced compaction cost, reduced life-cycle cost, and integration of design with construction and pavement performance (Petersen et al., 1975). Other related studies have evaluated the lowest air void limits of HMA and RAP as granular base course material (Willis et al., 2009). Other studies evaluated the effects of constructing granular layers at different densities (Patrick and Werkmeister, 2010). The loss of bonding between layers can affect the performance and life of the pavement. Numerous studies have been sponsored on APTs to focus on interface bonding (Harvey et al., 2000; Ozer et al., 2012), optimum tack rate for HMA overlay interface bonding (Sufian et al., 2016), the performance of asphalt layers with or without a tack coat (Harvey et al., 2000). As far as traffic opening criteria for concrete pavements, a study was able to find the affecting factors on the traffic opening using the APT facility of the Indiana Department of Transportation Research Division (Antico et al., 2015).

Material Characterization and Testing

The engineering properties of materials are essential for pavement design and performance. Knowledge of the behavior of materials is critical to understanding the performance of pavements as freight transportation increases (Yeo and Young, 2012). Researchers have investigated, through APT testing experiments, the different types of shear transfer devices for jointed plain concrete pavement (JPCP) (Hossain et al., 2012), stainless steel hollow tube dowels (Khazanovich et al., 1947), bearing capacity of pavements (Arraigada et al., 2016), the nonlinearity of granular materials and soils (Leiva-Villacorta et al., 2016) and the strength modulus and fatigue properties of cemented pavement materials (Yeo and Young, 2012). They were also used to determine the structural coefficients of Cold Central-Plant Recycling asphalt mixtures (Díaz- Sánchez et al., 2017), structural coefficients of the OGFC layer (Timm and Vargas-Nordcbeck, 2012), and the optimum properties of geocell reinforcement for building sustainable low-volume paved roads (Khoury et al., 2016).

Innovative Materials and Sustainable Technologies

The APT testing method is a practical approach to evaluating new pavement materials and structures before implementation in the field (Jansen et al., 2018). Several studies have used APTs to promote the implementation of WMA technologies and pervious concrete (Prowell et al., 2007; Worel and Deusen, 2015), thermally insulated concrete pavements (Worel and Deusen, 2015), RAP (West and Powell, 2012; du Plessis et al., 2018), Stone Matrix Asphalt (du Plessis et al., 2018), stress-absorbing membrane interlayers (Greene et al., 2012), Ground Tire Rubber to substitute Styrene-Butadiene- Styrene (SBS) (Willis et al., 2012), Polyphosphoric Acid Modified Asphalt (Worel and Deusen, 2015), and rubber modified binders (Caicedo et al., 2012) in HMA. Likewise, the evaluation of alternative binders like Trinidad Lake Asphalt and Thiopave pellets for use in asphalt mixtures (West et al., 2018) under long-term monitoring was made possible by APT facilities. In addition, the APT facilities monitored the effect of geocomposite reinforcement on pavement performance (Ingrassia et al., 2020). Other contributions of APT to promote sustainable pavements include cold central-plant recycling with 100 percent RAP and foamed asphalt as a recycling agent (Díaz-Sánchez et al., 2017), RAP in unbound granular layers (Ozer et al., 2012), bio-materials with RAP (Blanc et al., 2019), and crumb rubber modifier binders (Mohammad et al., 2000). With regards to subgrade and base stabilization, APT test sections evaluated the performance of geocell reinforcement (Caicedo et al., 2012) and nano-silane-modified emulsion (Rust et al., 2020), foamed bitumen (Gonzalez et al., 2009), stabilized base materials, and the performance of foam bitumen stabilized aggregates (Gonzalez et al., 2009). Other APT-related studies evaluated the technologies of rigid pavements, including fiber-reinforced roller-compacted concrete with RAP (Nguyen et al., 2012), roller-compacted concrete (Worel and Deusen, 2015; du Plessis et al., 2016), High- Performance Concrete Pavement (Worel and Deusen, 2015), recycled crushed concrete (Steven et al., 2012), permeable and skeletal soil block pavement systems (Ahmed et al., 2016), and evaluation of crack attenuating mix on slab concrete pavement (Willis et al., 2009). The research was undertaken with APT facilities to investigate the feasibility of using taconite aggregates (Worel and Deusen, 2015) and limestone and gravel blend mixture (Powell, 2016) for building pavements. Other APT applications include investigating porous asphalt pavements for low-volume roads (Worel and Deusen, 2015) and reinforced flexible pavements with geogrids (Tang et al., 2008, 2016).

Economic Benefits of APT Applications

The benefits of APT applications can be quantified in monetary terms. The process of quantifying these benefits has been at the fore of APT discussions. The second and third international APT conferences focused on the impacts and benefits of APT (Jones, 2012). Several authors have used different approaches to evaluate the benefits of the APT program. The benefits are generally reported in B/C ratios and agency cost savings. Louisiana DOT realized savings of about \$8.17 million (3-year analysis period) resulting in a benefit-cost (B/C) ratio of 5.3 from their ALF program (King Jr. and Rasoulian, 2004). The B/C ratio of the South Africa

HVS program approximately ranges from 2.0 to 10 (Sampson et al., 2008). A preliminary assessment of California's APT program is reported to approximately range from 3.0 to 10.0 (Plessis et al., 2008). MnROAD reported total economic benefits of more than $396 million obtained during the test track operation from (2000-2012) with a B/C ratio of 8.9 (Worel et al., 2008). The overall B/C of the Australian ALF program was estimated at 4.0 and 5.0 at a discount rate of 8 percent and 4 percent, respectively (Rose and Bennett, 1994). Steyn reports that the B/C ratio for most APT programs ranges between 1.4 and 11.6 (Steyn, 2012). The results show that APT programs are economically advantageous. The authors used deterministic and probabilistic approaches in addition to sensitivity analyses to determine the benefits of APT facilities. However, these approaches have their own limitations. The literature review on calculating APT benefits reveals some level of difficulty in the evaluation of the economic evaluation due to the uncertainties and subjectivities of input data and contributions of the findings. Du Plessis et al. (2011) and Jones (2012) used sensitivity analysis to address such limitation issues of uncertainties. APT researchers and owners are encouraged to consider using soft computing techniques like fuzzy logic, and spherical fuzzy logic to address the effects of uncertainties, subjectivities, and hesitancy in conducting an evaluation of the benefits of the program.

Summary of Findings

Based on the extensive literature review, APT facilities were found to have the ability to monitor structural performance, improve pavement modeling, develop construction technologies, enhance materials characteristics, and support rehabilitation techniques and novel materials usage under full-scale conditions. There is no doubt that the findings provide a sound basis to develop, validate and revise design specifications and policies that will improve pavement performance and its life cycle cost. APTs give highway agencies an ideal environment of how the pavement will behave in real life beforehand. It is a proactive technique in designing and managing pavements. They have proven effective in evaluating pavements quickly with little disruption to the traveling public and airfield operations. Table D1 summarizes the categories of APT application in pavement research.

Table D1. Example of APT Applications in Pavement Engineering.

Accelerated Pavement Testing Applications	**Subtopics**
Design specifications and policy	• Pavement Design Guides • Superpave Mixtures • MEPDG Refinements • Construction Guidelines • Load Restriction Policies
Structural performance	• Cracking Performance • Rutting Performance • Roughness • Bearing Capacity
Pavement modeling	• Deterioration Models • Mechanistic models • Finite Element models • Temperature models • Viscoelastic models • Performance models
Preservation and rehabilitation	• Chip Sealing • Crack Sealing • Micro-surfacing • Overlays • Full Depth Reclamations • Concrete Pavement Rehabilitation
Construction technology	• Intelligent Compaction • Interface Bonding • Traffic Opening Criteria
Material characterization	• Binder Grades • Layer Coefficients • Modulus
Innovation and sustainability	• Warm Mix Asphalt • Recycled Asphalt Pavements • Modified Binders • Alternative Binders • Bio-materials • Geocomposites Reinforcement • Roller Compacted Concrete • Fiber Reinforced Pavements • Alternative Aggregates

Studies on preservation treatments appear to be common among the different APT types. Test roads, HVS, and other linear devices have proven effective in evaluating preservation treatments to extend the service life of asphalt and concrete pavements. Making the construction techniques more intelligent can reduce road user costs, provide high-quality pavement with longer life, and improve safety. Space availability appears to give test roads more leverage to conduct more studies on intelligent compaction over the other testing alternatives. However, the HVS, ALF, Mobile Load Simulator (MLS), and others could explore opportunities to promote intelligent construction. Both full-scale (test roads, HVS, MLS) and scale-down versions (MMLS3, MLS66) of APT techniques have demonstrated the capacity in evaluating the performance of new technologies before large-scale implementation. The concept of transport innovation and sustainability appears to be growing among APT facilities around the world. These facilities play significant roles in promoting sustainability in infrastructure development, including exploring alternative aggregates, binders, modified asphalt mixtures, water-retaining pavements, and long-lasting pavements. The potential to reduce emissions, conserve virgin aggregates, promote safe construction, lower the life-cycle cost of pavements, and provide a more sustainable transportation system appears more achievable looking at the current contributions of APTs in innovation and sustainability. In the future, APT facilities could explore emerging pavement technologies like reflective, evaporative, and energy-harvesting pavements, bio-asphalt mixtures, nanoclay-modified binders, nanomaterials in concrete pavements, and prestressed concrete pavements. The objective of improving pavement cracking and rutting performance is shared among the different APT studies.

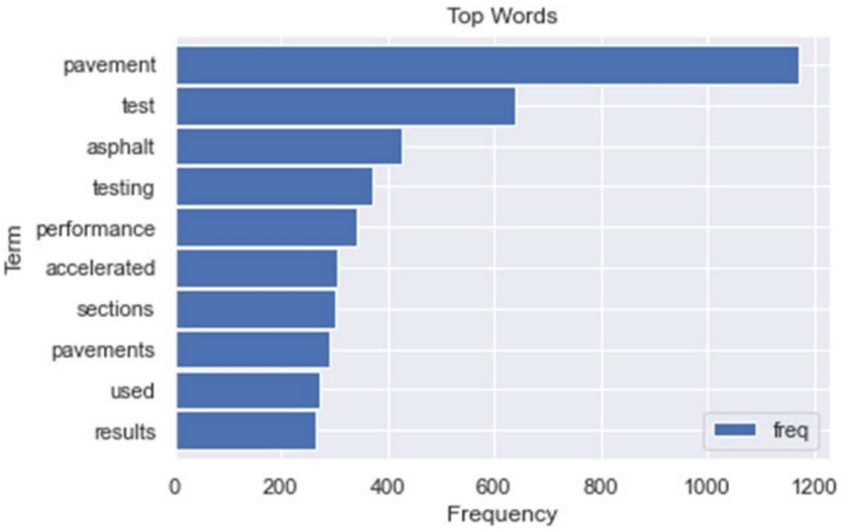
Integrating Text Mining of Apt Conference Papers

Conference proceedings have been a powerful platform where APT owners share data and experiences. The papers presented at these conferences cover diverse subjects and represent current trends and developments in APT. The number of papers accepted for presentation at the conference makes it challenging for an individual to read all the articles. Text mining offers the opportunity to extract knowledge from extensive unstructured textual data to visualize better and understand text trends. In this study, text analysis was done on 323 papers presented at the APT conference proceedings. Table D2 shows the six APT conferences, the venue, and the volume of accepted papers accepted for the conference proceedings. The table also shows the volume of papers used for the text analysis. The papers were taken from a compendium download available on the TRB website and publication of the conference proceedings. Some papers were excluded from the corpus due to errors or corrupted files. Others were also withdrawn because they were reviews of all APT facilities. The focus of this analysis was to look at what individual APT facilities were presenting at the conferences. The corpus is made up of the abstracts and titles of these papers. The conferences have been hosted in different parts of the world, signifying international alliances and diversity.

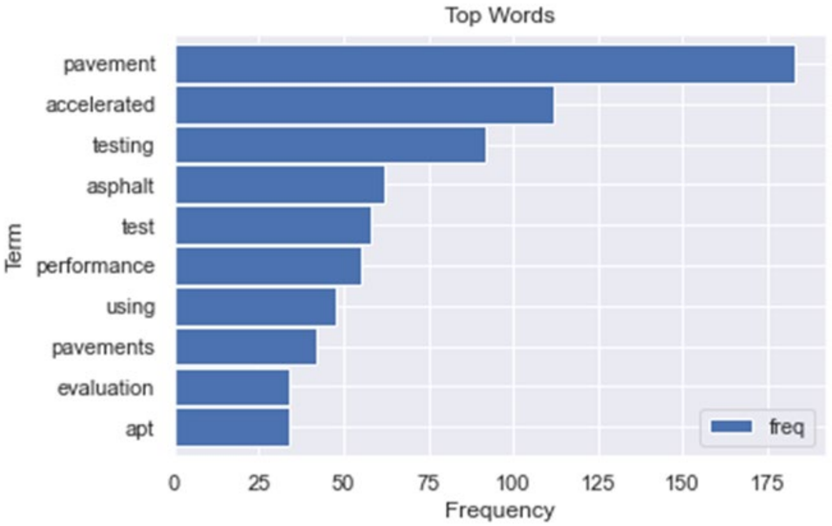
Table D2. Distribution of Papers in International APT Conference Proceedings from 1999 to 2021.

APT Conferences	Date Held	Venue	Number of Papers Accepted	Number of Papers in Corpus
1st International Conference on APT	1999	Nevada	62	48
2nd International Conference on APT	2004	Minnesota	63	44
3rd International Conference on APT	2008	Spain	65	54
4th International Conference on APT	2012	California	55	53
5th International Conference on APT	2016	Costa Rica	58	54
6th International Conference on APT	2021	France	73	69

A common task in text mining is the determination of the most frequently used terms in the corpus. Figure D2 illustrates the most frequently used terms in the corpus of paper abstracts and titles. The top three frequently used terms in the abstracts are "pavement," "test," and "asphalt." Likewise, in the title corpus, "pavement," "accelerated," and "testing" are the three most cited terms. It is evident that there is a slight difference in the most cited terms in the abstract and the title, but "pavement" is the most frequently used term in both groups. The paper abstract contains a brief introduction and summary of the entire paper. The word cloud is another way to represent the most frequently used terms in the text data set. The word cloud for the abstract and the title is shown in Figure D3.

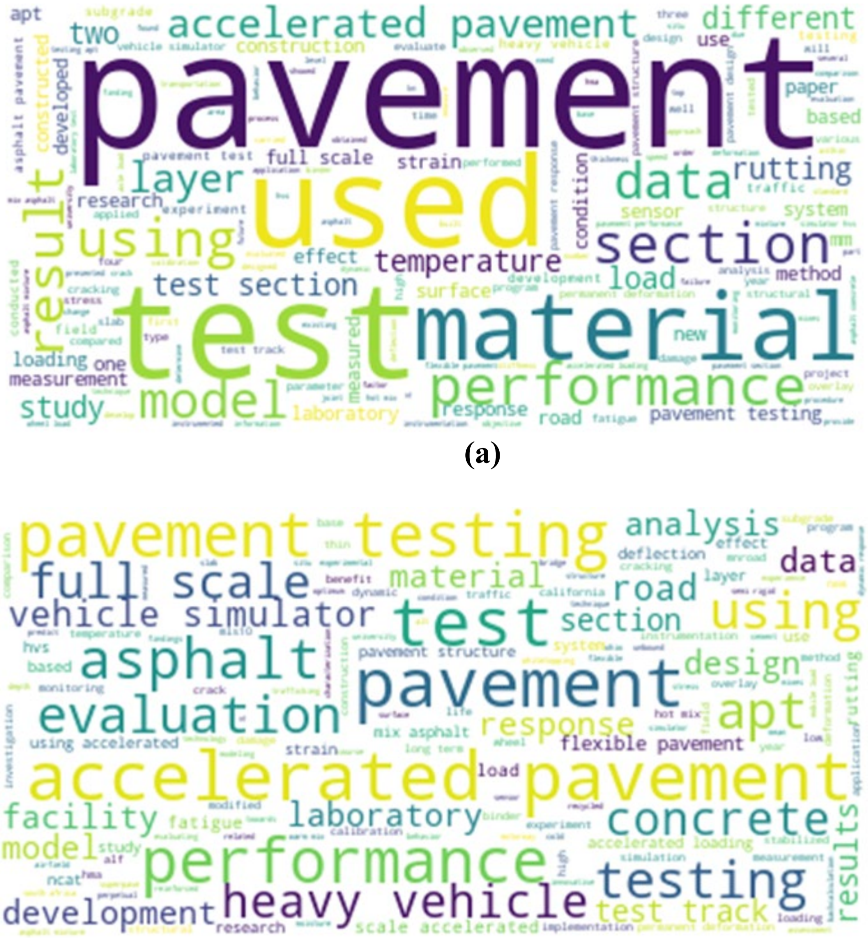


(a)



(b)

Figure D2. Top 10 Frequent Words in (a) Abstract (b) Top 10 Words in Title.



(a)

(b)

Figure D3. Word Cloud (a) Abstract (b) Title.

The heat map of the 13 most frequently used terms in the paper abstracts is shown in Figure D4. The darker colors indicate high-frequency usage, while the lighter color indicates otherwise. It is not surprising to see "pavement" and "test" remain popular terms over the years. The frequency of other terms changes with time. Another notice was found that asphalt was commonly mentioned in both titles and abstracts more than concrete. This indicates that most APTs programs have been focusing mainly on flexible experiments rather than concrete. This could be due to the fact that asphalt deteriorates at rapid rates due to both traffic and environmental conditions. The reliability of concrete pavement has been relatively higher than asphalt pavement. Hence, higher investigations were implemented for asphalt performance including rutting and cracking.

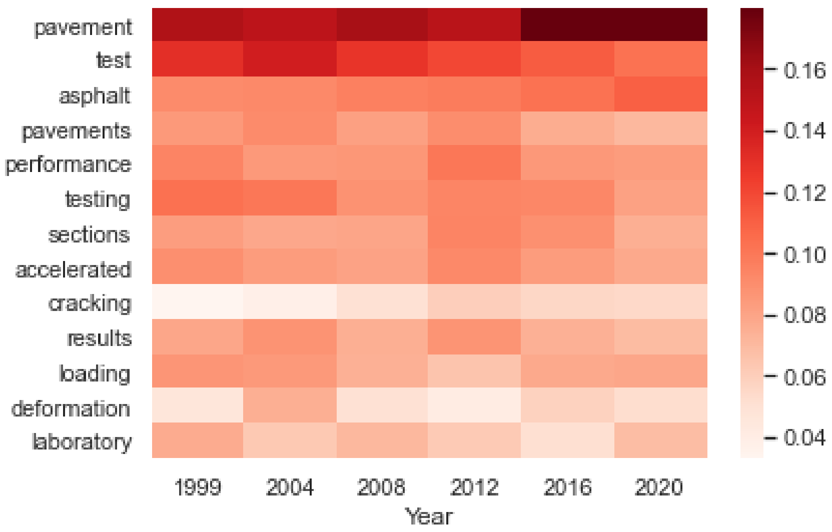


Figure D4. Heat Map of Most Frequently used Terms in Paper Abstract.

The study also investigated the network of the APT research community. Figure D5 shows the top 10 country affiliations in the published APT conference papers. APT conferences have accepted papers from different countries, with many papers coming from the U.S. (U.S). The U.S. has over 16 APT programs in operation. Some of the APT programs in the U.S have more than one testing device. The Florida DOT, for instance, operates two HVS machines (HVS Mark IV and HVS Mark VI) and has initiated the construction of a 2.5-mile concrete test road. The University of California Pavement Research Center (UCPRC) owns two HVSs for accelerated testing of full-scale pavements. The contribution of the U.S to APT development is therefore not coincidental but shows real interest to improve the understanding of pavements.

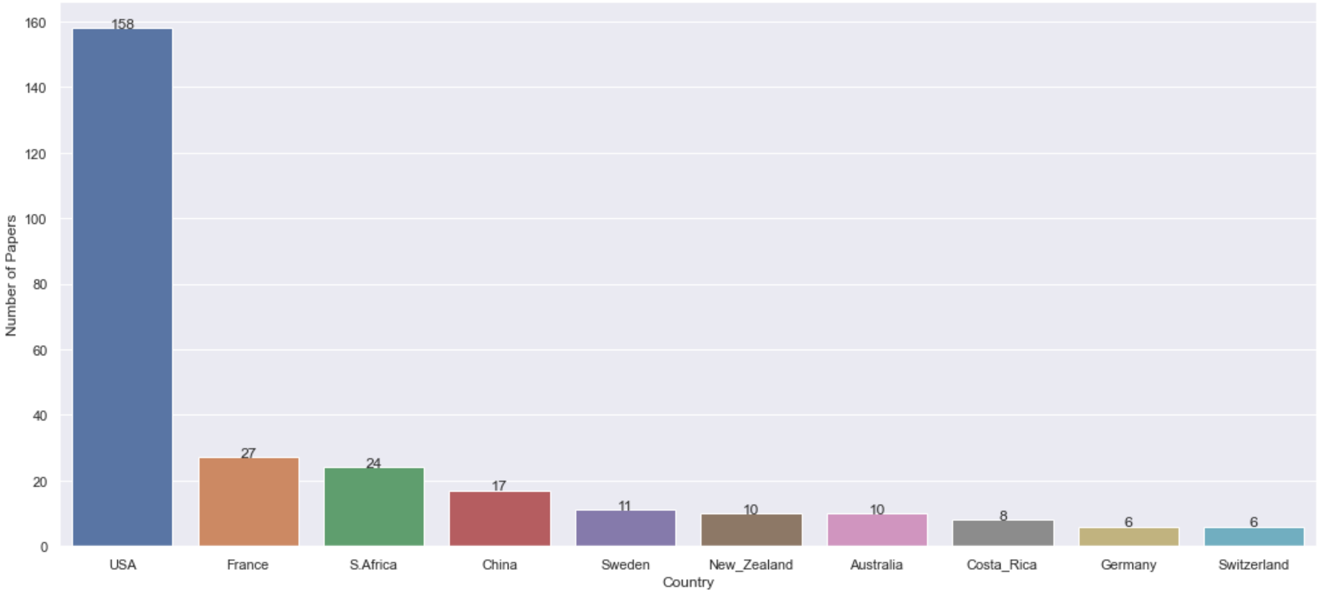


Figure D5. Top 10 APT Country Affiliations.

There are different types of APT loading techniques. Figure D6 illustrates the top 10 APT devices affiliated with the published papers. The definition of these devices is listed in Table D3. The HVS device is undoubtedly the most popular APT program. Its popularity may be attributed to the ability to produce results in a relatively short time, historical achievements, returns on investments, and the ability to modify the HVS to suit the needs of the owner, including environmental control. Moreover, the development of HVS user groups and the ability to share and transport the device may also be contributing factors. For instance, Finland and Sweden jointly operate the HVS-Nordic research program. The HVS can be operated both indoors and outdoors effectively. On the other hand, the use of test roads to evaluate pavement under real-world conditions is evident. Though the number of APT test roads is not many globally, they appear to be making significant contributions to pavement engineering. The different APT types have proven effective in evaluating long-term pavement performance under a range of loading and environmental conditions within a compressed time. However, each testing technique has its pros and cons, and it is up to an agency to choose which one best suit its needs and available resources.

Figure D7 shows the network analysis to represent the relationship between words. The network graph consists of nodes and edges. In Figure D7(a), the corpus of APT conference proceedings is represented as a network where each node is the APT device/technique, and the thickness or strength of the edges between them describes the similarities between the words used in any two documents. Likewise, the country network in Figure D7 (b) shows the similarities between the words used in any two documents. The nodes are colored by their cluster or modularity class. Networks with high modularity have dense connections between the nodes. The network graph of country affiliations indicates the connectedness in research interests. The diversity in APT research to improve pavement performance is evident in the country affiliation network.

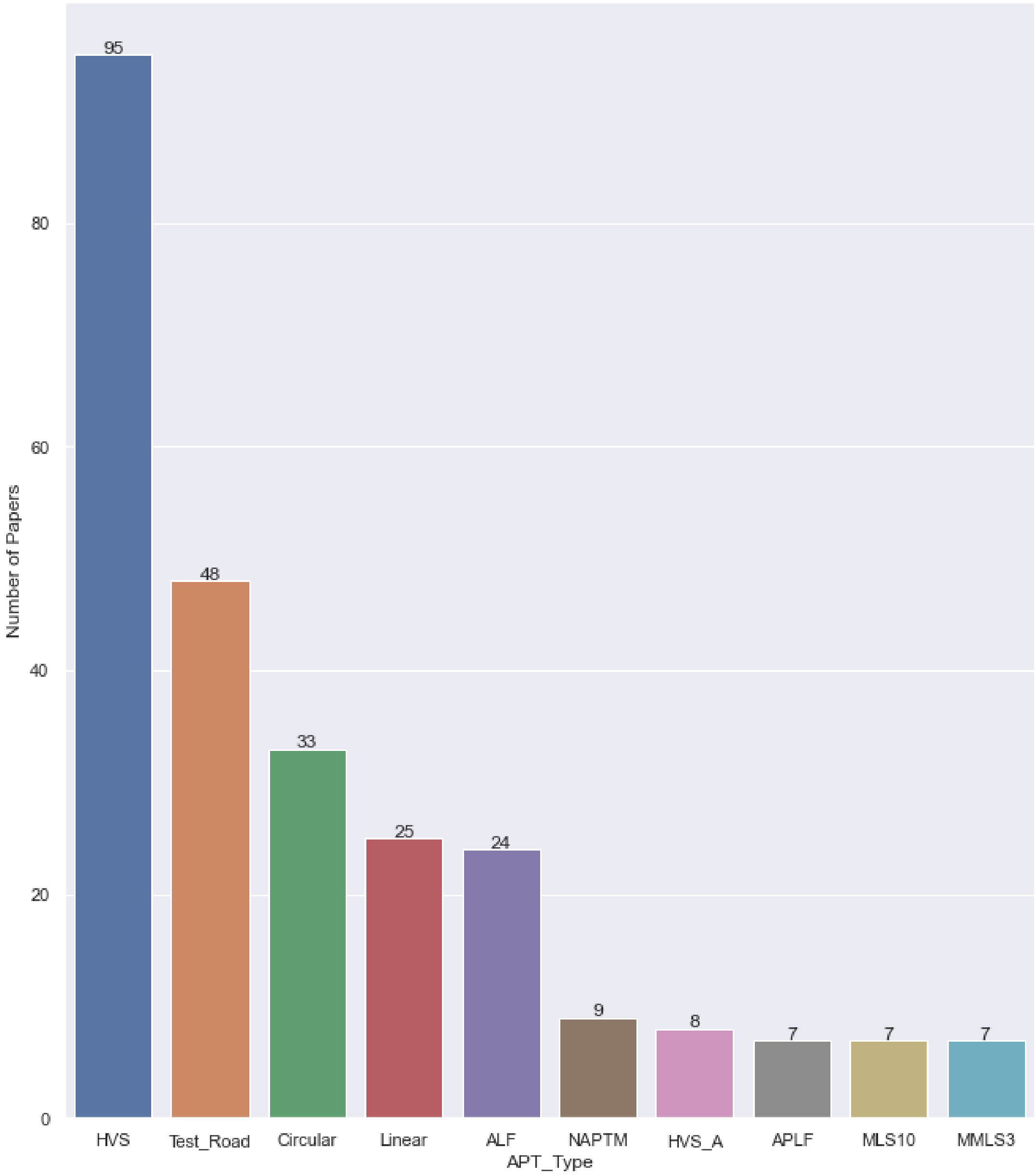
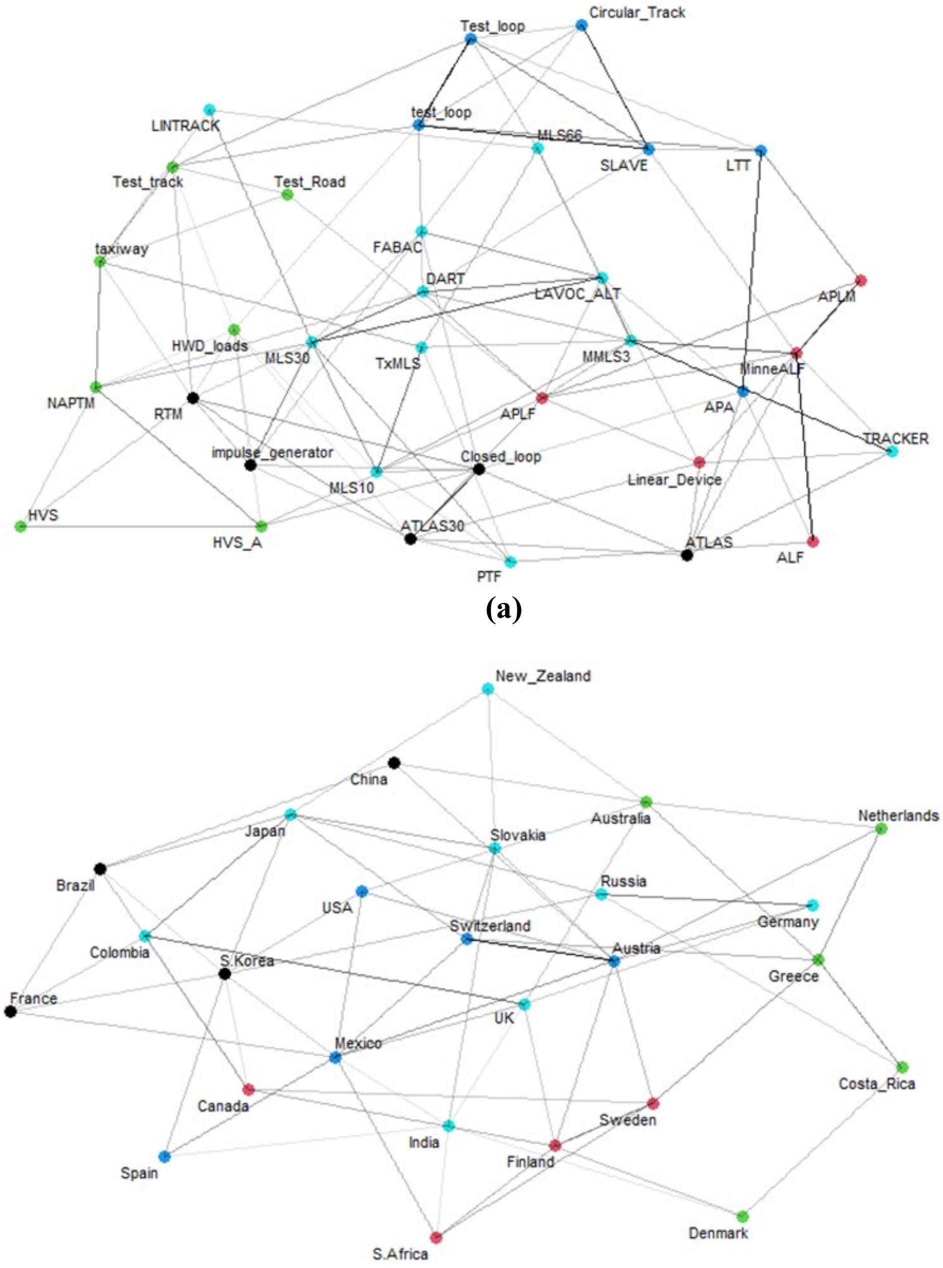


Figure D6. Top 10 APT Device/Technique Affiliations.

Table D3. List of APT Devices and their Abbreviations.

APT Device/ Facility	**Abbreviation**
Pavement Testing Machine	PTM
Mobile Load Simulator	MLS
Heavy Vehicle Simulator	HVS
Texas Mobile Load Simulator	TxMLS
Accelerated Loading Facility	ALF
Pavement Test Facility	PTF
Accelerated Pavement Load Facility	APLF
National Airport Pavement Test Machine	NAPTM
Asphalt Pavement Analyzer	APA
Accelerated Pavement Loading Machine	APLM
Accelerated Pavement Loading System	APLS
Accelerated Transportation Loading Assembly	ATLAS
Danish Asphalt Rut Tester	DART
Airport Heavy Vehicle Simulator	HVS-A
Heavy Weight Deflectometer	HWD
Accelerated Loading Testing	ALT
Linear Tracking Device	LINTRACK
Laboratory Test Track	LTT
Minnesota Accelerated Loading Facility	MinneALF
Model Mobile Load Simulator	MMLS
Danish Road-Testing Machine	RTM
Stationary Dynamic Deflectometer	SDD
Simulated Loading and Vehicle Emulator	SLAVE
Circular Test Tracks	Circular
Linear Test Tracks	Linear



(a)

(b)

Figure D7. Network Graph of (a) APT Devices (b) Country Affiliations based on Paper Abstracts.

An algorithm was developed to count certain keywords of interest to the authors. The objective is to identify the trend of these keywords across the APT meetings, as shown in Figure D8. It is evident that a wide scope of topics is addressed using the APT program with a traditional focus on HMA. The interest in HMA topics is higher than in Portland cement concrete (PCC). The figure shows an increased emphasis on HMA across APT meetings. The increased focus might be attributable to the large network of asphalt pavements in countries. The U.S, for instance, has about 2.6 million miles of paved roads with over 94 percent asphalt surfacing (about 18 billion tons of asphalt), according to the National Asphalt Pavement Association. The interest may also be attributed to the concerns about its complex viscoelastic behavior at different temperatures and loadings and the need to enhance its property compared to the more rigid and stable PCC pavement.

Investigation of airfield pavements was evident at the conference discussion. This implies that APTs are capable of investigating both highway and airfield pavements. There appears to be a rising interest in airfield pavements since the 4th APT conference. This may be attributable to the need to evaluate airfield pavements due to the changing aircraft designs and configurations and the use of heavy airplanes with high weight and high tire pressures. It is evident that cracking and rutting have been evaluated most often with APT devices. Permanent deformation or rutting performance of pavements appears a popular distress topic investigated than cracking/cracks. Pavement serviceability is affected by asphalt rutting and conducting this study under full-scale testing may have more direct benefits on the serviceability of pavement than cracking. This may be the reason behind the interest in rutting studies. However, a decline in the term "rut" in the last APT conference suggests that agencies may have identified ways to improve the rutting performance of pavements using APT facilities. The frequency of the term "crack" change with time, but a sharp increase is seen in the last conference (2020). The renewed interest to gain a better understanding of the crack phenomenon and propagation may have accounted for the increase. The term “models” has changed over the years but appears to be a prominent keyword in APT programs. APTs have been used to build or validate models for predicting pavement behavior and performance. It appears that APT programs apply a range of models to analyze research data.

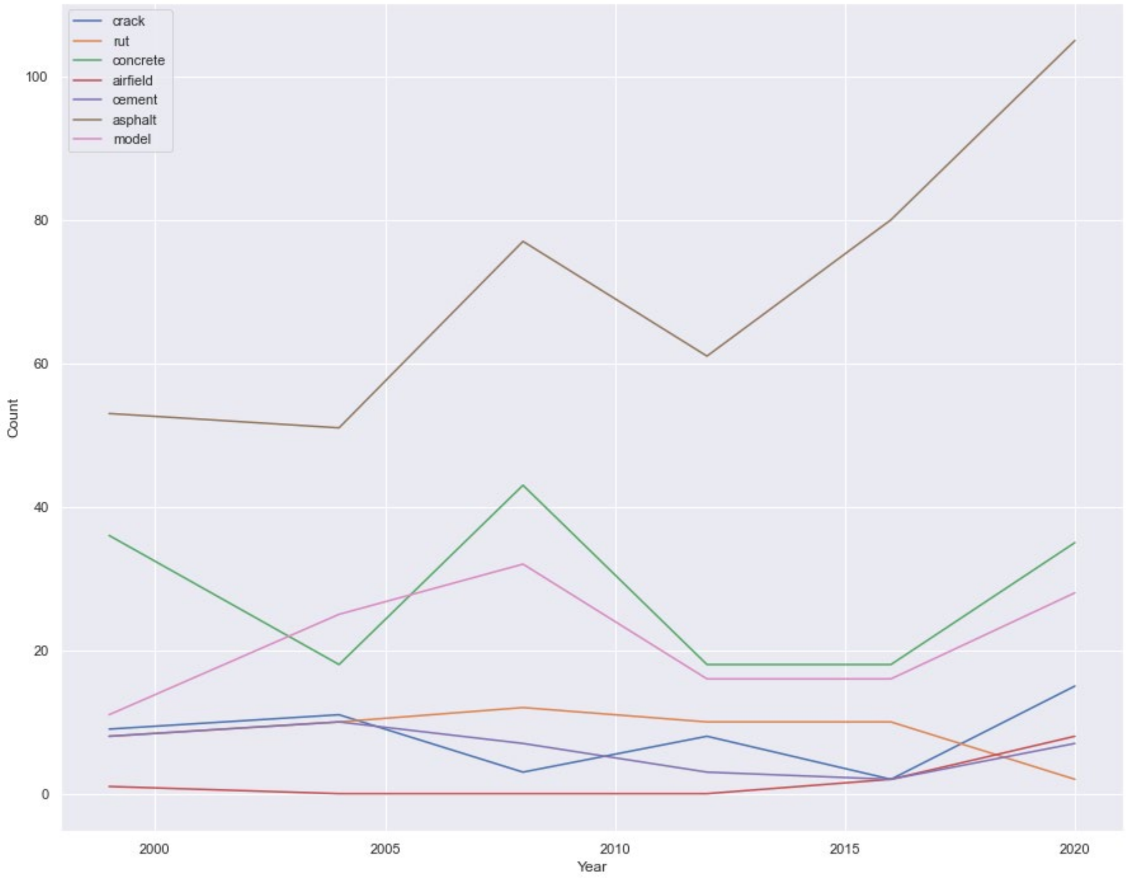


Figure D8. The trend of certain Words in Corpus across the International APT Conferences.

Conclusions

Findings from APT have supported decision-making in specification development and revision; enforcement of axle loading policies which could not have been achieved alone with laboratory evaluations. These facilities provide engineers with an improved understanding of pavement materials, structure, and responses under loading effects, providing improved cost-effective designs, preservation, and rehabilitation. The concept of technology, innovation, and sustainability in pavements is evident in APT research efforts. An integrated program of APT, extensive laboratory testing and modeling promotes the implementation of findings and the success of the APT program. Text mining is a straightforward approach that can help pavement engineers to extract valuable information from texts that takes advantage of language characteristics particular to the pavement industry. Indeed, APT discussions have primarily focused on accelerated testing of pavements with more focus on asphalt pavement performances, including rutting and cracking. APT of asphalt pavements using Heavy Vehicle Simulators (HVS) dominated the meetings of APT conferences. Laboratory evaluations with full-scale testing are essential to relate in-service conditions and laboratory performance. Research on airfield pavements was presented at the conference. Findings from the text mining agree with the significant findings from full-scale APT published in National Cooperative Highway Research

Program (NCHRP) 433. Text mining has shown promise in identifying developments and trends in APT research. Opportunities exist for future research in emerging pavement technologies, including nanotechnologies. More advanced text analytics tools like the Latent Dirichlet Allocation (LDA) models are potential tools for future analysis in APT.

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APPENDIX E: NON-PAVEMENT RESEARCH NEEDS AND TEXT DATA MINING

Introduction

In this appendix, a review of the applications of APT facilities for non-pavement research is presented based on experiences from around the world. The applications of APT in non-pavement research over the years are put under nine broad categories: (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 review fills that gap and raises the awareness and familiarity of applying APTs for non-pavement research activities. Suggestions for the proposed Wyoming test road facility and other APTs are made regarding non-pavement research applications based on the findings.

In general, collaboration in scientific research has seen tremendous growth in recent decades (Abramo et al., 2019) 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 requires multidisciplinary collaborations; the integration of theories, methods, and instruments from diverse fields (Abramo et al., 2019). In addition, these research collaborations can be made through policy and research–management initiatives (Cassi et al., 2017; Van and Hessels, 2011). Research collaborations can either be among institutions in the same or different fields (Abramo et al., 2019). Tompkins and Khazanovich (2007) 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 (Worel, 2021). 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 (Worel, 2021).

Using APTs for non-pavement research may come with its own benefits. According to (Wore et al., 2020), 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 (Wore et al., 2020). Operation costs and the lack of consistent institutional support partly due to political changes are major hindrances to the activities of APT facilities (Wore et al., 2020; Powell, 2012; JvdM Steyn and Hugo, 2016). The building of experimental sections alone can be costly (Choubane and Greene, 2021; NCAT, 2021), and thus make partnerships and collaborations, imperative for cost-effectiveness (Steyn, 2012). 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 help to diversify funding needed for fiscal stability, successful operations, prolonged existence, and resilient (Wore et al., 2020).

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 (Highway Research Board, 1962) is quite diversified. In Figure E1, 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 study covers an interesting aspect of APT facilities that is not widely appreciated by the public. The information should provide a useful basis for the application of APT facilities in other areas apart from pavement research.

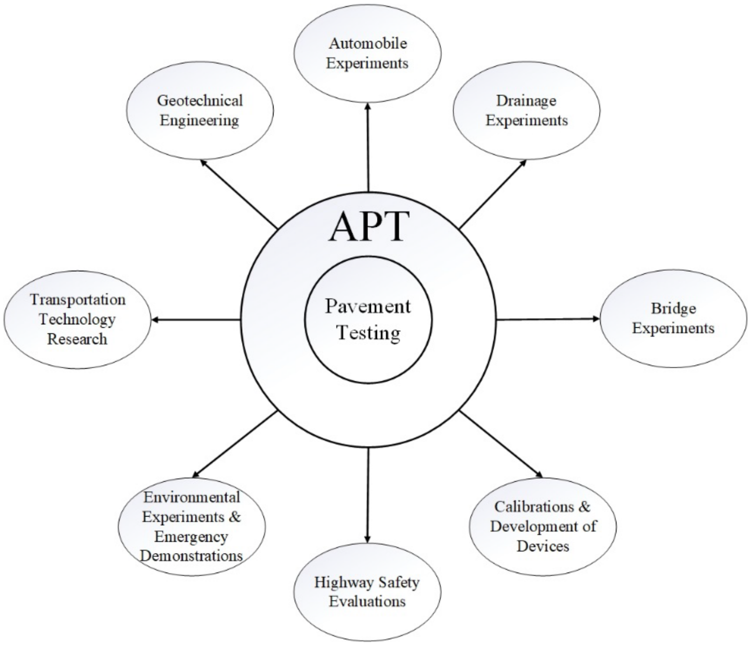

Figure E1. Schematic of Pavement and Non-Pavement Research Applications of APT facilities.

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 (ASCE, 2021), the U.S. has 617,000 bridges with an overall grade of C. It reports that structurally deficient bridges constituted 7.5 percent 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 keeps increasing. On the other hand, studies on recent bridge failures in the U.S. categorized the principal causes of bridge failures as deficiencies in design, detailing, construction, maintenance, use of materials, and inadequate consideration of external events (Sanders and Zhang, 1994). According to (Tolliver et al., 2011), bridge decks deteriorate faster than the other parts due to 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 (Madanat et al., 1997), deteriorate bridges faster. Research efforts to understand bridge responses to traffic loading are 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 (Highway Research Board, 1962), the AASHO Road Test was used to conduct studies on bridges. Trafficking in the bridge section is shown in Figure E2. 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 (Highway Research Board 1962; AASHO, 2021). 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 its test track facility to investigate the overload behavior of an experimental precast prestressed concrete segmental bridge (Abdel-Halim et al., 1987). The same facility has also been involved in the investigation of bridge loadings, designs, construction, monitoring, and evaluation (Penn State Engineering, 2021). 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 (Jones et al., 2012a). 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 (Chehab et al., 2007). Testing bridges under real-world conditions, while costly, can offer the best approach to understanding their responses and performance.

Figure E2. Bridge Testing at AASHO Road Test (Highway Research Board, 1962).

Transportation Technology Research

The U.S Department 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. 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 (Worel, 2021; Tompkins and Khazanovich, 2007). The MnROAD testing facility was used to investigate and test assistive or autonomous vehicles and other associated technologies to improve driver safety (Shankwitz, 1995; Alexander et al., 1997; Rakauskas et al., 2003). Figure E3 shows an example of such applications on MnROAD, where a driver-assistive system (DAS) was equipped with a snowplow truck to assist in tracking the position of the truck and avoiding unwanted paths that may lead to a 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 (WesTrack, 2021). Even more recently, a new autonomous vehicle research facility has been built at NCAT's test track facility in Alabama (Auburn University, 2021). The facility's oval test track is being used as the main test site for autonomous vehicle technology and applications (Worel et al., 2020).

Figure E3. Snowplow equipped with Driver assistive system (DAS) technologies at MnROAD (Tompkins et al., 2007).

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. The benefits of truck platooning include lower fuel consumption, improved driver output, fewer crashes, less congestion, and reduced carbon emissions (Janssen et al., 2015). The PTI test track was also utilized for the comprehensive testing of new bus models, trucks, and trains. The facility has been recognized as a designated testing ground for autonomous vehicles by the U.S DOT since 2017 (Penn State Engineering, 2021).

Drainage Experiments

Drainage significantly affects pavement performance (Gurjar et al., 2013) due to the effect of moisture on soil strength and properties. According to (Rokade et al., 2012), proper drainage systems increase the service life of pavements by 50 percent. It also impacts the safety of motorists as water that remains on the surface of the pavement can cause hydroplaning. Therefore, proper drainage is important to ensure the long life of the pavement and the safety of users. A survey found that several APT programs explored the effects of water on pavement performance (Hugo and Martin, 2004). 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 a 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 (Worel, 2021; Tompkins and Khazanovich, 2007).

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 (Mateos and Balay, 2008). 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 (Greene, 2016).

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 is 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 (Worel, 2020). 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 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 (Petersen, 2005). According to research, IC technology has shown promise in quality control during construction (Camargo et al., 2006). A model of the compactor that was used for this study is shown in Figure E4, 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 (Worel and Deusen, 2015). 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 (Du Plessis et al., 2017).

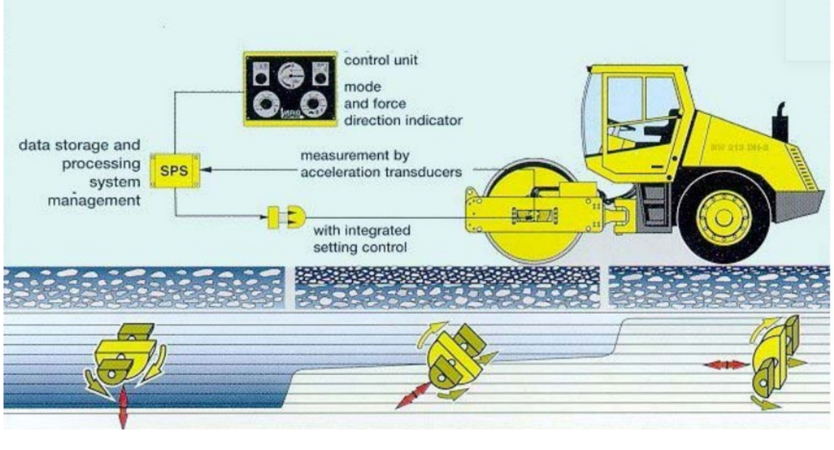

Figure E4. Schematic of BOMAG Compactor used for the IC demonstration at MnROAD (Petersen, 2005).

The circular facility of the University of Los Andes in Colombia investigated various techniques used in soil stabilization using accelerated pavement testing (Mateos and Balay, 2008). In order to provide geosynthetic solutions to weak formations, Hugo and Martin (2004) 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.

Automobile Research

The automobile industry constitutes a significant portion of the U.S. gross domestic product (GDP) quarterly (Bea, 2020). In the automobile industry, some of the product quality criteria include safety, product design, and functional qualities (Jahanshahi et al., 2011). 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 development of new heavy vehicle suspension systems and improved vehicle tires (Highway Research Board, 1962). Moreover, the PTI was used for advanced research on hybrid, electric, and other alternative-fuel vehicles (Penn State Engineering, 2021). Likewise, NCAT was involved in a study that evaluated alternative fuels for vehicles (NCAT, 2021). These are great steps towards reducing carbon emissions and fuel costs, and providing alternate power to vehicles. Furthermore, the NCAT test track has contributed to the development of advanced propulsion systems and vehicle rollover prediction systems, including providing opportunities for the valuation of improved vehicle electronics and safety (NCAT, 2021). Under vehicle operations, MnROAD initiated a study to investigate the relationship between road characterization, vehicle dynamics, and fuel consumption. The idea was to find out the factors that contributed to fuel consumption (Worel and Deusen, 2015). With regard to transport modes, the NCAT test track was used for transit bus testing (Worel et al., 2020). In 2009, the FDOT heavy vehicle simulator (HVS) investigated new-generation wide-base tires and made significant recommendations to the trucking industry (Greene et al., 2013). The FABAC machine, which is a small linear traffic simulator, was used to validate the behavior of an electric road systems (ERS) embedded in asphalt pavement in 2019 (Hornych et al., 2020). The FABAC traffic simulator was considered for the evaluation due to the limitations of the laboratory to represent real-world conditions (Aunis and Balay, 1998). The ERS was developed by Alstom to charge and supply power to heavy goods vehicles over long distances to reduce greenhouse gas emissions. Hornych et al., (2020) 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.

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 (Worel et al., 2020). 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 E5. The research concluded that the mechanism could reduce pollution by 54 percent (Biesboer and Elfering, 2003). In another study, MnROAD investigated “the effects of novel soil amendments on roadside establishment of cover crop and native prairie plant species” (Gale and Biesboer, 2004). 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 (Worel, 2021; Gale and Biesboer, 2004). Other activities that have been done off-track at MnROAD include studies on sinkholes and herbicides (Worel et al., 2020).

Figure E5. Pollution control research showing the check dam at MnROAD (Worel, 2021).

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 toward improving highway safety were 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, the NCAT test track investigated pavement striping and markings (Worel, 2021). Transportation agencies in the U.S. and Canada invested about $1.5 billion in pavement markings in 2000 (Migletz and Graham, 2002). Pavement markings provide visual guidance by delineating the travel lanes and other roadway features to improve safety (Carlson, 2015). They have the potential to reduce roadway crashes (Migletz and Graham, 2002). 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 retro-reflectivity of raised pavement markings with accelerated pavement testing using the HVS machine (Choubane et al., 2006). 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) (Du Plessis et al., 2017). According to (Donnell et al., 2009), 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 to (Donnell et al., 2009). 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 (Torbic et al., 2001). They can reduce roadway departure crashes by 20–50 percent. 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 (Torbic et al., 2001). 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 (Torbic et al., 2001). Snowfall creates slick pavement surface conditions which increase the risk of crashes among motorists in northern Europe and America. According to (Eisenberg et al., 2005), U.S roadways record more injuries and vehicle damages on snowfall 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 U.S. 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 (Al-Qadi et al., 2002). 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 E6. 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 (Salimi et al., 2014). Similarly, the PTI circular test track was used to investigate the effectiveness of applying hot sand for winter ice control (Hayhoe, 1984).

Figure E6. Sand applied on icy road surface at IRRF test road in Canada (Hayhoe, 1984).

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 the in-place density of pavement layers. A non-destructive device for measuring frost depth was developed at the same facility. In another study, a dynamic pavement testing device, which was developed by the Waterways Experiment section and the U.S. Army Corps of Engineers, was evaluated and demonstrated using the AASHO Road Test (Hayhoe, 1984). WASHO Road Test was used by A.C. Benkelman to develop the Benkelman Beam, a pavement deflection-measuring device in 1953 (Root et al., 1954). 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 (Greenslade, 2016). The upgraded device was inexpensive, reliable, and easy to operate. It is an effective device that measures the deflection of flexible pavements under loads. The work 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 (Worel and Deusen, 2015). 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 (Worel and Deusen, 2015). Furthermore, during the intelligence compaction studies at MnROAD, the guidelines for using a lightweight deflectometer (LWD) and the dynamic cone penetrometer (DCP) were developed for quality control assurance purposes (Siekmeier et al., 2009), and the ground penetrating radar (GPR) (Loken, 2005). 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 (Loken, 2005; Tompkins, 2008). Consequently, MnROAD is described as a site for equipment certification (Tompkins and Khazanovich, 2007; Burnham, 1993; Thomas, 2005). 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 E7 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 (Jones et al., 2012b; Farshidi et al., 2011).

Figure E7. Measuring VOCs using the transportable flux chamber (Jones et al., 2012b).

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 weaknesses, and areas that need improvement and potential best practices (Federal Emergency Management Agency (FEMA), 2021). The NCAT test track has been used to undertake emergency response exercises (Worel et al., 2020). Likewise, the MnROAD farm loop was used to demonstrate the dangers associated with improper hauling of trailers and goods on roadways (Greene et al., 2013). In the area of national security issues, APT facilities have shown some success. Anti-terrorist policies can either be defensive or proactive (Faria, 2007). Terror attacks in Nice, Berlin, Barcelona, and London in recent times involved vehicles ramming into 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 (Faria, 2007).

Findings

Summary of Non-Pavement Research Using APT

The contributions of APT facilities to non-pavement research are summarized in Table E1. The test roads appeared to have been extensively used for various aspects of non-pavement research for years. This may be attributed to the large amount of space required for test road facilities and the 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 automobiles have relationships with the structural or functional performance of the pavement.

Table E1. 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 PTI	Cal-APT	
Transportation Technology Research	MnROAD WesTrack NCAT Test track PTI		
Drainage Experiments	MnROAD FDOT Concrete Test Road		Brazil APT
Geotechnical Investigation	NCAT MnROAD	USACE CRREL	University of Los Andes in Colombia
Automobile	AASHO Road Test PTI NCAT Test track MnROAD	FDOT	FABAC machine
Environmental Research	NCAT Test track MnROAD		
Highway Safety	NCAT Test Track PTI	FDOT FAA IRRF	MMLS3
Calibrations, measurements and testing devices	AASHO Road Test WASHO Road Test NCAT Test Track MnROAD	Cal-APT	CAPTIF
Miscellaneous Emergency response Haulage Utilities Security	NCAT Test MnROAD PTI	USACE CRREL	

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

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 from the text. This technique has been used in other studies to analyze trends in conference proceedings (Steyn, 2020; Voyant, 2021). The Voyant tool, which is an open-sourced text reading and analysis environment (Voyant, 2021), 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 study 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, conference proceedings, and reports that involved non-pavement research using APTs. The aim is to identify trends related to non-pavement research. Figure E8 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 E8. Word cloud describing non-pavement application terms using APT.

Table E2 shows the results of words that appeared four times or more based on the counts and representative trends. The count represents the number of 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 E2. 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 E2. 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

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.

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.

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.

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.

Innovative Sustainable Drainage Systems

Innovative stormwater 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.

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. 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.

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, and project delivery, and increases the confidence of geotechnical characterizations.

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.

Unmanned Aerial Systems (UASs)

UASs offer a technological revolution for highway transportation, asset management, traffic incident management, 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.

Summary and Conclusions

The versatility of APTs is evident. Successful applications of APT facilities for non-pavement research have been reviewed in this study. 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 study is to raise awareness and encourage the participation of APTs in non-pavement research. Different APT types have the capacity and expertise to meet the needs of different customers. Moreover, the staff of APT facilities has 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 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 study, 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 study 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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