AAPTP
Airport Asphalt Pavement Technology Program

Advanced Technologies for Airfield Pavement Projects

Final Report

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Airport Asphalt Pavement Technology Program

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The Airport Asphalt Pavement Technology Program (AAPTP) is a cooperative agreement effort between the **National Asphalt Pavement Association** (NAPA) and the **Federal Aviation Administration** (FAA) to advance asphalt pavements and pavement materials. The AAPTP advances solutions for asphalt pavement design, construction, and materials deemed important to airfield reliability, efficiency, and safety. The program leverages NAPA's unique technology implementation capabilities with assistance from the FAA and industry to advance deployment and adoption of innovative asphalt material technologies.



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List of Acronyms and Abbreviations

2D	Two-dimensional
3D	Three-dimensional
AAMD	Availability-adjusted mix design
AAPTP	Airport Asphalt Pavement Technology Program
AAS	Airports Safety and Standards
AASHTO	American Association of State Highway and Transportation Officials
AC	Advisory Circular
ACN	Aircraft classification number
ADCMS	Advanced Digital Construction Management Systems
ADO	Airports District Office
ADSR	Aramid Dispersion State Ratio
AE	Asphalt emulsion
AGV	Autonomous ground vehicles
AHP	Analytic Hierarchy Process
AI	Artificial intelligence
AIP	Airport Improvement Program
AIPV	Autonomous impact protection vehicles
AMG	Automated machine guidance
AMPT	Asphalt Mixture Performance Tester
AOA	Air Operations Area
APA	Asphalt Pavement Analyzer
API	Application programming interface
APMS	Airport Pavement Management Systems
AR	Augmented reality
ASA	Anti-strip additives
ASCE	American Society of Civil Engineers
ATMA	Autonomous truck-mounted attenuator
AV	Air voids
BCA	Benefit-cost analysis
BCR	Benefit-cost ratio
BIM	Building Information Modelling
BLE	Bluetooth Low Energy
BMD	Balanced Mixture Design
BV	Best-value
CCPR	Cold central plant recycling
CFME	Continuous friction measurement equipment
CIR	Cold in-place recycling
CM/GC	Construction manager/general contractor
CMAR	Construction manager-at-risk
CNN	Convolutional Neural Networks
COV	Coefficient of variation
CSPP	Construction Safety and Phasing Plan
DB	Design-bid
DBB	Design-bid-build
DCT	Disk-shaped Compact Tension
DEM	Digital elevation model

DFOS	Distributed fiber-optic sensing
DGA	Dense-graded asphalt
DL	Deep learning
DOD	Department of Defense
DOT	Department of Transportation
DPS	Dielectric profiling system
EM	Electromagnetic
EME2	High-modulus asphalt
EO	Electro-optical
ERDC	Engineer Research and Development Center
ESAL	Equivalent single axle loads
FA	Fly ash
FAA	Federal Aviation Administration
FDR	Full-depth reclamation
FE	Finite element
FEA	Finite element analysis
FEM	Finite element method
FHWA	Federal Highway Administration
FN	Flow number
FOD	Foreign object debris
FOG	Foot-on-ground
FR	Fuel-resistant
FRAC	Fiber-reinforced asphalt concrete
FWD	Falling weight deflectometer
GCP	Ground control points
GHG	Greenhouse gas
GIS	Geographic Information Systems
GMP	Guaranteed maximum price
GN	Grip number
GNSS	Global navigation satellite system
GPA	Global Positioning System
GPR	Ground-penetrating radar
HHPS	Hydronic heated pavement systems
HiMA	Highly polymer modified asphalt
HIRF	High-Intensity Radiated Fields
HMA	Hot mix asphalt
HVS	Heavy Vehicle Simulator
HWD	Heavy weight deflectometer
HWTT	Hamburg Wheel-Tracking Test
IC	Intelligent compaction
ICAO	International Civil Aviation Organisation
ICMV	Intelligent compaction measurement value
IDT	Indirect tensile
IDT-CT	Indirect Tensile Cracking Test
INS	Inertial Navigation System
IoT	Internet of Things
IR	Infrared
IRI	International Roughness Index

IRTP	Infrared thermal profiling
LCCA	Life-cycle cost analysis
LCMS	Laser Crack Measurement System
LLM	Large language model
LTPP	Long-Term Pavement Performance
M&R	Maintenance and rehabilitation
MAE	Mean absolute error
MDMS	Material Delivery Management System
M-E	Mechanistic-empirical
MEMS	Micro-electro-mechanical systems
MEPDG	Mechanistic-Empirical Pavement Design Guide
ML	Machine learning
MMS	Mobile Mapping Systems
MOS	Modification of Standards
NAPA	National Asphalt Pavement Association
NAPTF	National Airport Pavement Test Facility
NCAT	National Center for Asphalt Technology
NCHRP	National Cooperative Highway Research Program
NDT	Nondestructive testing
NMAS	Nominal maximum aggregate size
NPV	Net present value
PAC	Polycyclic aromatic compounds
PBC	Performance-based contracting
PC	Portland cement
PCC	Portland cement concrete
PCI	Pavement Condition Index
PCN	Pavement classification number
PDB	Progress design-build
PG	Performance graded
PINN	Physics-informed neural network
PMA	Polymer-modified asphalt
PMED	Pavement ME Design
PMP	Pavement management plan
PMTP	Paver-mounted thermal profiling
PPK	Post-processed kinematic
PQI	Pavement Quality Index
PRS	Performance-related specifications
QA	Quality assurance
QC	Quality control
RAP	Reclaimed asphalt pavement
RAS	Recycled asphalt shingles
RBA	Recycled binder availability
RBC	Recycled binder contribution
ROI	Return on investment
SAFEM	Semi-analytical finite element method
SBS	styrene–butadiene–styrene
SCB	Semi-Circular Bend
SCI	Structural Condition Index

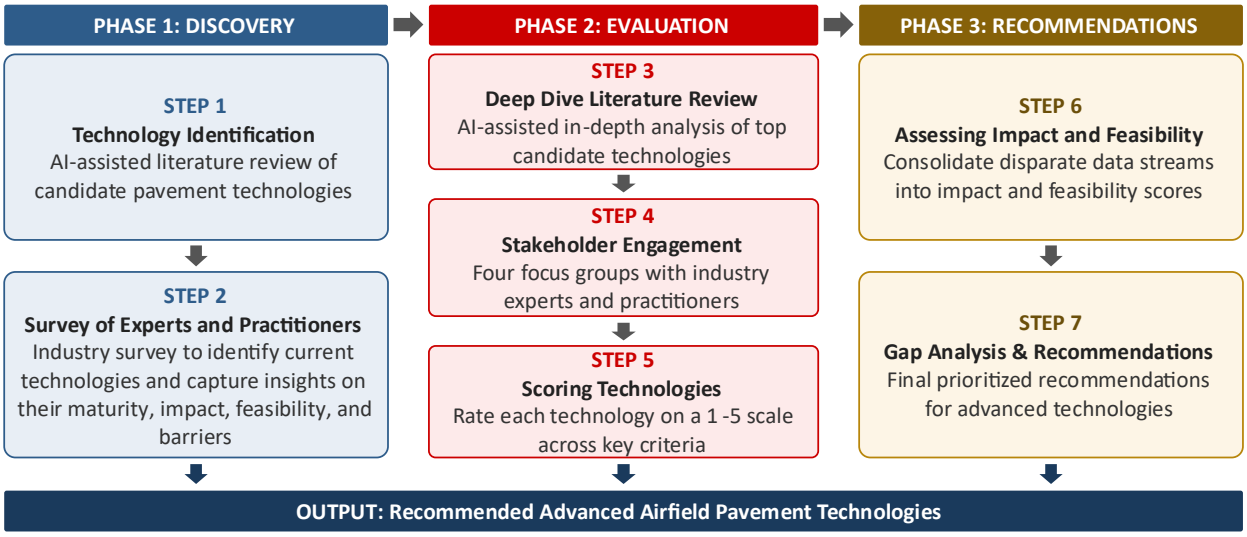
SMA	Stone mastic asphalt
sUAS	Small unmanned aircraft system
TDR	Time-domain reflectometry
TOM	Total organic matter
TRB	Transportation Research Board
TRB	Transportation Research Board
TRID	Transportation Research International Documentation
TRM	Traditional maintenance
TSD	Traffic-speed deflectometer
TSR	Tensile Strength Ratio
UCS	Unconfined compressive strength
VCA	Voids in the coarse aggregate
VMA	Voids in mineral aggregate
VTRC	Virginia Transportation Research Council
WBGT	Wet bulb globe temperature
WMA	Warm mix asphalt

Project Objective

The objective of this project is to conduct a detailed synthesis of both current and emerging technologies with the potential to enhance airfield pavement projects. This synthesis will involve a thorough investigation into the practicalities of implementing these technologies, including an assessment of the steps necessary to facilitate their current and future adoption. The project will also critically evaluate the impact of these technologies on airfield pavement projects. The outcome will be a comprehensive report providing actionable recommendations, an implementation framework, and a strategic roadmap for industry stakeholders to advance airfield pavement practices with innovative solutions.

Methodology

The overall methodology is summarized in Figure 1, which outlines the three phases: discovery (technology identification and expert surveys); evaluation (literature review, stakeholder engagement, and scoring); and prioritization of recommendations (impact and feasibility assessment and gap analysis). Subsequent sections provide further details on each step.



Source: AAPTP

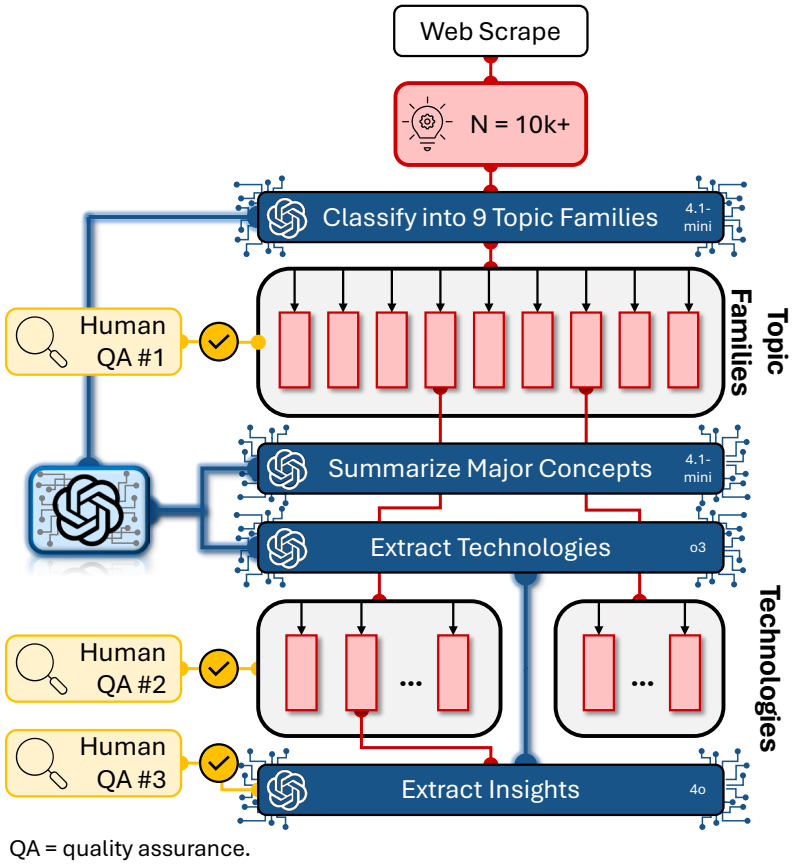
Figure 1. Flowchart of the Three-Phase Methodology for Identifying, Evaluating, and Prioritizing Advanced Airfield Pavement Technology Recommendations

Phase 1: Discovery

Step 1: Technology Identification

Using web-scraping techniques, the team programmatically accessed over 30 public repositories and conference databases relevant to asphalt pavement and airfield technologies. This process resulted in an initial dataset of 10,677 article titles and

abstracts. The complete list of repositories can be found in Appendix A of this report. Figure 2 illustrates the multi-step process used to classify over 10,000 abstracts into 9 topic families, extract 97 technologies, and generate structured insights.



Source: AAPTP

Figure 2. AI-Assisted Workflow for Literature Classification and Technology Extraction

Technology Extraction

The collected articles were categorized into technological families based on their thematic content and relevance. A technology extraction pipeline was then developed to identify key technologies mentioned within each family, resulting in an initial list of 97 candidate technologies for further analysis.

Classification of Abstracts into Technology Families

To support automated classification, a custom pipeline was implemented to match articles with specific technology families of interest. This included customizing an artificial intelligence (AI) assistant (through large language model [LLM] selection, prompt design, system instruction refinement, and retrieval-augmented generation setup) and programming an algorithm to apply and reproduce this classification process at scale. In addition, an evaluation system was created to extract key insights (benefits, limitations,

and readiness levels) associated with each identified technology. This system connects the literature database to a tailored AI assistant, designed to process and summarize the relevant information. At this step, only abstracts were used, so the extracted characteristics were considered preliminary insights based on available abstract-level content.

Quality Assurance with Human Oversight

To ensure reliability, quality assurance (QA) checkpoints were embedded throughout the AI pipelines. At each checkpoint, human reviewers assessed AI-generated results for accuracy, relevance, and consistency with project goals. This hybrid approach enabled early detection of potential issues and maintained data integrity.

Panel Survey

A preliminary list of 97 technologies was identified through the analysis of 10,677 article abstracts collected from selected online repositories. A project panel survey was then administered to better understand the panel's priorities and expectations regarding the types of technologies they considered most important for the project. Given the broad scope of topics covered, from materials and construction processes to digital and emerging technologies, the survey aimed to capture where panelists believed the greatest needs and opportunities lie.

Methodology

To facilitate structured analysis, all 97 technologies were classified into nine overarching families:

1. Materials and Mixtures
2. Evaluation and Performance Monitoring
3. Pavement Design and Analysis
4. Digital and Smart Technologies
5. Advanced and Emerging Concepts
6. Production and Placement
7. Peripheral and Enabling Technologies
8. Project Delivery and Contracting
9. Other/Uncategorized Cross-cutting

Panelists were asked to rate each technology using a six-point Likert scale, defined as: no input (Not Applicable), not a priority (1), slightly important (2), moderately important (3), very important (4), and critical (5). Given that the survey included 97 technologies, brevity and clarity were prioritized to reduce respondent fatigue and maintain response quality. Only concise descriptions of each technology and brief overviews of their respective families were provided.

The Likert-scale format was selected to reduce the cognitive load associated with survey completion while maintaining an appropriate level of feedback depth. Compared with ranking or matrix-based formats, Likert scales tend to impose a lower cognitive demand and yield more consistent response quality in large, multi-item instruments.

Data Interpretation and Variability

As anticipated, the survey results exhibited notable variability both within individual technologies and across panel members. Differences in background, organizational roles, and professional priorities likely led to diverse perceptions of importance among respondents. This variability is not only expected but also informative, as it reflects the multidimensional nature of technology adoption in the airfield pavement sector.

To illustrate this variability, Table 1 provides statistical metrics per panelist. For example, Panelist 1 demonstrated a lower overall mean score and higher standard deviation, indicating a more conservative and heterogeneous evaluation pattern, whereas Panelist 5 exhibited a higher mean with lower variability, suggesting a more uniform perception of importance. Appendix B shows the detailed results for each technology.

Table 1. Metrics Variation Per Panel Member

Panelist Number	Average	Standard Deviation
Panelist 1	2.0	1.2
Panelist 2	3.7	1.1
Panelist 3	3.6	1.1
Panelist 4	3.4	0.5
Panelist 5	3.9	0.8
Panelist 6	3.7	0.8
Panelist 7	3.0	1.1
Panelist 8	3.1	0.9

Ranking and Technology Selection

The survey results were analyzed based on both average rating and standard deviation for each technology. Technologies with the highest mean scores were interpreted as the most strongly prioritized by the panel. The top 21 technologies, representing those with the highest overall ratings, are presented in Table 2.

Table 2. Highly Ranked Technologies Based on Panel Survey

Category	Statistical Requirement	Technologies
High Priority, High Consensus	Avg ≥ 4 Std < 0.9	- Balanced Mixture Design (BMD) - 3D Machine Control for Asphalt Paving
High Priority, Moderate Consensus	Avg ≥ 4 Std ≥ 0.9	- Resilient Pavement Design - Intelligent Compaction (IC) - Infrared Thermal Profiling (IRTP)

Category	Statistical Requirement	Technologies
Moderate Priority, High Consensus	3.5 ≤ X < 4 Std < 0.9	- Multi-Criteria Decision Support Tools - Progressive & Alternative Contracting Methods - Bio-Oil or Bio-Binder - Wearable Heat-Stress Monitoring for Construction Workers - Fiber-Reinforced Asphalt Concrete - Computer Vision/AI Methods for Remote Sensing - Drone Swarms for FOD Detection
Moderate Priority, Moderate Consensus	3.5 ≤ X < 4 0.9 ≤ Std < 1.3	- AI Vision Alerts for Work Zones - Mechanistic-Empirical (M-E) Pavement Design - Full-Depth Reclamation (FDR) - High-Density Longitudinal Joints - Highly Polymer Modified Asphalt (HiMA) - Machine Learning/AI Methods for NDT Data Interpretation - Stone Mastic Asphalt (SMA) - Warm Mix Asphalt (WMA) - Dielectric Profiling System (DPS)

3D = three-dimensional; FOD = foreign object debris; NDT = nondestructive testing.

In addition to these top-ranked items, the analysis also identified technologies characterized by highly polarized responses. These technologies are those where individual panelists provided both very low and very high ratings (e.g., combinations of 1 and 5, 1 and 4, or 2 and 5). These were considered controversial technologies, meriting further examination due to their potential significance despite divergent opinions. These technologies are summarized in Table 3.

Table 3. Other Technologies for Further Assessment

Other Technologies
- Embedded Pavement Sensors - Self-Sensing Asphalt Materials - Building Information Modelling & Pavement Digital Twins - Self/Assisted Healing Asphalt Technologies - Wearable Back-Support Exoskeletons for Construction Workers - Augmented Reality (AR) for Construction QC/QA & Training - Autonomous Truck-Mounted Attenuators (ATMA) - Embedded Electromagnetic Work-Zone Alerts - Agent-Based Models of Construction Bidding - High-Visibility Colored Pavement Markings - Autonomous Ground Vehicles for FOD Detection - Physics-Informed AI for Pavement Performance Prediction - Ground Penetrating Radar (GPR) - Vehicle-Mounted Systems for Pavement Inspection - Energy-Efficient Asphalt Plant Technologies - Small Unmanned Aircraft Systems (sUAS) for Pavement Inspection

Other Technologies
- Dash-Cam/Smartphone for Pavement Inspection - Traffic-Speed Deflectometer (TSD) - e-Ticketing & Digital Quality Assurance - Runway Grooving - Fixed Systems for FOD Detection - Runway Texture and Friction Monitoring Technology - Heated Airport Pavements

QC/QA = quality control/quality assurance.

Step 2: Survey of Experts and Practitioners

The team designed and distributed a survey to identify advanced technologies currently in use in airfield pavement practice. Distribution channels included National Asphalt Pavement Association (NAPA) communications and direct outreach by the project team. Participants were identified through Transportation Research Board–Federal Aviation Administration/Department of Defense (TRB–FAA/DOD) Airfield Asphalt User–Producer Group members; Asphalt Institute and National Center for Asphalt Technology (NCAT) course instructors; State Asphalt Pavement Associations; authored reports listed in the Transportation Research International Documentation (TRID) database; and database searches for relevant titles (e.g., pavement, airfield, and maintenance engineers and executives).

The survey also requested recommendations for additional contacts, and the team reached out to those referrals as well. To ensure global representation, international contacts were invited to contribute their perspectives. A total of 59 responses were received.

Survey Content Overview

The survey was designed to identify technologies with potential application in airfield pavements and capture insights on their maturity, impact, feasibility, and barriers. The full survey can be found in Appendix C. The survey began with a general information section collecting background data about each respondent's organization type, professional role, geographic region, and years of experience. This information ensures responses can be contextualized in the analysis.

The core of the survey focused on technology identification, asking participants whether their organizations had researched, piloted, or implemented advanced technologies within the past five years. For each reported technology, respondents were asked to provide a brief description, indicate its stage of deployment (ranging from concept to full implementation), and rate it across nine dimensions (performance, return on investment [ROI], efficiency, sustainability, technical barriers, cost barriers, regulatory/operational barriers, and stakeholder acceptance) using a five-point scale. Open-ended questions

invited experts to elaborate on the technology's intended purpose, main benefits, challenges, and to share supporting documentation where available.

The survey concluded with an additional input section that sought respondents' perspectives on the most pressing gaps or challenges in asphalt airfield pavement practice, along with an optional invitation to participate in follow-up discussions or focus groups. Overall, the instrument combined structured ratings with qualitative feedback, enabling both quantitative comparison and deeper contextual understanding of advanced technologies.

Respondent Profile

Survey participants spanned consultants, contractors, government agencies, airport owners, academia, material suppliers, and equipment manufacturers. Figure 3 through Figure 6 summarize the profile characteristics of the 59 usable responses.

Consultants formed the largest group (27 percent), followed by contractors (20 percent), government agencies (12 percent), and airport operators (12 percent). Academia, material suppliers, non-profit trade associations, and equipment manufacturers collectively accounted for the remaining 29 percent.

Nearly half of respondents (47 percent) identified with engineering and design roles, underscoring a technically focused respondent base. The majority of responses originated from North America (73 percent). The Asia/Pacific (14 percent), South America (8 percent), Africa (3 percent), and Europe (2 percent) segments ensured the survey captured technologies from a global perspective.

Respondents were overwhelmingly seasoned professionals: 70 percent reported more than 15 years of experience, and another 22 percent had between 5 and 15 years. Only a small fraction (8 percent) fell into the early-career range (2–5 years). This experience profile reinforces the survey's credibility as most contributors have long-term familiarity with the industry. Altogether, the respondent profile indicates that the survey reflects the perspectives of experienced practitioners with deep technical and managerial backgrounds, predominantly from North America but inclusive of key international viewpoints.

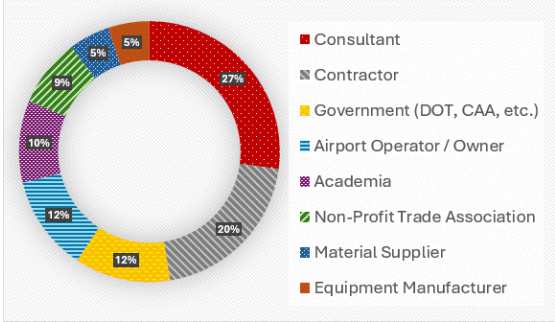


Figure 6. Survey Results for Organization Type

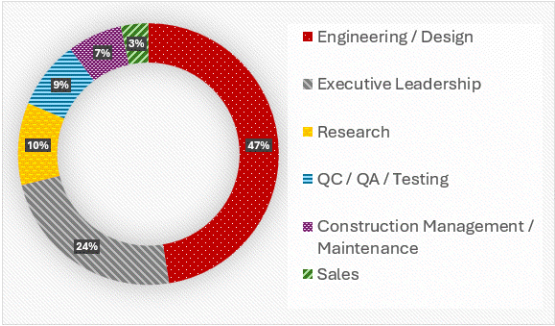


Figure 6. Survey Results for Respondent Professional Role



Figure 6. Survey Results for Geographic Location

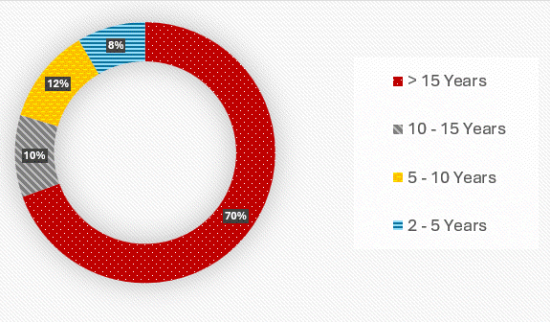


Figure 6. Survey Results for Respondent Years of Experience

DOT = department of transportation; CAA = Civil Aviation Authority

Source: AAPTP

Technology Landscape

Responses pointed to a broad set of technologies spanning materials, design frameworks, construction automation/real-time quality control (QC), condition assessment, structural/drainage methods, and digital delivery, as shown in Table 4. Two clusters dominate: (1) materials innovation, with highly polymer modified asphalt (HiMA) most frequently cited, and (2) BMD. A second tier of responses clusters on field execution and data capture (roller-mounted ground-penetrating radar [GPR], dielectric gauges, real-time QC software; 3D machine control). Lower-frequency mentions capture structural rehabilitation, non-destructive/remote sensing, and forward-looking concepts such as energy harvesting.

The materials cluster is anchored by HiMA (five mentions), described as a maturing solution for rutting/cracking resistance with documented airfield deployments in South America. BMD (five mentions) emerges as the leading design framework, both already in use and explicitly positioned by respondents as the mechanism to de-risk adoption of new materials (e.g., high-reclaimed asphalt pavement [RAP], fibers, fuel-resistant systems) by tying acceptance of new materials or additives to measured performance.

Most technologies reaffirm the study's initial scope. Based on explicit survey mentions, the team expanded the list of technologies to monitor to include high-modulus asphalt (EME2), fuel-resistant asphalt mixtures, energy-harvesting pavements, cold in-place recycling (CIR), RAP (high-RAP acceptance), anti-strip additives, and base/subbase construction methods (e.g., paver-laid crushed rock layers).

Table 4. Technology Landscape Reported by Survey Respondents

Category	Technology	Number of Mentions
Materials	Highly Polymer Modified Asphalt (HiMA)	5 mentions
	Fiber Reinforcement	3 mentions
	Fuel-Resistant Binders/Additives	3 mentions
	Recycled Materials	2 mentions
	High-Modulus Asphalt (EME2)	1 mention
	Warm Mix Asphalt (WMA)	1 mention
	Epoxy Asphalt Binder	1 mention
	Dry-Process Tire Rubber Modifier	1 mention
	Nano-Silane Aggregate Treatments	1 mention
Design, Guidance	Balanced Mix Design (BMD)	5 mentions
	Asphalt Paving Handbook (2025 Edition; AAPTP)	1 mention
Construction Automation, Real-Time QC	Compaction and Density Technologies (roller-mounted ground-penetrating radar (GPR), dielectric gauge, real-time digital capture software)	3 mentions
	3D Machine Control for Paving and Milling	2 mentions
Condition Assessment	Ground-Penetrating Radar (GPR)	1 mention
	Small Uncrewed Aircraft System (Drone) Inspection	1 mention
Structure, Drainage	Full-Depth Reclamation (FDR)	1 mention
	Full-Depth In-Place Cold Recycling	1 mention
	Porous Pavement	1 mention
	Paver-Laid Crushed Rock Base and Subbase Layers	1 mention
Digital Delivery	Building Information Modeling (BIM)	1 mention
Forward Looking	Energy Harvesting Pavements	1 mention

Challenges and Barriers

Specifications

Across responses, the most frequently cited barrier concerns the rigidity and inconsistency of the FAA P-401 specification. Participants emphasized the need to modernize and harmonize P-401 with practices at State departments of transportation (DOTs), particularly those based on Superpave and BMD frameworks. Respondents described current specifications as restrictive and inconsistently interpreted, limiting opportunities for innovation and the use of advanced or sustainable materials. Several advocated for refinement of aggregate gradation bands, greater use of local specifications and materials, and clearer guidance bridging airfield and highway standards.

"Lack of consistency designing and constructing using FAA specifications."

Consultant — Engineering/Design — North America

"Ambiguity of standard specifications"

Contractor — Executive Leadership — North America

"Moving P401 to a Superpave design and taking the next step and implementing BMD/Performance Testing. This opens the door for incredible innovation on the materials side. Performance tests will help to qualify innovate mixes such as high RAP and other recycled materials."

Contractor — QC/QA/Testing — North America

"P-401 Mixtures; Aggregate Gradation Bands — Refine gradation requirements when paving airports without compromising mixtures performance."

Consultant — Engineering & Design — North America

"The use of local specifications and materials is not used nearly as often as the FAA allows. EOR often assumes that P401 specifications are required, when they often can be replaced by local DOT specifications."

Contractor — Executive Leadership — North America

"Lack of knowledge about mixture design among FAA, airport personnel and their designers."

Contractor — Executive Leadership — North America

"The mix designs are also very prescribed. If there is a way to lean more on performance testing and information, the volumetric and recipe specification can be relaxed."

Consultant — Engineering/Design — North America

"The hesitation in implementing new materials due to performance concerns could be significantly reduced by using robust performance-based methods (e.g., Balanced Mix Design)."

Academia — Research — North America

"Not using polymer modified binders and performance based design for P401 and P403"

Government (DOT, CAA, etc.) — QC/QA/Testing — North America

"Development of pavement mixtures that combine high performance with reduced need for frequent maintenance, even in areas with significant temperature and humidity variations. It is essential to incorporate the use of balanced mix design into standard practices, focusing on pavement performance and operational requirements."

Airport Operator/Owner — Construction Management/Maintenance — South America

"We have worked with the Department of Transportation and the Bureau of Aeronautics to create a specification. The technology bridges the gap between big airfield P401 pavements and state highway specifications to create the appropriate mixtures for the airfield stresses… This helped bridge the gap of airfield pavements not achieving additional density under loading because it doesn't behave like a traditional roadway pavement."

Non-Profit Trade Association — Executive Leadership — North America

Construction Quality and Techniques

Respondents consistently identified construction quality as the decisive factor in pavement performance. Responses indicate a call for real-time quality feedback during paving operations, reducing reliance on delayed, destructive coring and enabling quicker corrective actions in the field. Participants also cited variability in density control, challenges in compacting highly polymer modified mixtures, and the need for improved construction techniques, particularly around longitudinal joints.

"Construction will make or break a project. You can use the best materials in the world, but if it is poorly constructed, it will not last."

Contractor — Engineering/Design — North America

"Providing pavement construction quality feedback in real-time, vs. finding problems post-construction. Better use of in-place and local to design new pavement mixes to meet current and future aircraft loadings."

Consultant — QC/QA/Testing — North America

"The time to get sensitive data for decision-making. Destructive coring and how the data is biased based of the minimal percent of what it represents that is placed or performed in the field"

Consultant — QC/QA/Testing — North America

"In my view, construction quality and experience"

Consultant — Engineering/Design — North America

"Consistent density"

Equipment Manufacturer — Construction Management/Maintenance — North America

"Construction techniques - especially joints, and lack of RAP mixes"

Consultant — Engineering/Design — North America

"The compaction is not easy due to High viscosity HMA, but NEWTLAC cannot make a negative impact on compaction because of no change viscosity."

Material Supplier — Sales — North America

"Recycle, using Superpave technology instead of Marshal, Lift Thickness, Test Strips"

Contractor — Executive Leadership — North America

Mechanistic Design Adoption and Analysis Tools

Respondents voiced that airfield pavement design practices lag behind state-of-the-art mechanistic approaches used in highway engineering. There is recognition that existing tools do not allow flexibility to differentiate among asphalt mix types. Participants called for expanded access to design software, clearer differentiation among asphalt mix types, and raised concerns regarding life-cycle cost analysis (LCCA) methods to improve accuracy and reduce bias.

"Pavement design software is not readily available to interested parties; asphalt pavement mix types are not well differentiated in current pavement design."

Contractor — Engineering & Design — North America

"In my opinion, airfield pavement designs are behind the times in using mechanistic material properties."

Consultant — Engineering & Design — North America

"Understanding what is available to address cost and life cycle."

Contractor — Executive Leadership — North America

"Are current LCCA tools accurate and unbiased?"

Consultant — Engineering & Design — North America

"EME2 at airports are a classic example of not being implemented on a larger scale because designer don't know how to model in FAARFIELD and contractors will not risk proposing it."

Airport Operator/Owner — Engineering & Design — Asia/Pacific

Workforce and Training

Respondents repeatedly highlighted human capability gaps as a critical barrier to quality and innovation in pavement projects. The comments point to deficiencies at multiple levels (inspectors, designers, and field crews) who often lack adequate training or experience to interpret evolving specifications, implement performance testing, or manage advanced materials and construction technologies.

> ***"Having qualified inspectors & engineers on the job to understand the specifications in which they are trying to enforce or changing."***
>
> *Consultant — Engineering/Design — North America*

> ***"Lack of knowledge about mixture design among FAA, airport personnel and their designers."***
>
> *Contractor — Executive Leadership — North America*

> ***"Training on field operations"***
>
> *Equipment Manufacturer — Engineering/Design — North America*

> ***"Crew training and understanding of pavement design, construction, and maintenance."***
>
> *Equipment Manufacturer — Sales — North America*

Innovation and Change Management

A recurring theme across responses is the difficulty of achieving acceptance and implementation of new technologies in pavement projects. While respondents broadly support innovation, they describe an environment where institutional inertia, risk aversion, and procedural rigidity slow or discourage adoption. Several noted that the industry often relies on proven but outdated methods, creating a "comfort zone" that restricts advancement. Performance methods, especially BMD, were cited as practical enablers that could provide the objective evidence needed to overcome resistance and de-risk trials of new materials or techniques. However, respondents also pointed to uneven contractor capacity, where smaller firms struggle to meet the technical and procedural requirements of newer technologies or methods. Overall, the responses portray an industry that recognizes the value of innovation but lacks consistent mechanisms to evaluate, approve, and operationalize change.

> ***"Innovation is not always supported or encouraged"***
>
> *Material Supplier — Engineering/Design — North America*

> ***"Acceptance of new standards, technologies, and practices."***
>
> *Consultant — Executive Leadership — North America*

"Blend of old technologies that are proven but at times restricts the growth or advancement of new methodologies."

Material Supplier — Engineering/Design — North America

"Implementation of new technology"

Consultant — Executive Leadership — North America

"The hesitation in implementing new materials due to performance concerns could be significantly reduced by using robust performance-based methods (e.g., Balanced Mix Design)."

Academia — Research — North America

"I don't feel that there is any issues with the current designs but implementing them seems to be the biggest issue along with the ability of the contractors to meet the requirements of the designs. Larger contractors can easily meet the requirements but a lot of smaller airport project rely on smaller contractors and they struggle to meet the requirements of the mix design and construction requirements."

Government (DOT, CAA, etc.) — QC/QA/Testing — North America

"Having no experience in airfield, the most pressing problem is implementing efficient, well defined processes and capturing in software. It is the year 2025 and why this is a problem i do not know but it is."

Government (DOT, CAA, etc.) — Engineering/Design — North America

Budget

Budgetary limitations emerged as a consistent constraint across responses, particularly affecting smaller airports and local contractors. Participants described a recurring imbalance between available funding and the performance expectations set by design and maintenance requirements.

"Budget appropriate pavement and preservation design and maintenance plans for smaller local and regional airfields - it seems they are either extremely robust and cost prohibitive, or minimalistic and budget friendly, but at times inadequate"

Contractor — Executive Leadership — North America

"We know what we have to do but we don't have the budget to do what we supposed to do."

Non-Profit Trade Association — Engineering/Design — North America

List of Technologies

Table 5 presents the 51 technologies identified for further evaluation. These technologies advanced to the subsequent phases of the study, where they were subjected to detailed literature review, stakeholder input, and structured scoring.

Table 5. Technologies Identified for Further Assessment

Technology Name	Technology Name
- Balanced Mixture Design (BMD) - 3D Machine Control for Asphalt Paving - Agent-Based Models of Construction Bidding - AI Vision Alerts for Work Zones - Airfield Base and Subbase Technology - Anti-Strip/Moisture Additives - Augmented Reality (AR) for Construction QC/QA & Training - Autonomous Ground Vehicles for FOD Detection - Autonomous Truck-Mounted Attenuators (ATMA) - Bio-Oil or Bio-Binder - Building Information Modelling & Pavement Digital Twins - Cold In-Place Recycling (CIR) - Computer Vision/AI Methods for Remote Sensing - Dash-Cam/Smartphone for Pavement Inspection - Dielectric Profiling System (DPS) - Drone Swarms for FOD Detection - Embedded Electromagnetic Work-Zone Alerts - Embedded Pavement Sensors - Energy-Efficient Asphalt Plant Technologies - Energy-Harvesting Pavements - e-Ticketing & Digital Quality Assurance - Fiber-Reinforced Asphalt Concrete - Fixed Systems for FOD Detection - Fuel-Resistant Asphalt Mixtures - Full-Depth Reclamation (FDR) - Ground-Penetrating Radar (GPR) - Heated Airport Pavements	- High-Density Longitudinal Joints - Highly Polymer Modified Asphalt (HiMA) - High-Modulus Asphalt (EME2) - High-Visibility Colored Pavement Markings - Infrared Thermal Profiling (IRTP) - Intelligent Compaction (IC) - Machine Learning/AI Methods for NDT Data Interpretation - Mechanistic-Empirical (M-E) Pavement Design - Multi-Criteria Decision Support Tools - Physics-Informed AI for Pavement Performance Prediction - Progressive & Alternative Contracting Methods - Reclaimed Asphalt Pavements (RAP) - Resilient Pavement Design - Runway Grooving - Runway Texture and Friction Monitoring Technology - Self/Assisted Healing Asphalt Technologies - Self-Sensing Asphalt Materials - Stone Mastic Asphalt (SMA) - Traffic-Speed Deflectometer (TSD) - Small Unmanned Aircraft Systems (sUAS) for Pavement Inspection - Vehicle-Mounted Systems for Pavement Inspection - Warm Mix Asphalt (WMA) - Wearable Back-Support Exoskeletons for Construction Workers - Wearable Heat-Stress Monitoring for Construction Workers

Phase 2: Evaluation

Step 3: Deep-Dive Literature Review

A structured literature search was performed across the TRID database and peer-reviewed journals to identify publications relevant to each of the 51 selected technologies. In total, 3,469 publications were retrieved, averaging 68 documents per technology, with individual totals ranging from 18 to 248 documents. The scale and breadth of this corpus underscore the necessity of using AI-enabled methods for screening, organizing, and synthesizing information, a volume of material that would not be practically manageable through manual review alone.

Identification of Documents

The research team developed a semi-automated pipeline that integrates web-scale search, citation analytics, AI-assisted screening, and human QA. First, the initial technology topic (e.g., "Highly Polymer Modified Asphalt (HiMA)") was expanded using an AI model to generate a list of related search phrases. These AI-generated terms were then manually reviewed by the research team, who removed or modified irrelevant terms, consolidated overlapping concepts, and ensured alignment with the technology of interest. The goal of this step was to enrich the subsequent search, ensuring broader coverage in literature mining.

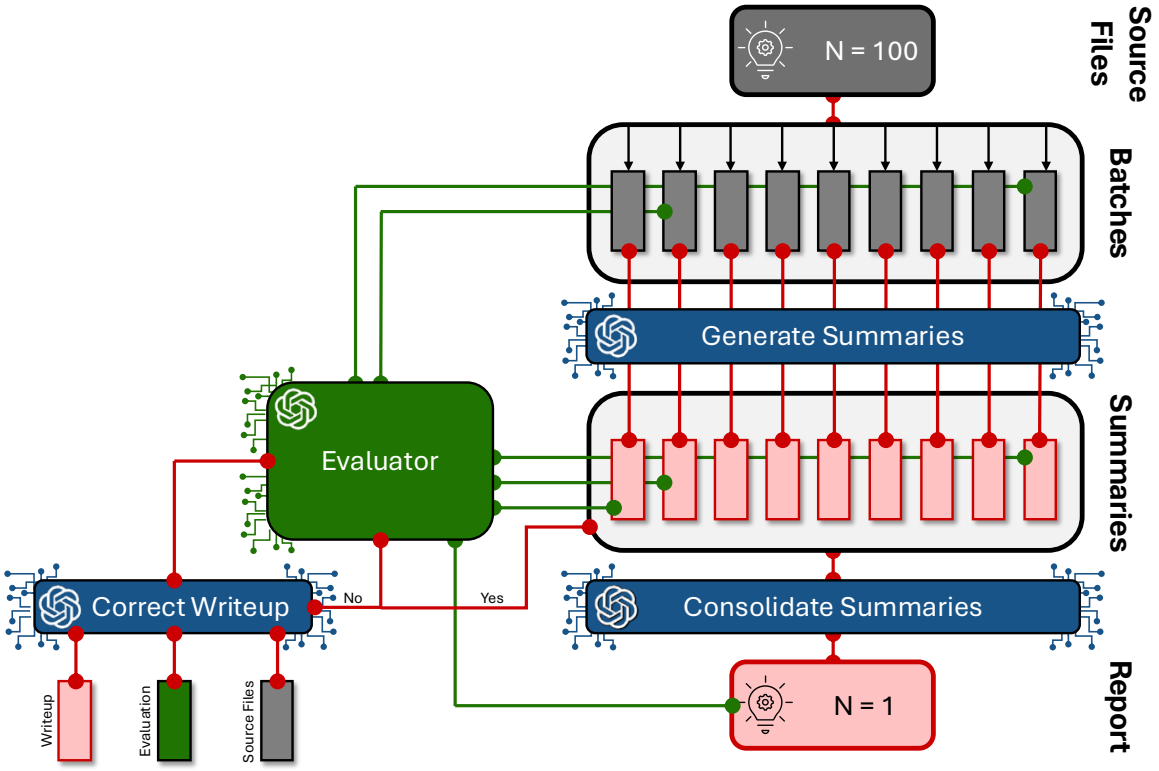
The validated terms were used to automatically retrieve publications from Google Scholar and TRID. Google Scholar results were restricted to 2010 onward and filtered using year-specific citation thresholds based on Clarivate Analytics' InCites Essential Science Indicators field-normalized baselines. The goal of this step was to ensure that selected publications perform above the normal citation level for their publication year and field. Using year-specific citation thresholds helps ensure a fair comparison across publications by recognizing that newer papers naturally have fewer citations and therefore require lower thresholds, while older papers are expected to accumulate more citations and are evaluated against higher thresholds. For each identified document, the title, citation count, abstract, and URL were stored for subsequent screening and analysis.

Subsequent analysis involves deduplicating titles and ranking them by frequency across search terms. A second AI step analyzed this information to identify the most relevant publications for the target technology. The resulting AI-selected list was then subjected to a final human QA review, during which the research team verified the relevance of each entry and added key publications known to the field but not detected by automated searches.

Synthesis of Information

The research team developed a semi-automated pipeline to extract, organize, and summarize information from the publication corpus for each technology. For any given

technology, the workflow consisted of dividing the full set of publications into manageable batches, processing each batch individually, and then consolidating and globally merging the results. This end-to-end process leveraged OpenAI's vector store capabilities alongside its application programming interface (API) to enable efficient retrieval, evaluation, and synthesis of information. A key feature of this methodology is the use of LLM-as-a-Judge, a technique that has become widely adopted across AI research and industry since 2022 because of its strong performance in evaluating, scoring, and selecting the highest-quality outputs. This approach improves consistency and is now considered a standard tool for benchmarking and decision-making in modern AI workflows. A schematic of the pipeline is shown in Figure 7, and a brief description of each component follows.



Source: AAPTP

Figure 7. AI-assisted Summarization, Consolidation, and Evaluation Workflow

Vector Store: A vector store is a specialized database designed to store and search numerical representations of text, known as embeddings. When a document, such as a PDF, is processed, its text is converted into these numerical vectors, which capture the meaning and context of the content. Vector stores allow efficient retrieval of semantically related information based on similarity rather than exact keyword matches. The use of vector stores allows the system to quickly retrieve the most relevant information during summarization, even across large and diverse sets of publications.

OpenAI API: The OpenAI API provides programmatic access to language models, enabling customized workflows that are not limited by the graphical interface. It allows users to send text data, manage prompts, and handle results directly in code, which increases reproducibility, control over inputs and outputs, and integration with other data processing steps.

LLM-as-a-Judge: This concept refers to using an LLM to evaluate or score outputs, such as summaries, answers, or classifications, rather than generating content alone. The LLM acts as an automated reviewer, comparing responses, checking for correctness or relevance, and selecting the best or most accurate result based on predefined criteria.

The methodology is divided into two main stages: Batch-Level Evaluation and Consolidation. Appendix D expands and provides more details on each stage. The output of this AI-assisted literature synthesis is a report providing a description of each technology, definitions of key terms, and key evidence that points to the technology performance, ROI, safety, efficiency, sustainability, readiness levels, technical barriers, upfront cost, operational hurdles, and stakeholder acceptance issues. The report also contains in-text citations and a list of references.

It is important to note that the workflow and evaluation architecture were shaped through multiple rounds of human QA, iterative redesign, and external review to ensure that the final reports are technically robust. Before finalizing the methodology described above and shown in detail in Appendix D, a subset of technologies was run through multiple end-to-end versions of the pipeline, and each version was subjected to detailed manual review. The team read the underlying papers and reports, checked unit conversions and numerical ranges, verified citations, and challenged whether claimed benefits, limitations, and readiness levels were actually supported by the evidence. Internal reviewers flagged issues such as incorrect unit conversions, missing or misattributed citations, optimistic framing that downplayed drawbacks, double counting of benefits across categories (e.g., ROI versus Efficiency), and omission of important negative or ambiguous findings from the source studies.

One technology was also assessed by an external subject matter expert, who concluded that the first version of the report was overly optimistic and did not adequately highlight performance risks, cost uncertainties, or operational constraints, which is an issue that was traced to both the generative model's tendency toward positive framing and the fact that technical publications themselves often emphasize benefits more than downsides.

These findings directly motivated the final design of the system. Definitions were sharpened to clearly separate performance, ROI, efficiency, affordability, and other dimensions. The LLM-as-a-Judge concept and repair loops were introduced and configured to prioritize the following factors: (1) factual accuracy, (2) tone neutrality, (3) information completeness, and (4) technical depth. The evaluator rubrics and pass/fail thresholds that

control the LLM evaluator were tuned to penalize unsupported claims, lack of explicit limitations, and promotional tone. In parallel, the project couples these literature-based, AI-assisted syntheses with focus groups and expert discussions, so that literature findings can be compared against practitioner experience, highlight practical concerns that the literature underreports, and surface additional risks and implementation barriers that must be considered in decision-making.

Step 4: Stakeholder Engagement

Participants and Session Themes

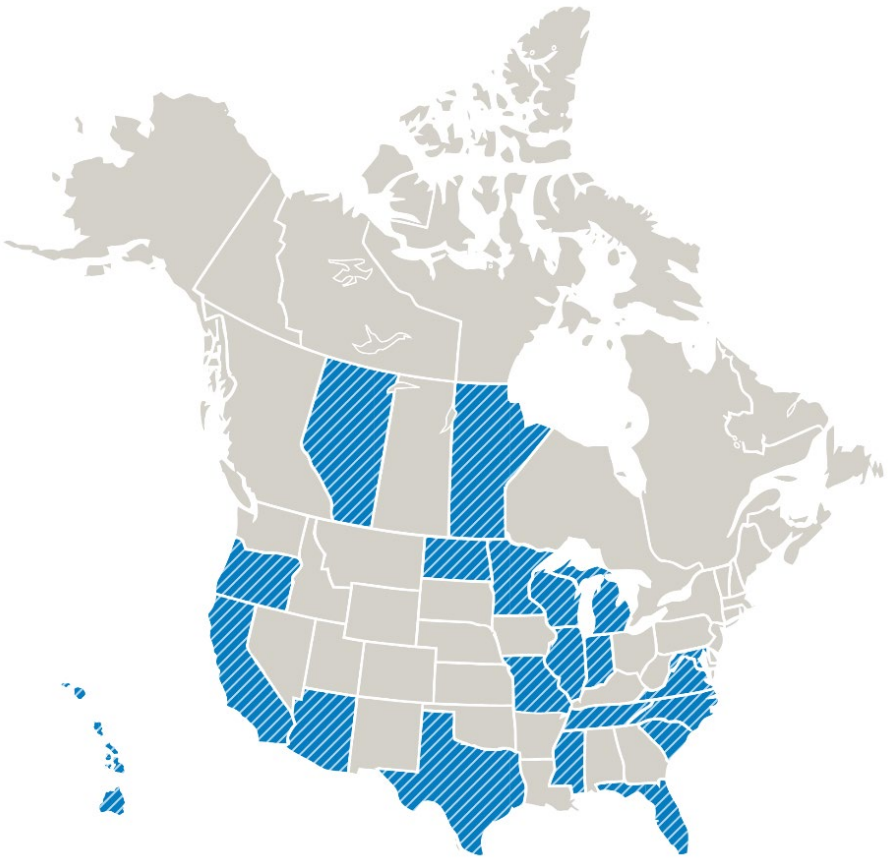
To supplement the AI-assisted literature mining and ensure inclusion of practitioner input, the team conducted a structured series of focus groups with subject-matter experts representing agencies, academia, industry, and technology developers. A total of 31 stakeholders participated. Table 6 lists all participants and their affiliations. Figure 8 shows the representation across the 18 U.S. States, the D.C. metro area, and two Canadian provinces.

Because of the breadth of technologies under evaluation and the limited time availability of participants, it was not feasible for every stakeholder to review all technologies. Instead, the team organized four thematic focus groups, each met virtually for 60 min, and assigned relevant subsets of technologies to each group as shown in Table 7 and Table 8. In addition to the group sessions, the team held supplemental one-on-one meetings with Jeb Tingle, and a joint meeting with Juan Gallego Medina and Federico Gulisano, whose schedules did not align with the main groups. In total, six recorded sessions (focus groups plus individual meetings) were generated, each accompanied by transcripts for subsequent qualitative analysis.

Table 6. Names and Affiliations of Focus Group Participants

Name	Affiliation
Abe Kusam	Trimat Materials Testing, Inc.
Anand Jagadeesh Puppala	Texas A&M University
Bill Pine	Heritage Research Group
Bob Siffert	Ingevity
Bryce Wuori	Pavewise
Christopher Piche	Kraton Polymers
Curtiss Dorr	Topcon Positioning Group
Dan Trapp	MidAmerica St. Louis Airport
Debbie Schwerman	Wisconsin Asphalt Pavement Association
Ervin Dukatz	Flyereld Consulting, LLC
Federico Gulisano	Universidad Politécnica de Madrid
Hamid Soleymani	City of Edmonton
Harold Von Quintus	Applied Research Associates, Inc.
Hassan Tabatabaee	Cargill Industrial Specialties

Name	Affiliation
Heather Dylla	Construction Partners, Inc.
Jason A. Moore	Federal Highway Administration (FHWA) Eastern Federal Lands
Jeb S. Tingle	U.S. Army Engineer Research and Development Center
Jeff Kern	Evergreen Roadworks
Jim Preston	Topcon Positioning Group
Jon Young	Hawaii Asphalt Paving Industry (HAPI)
Juan Gallego Medina	Universidad Politécnica de Madrid
Matthew Brynick	Applied Research Associates, Inc.
Matthew Corrigan	Federal Highway Administration (FHWA)
Mayank Sukhija	Oregon State University
Myron Thiessen	Department of National Defence–Canada/Canadian Armed Forces
Parnian Ghasemi	City of Phoenix
Ron Corun	Ron Corun Consulting, LLC
Stacey Diefenderfer	Virginia Transportation Research Council
Surya S. C. Congress	Michigan State University
Tanya Nash	Asphalt Testing Solutions & Engineering
Todd Mansell	Caterpillar, Inc.



Source: AAPTP

Figure 8. Distribution of Focus Group Participants Across the United States and Canada

Table 7. Theme and Technologies of Focus Groups One and Two

Materials, Mixture Design	Planning, Design, Management and Digital Decision-Support
Nov. 20, 2025, 9–10 AM (ET)	Nov. 20, 2025, 1–2 PM (ET)
- Balanced Mixture Design (BMD) - Highly Polymer Modified Asphalt (HiMA) - Reclaimed Asphalt Pavements (RAP) - High-Modulus Asphalt (EME2) - Stone Mastic Asphalt (SMA) - Warm Mix Asphalt (WMA) - Fiber-Reinforced Asphalt Concrete - Fuel-Resistant Asphalt Mixtures - Bio-Oil or Bio-Binder - Anti-Strip/Moisture Additives - High-Visibility Colored Pavement Markings - Self-Sensing Asphalt Materials - Self/Assisted Healing Asphalt Technologies	- Progressive & Alternative Contracting Methods - Multi-Criteria Decision Support Tools - Agent-Based Models of Construction Bidding - Mechanistic-Empirical (M-E) Pavement Design - Building Information Modelling & Pavement Digital Twins - e-Ticketing & Digital Quality Assurance - Physics-Informed AI for Pavement Performance Prediction - Resilient Pavement Design - Energy-Efficient Asphalt Plant Technologies

Table 8. Theme and Technologies of Focus Groups Three and Four

Sensing, Monitoring, and Smart Pavement Technologies	Construction, QA, and Real-Time Paving Technologies
Nov. 24, 2025, 12–1 PM (ET)	Nov. 24, 2025, 3–4 PM (ET)
- Fixed Systems for FOD Detection - Drone Swarms for FOD Detection - Autonomous Ground Vehicles for FOD Detection - Vehicle-Mounted Systems for Pavement Inspection - Small Unmanned Aircraft Systems (sUAS) for Pavement Inspection - Dash-Cam/Smartphone for Pavement Inspection - Computer Vision/AI Methods for Remote Sensing - Ground-Penetrating Radar (GPR) - Traffic-Speed Deflectometer (TSD) - Machine Learning/AI Methods for NDT Data Interpretation - Embedded Pavement Sensors - Energy-Harvesting Pavements - Heated Airport Pavements	- Infrared Thermal Profiling (IRTP) - 3D Machine Control for Asphalt Paving - Intelligent Compaction (IC) - Dielectric Profiling System (DPS) - Full-Depth Reclamation (FDR) - Cold In-Place Recycling (CIR) - Airfield Base and Subbase Technology - High-Density Longitudinal Joints - Runway Texture and Friction Monitoring Technology - Runway Grooving - Wearable Back-Support Exoskeletons for Construction Workers - Wearable Heat-Stress Monitoring for Construction Workers - Augmented Reality (AR) for Construction QC/QA & Training - Autonomous Truck-Mounted Attenuators (ATMA) - Embedded Electromagnetic Work-Zone Alerts - AI Vision Alerts for Work Zones

Session Structure and Facilitation Approach

Each focus group followed a consistent structure to maximize discussion depth while respecting the 1-hr time limit:

1. Introductions

Participants introduced themselves, their organizations, and areas of expertise.

2. Project Overview

The team provided a concise summary of the project objectives, work completed to date, the session objective, and stakeholder roles and insights in shaping the technology evaluation.

3. Orientation to the Impact–Feasibility Framework

Before reviewing technologies, the team established a common assessment language using the framework shown in Figure 9. Impact includes performance, ROI, safety, efficiency, and sustainability. Feasibility includes technical issues, maturity, upfront cost, regulatory/operational hurdles, and stakeholder acceptance issues.

The team emphasized that this framework was not intended to constrain views but to align terminology so that statements such as “high impact, low feasibility” would be interpreted consistently across participants.

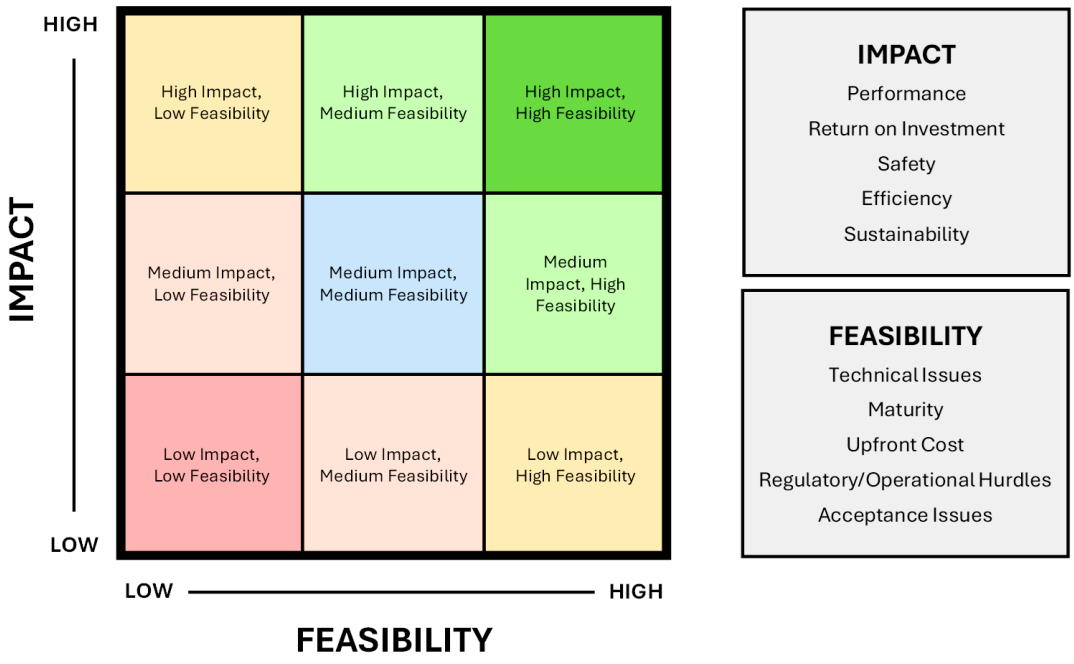
4. Technology Review

For each technology cluster, the team presented a brief, standardized explanation in the form of “what it is” and “how it works” designed to ground the discussion, clarify assumptions, and support contributions even from those less familiar with certain technologies.

5. Facilitated Discussion

The majority of each session was dedicated to capturing nuanced perspectives, including expected benefits, challenges, potential adoption barriers, and any context-specific considerations.

Because each session included numerous technologies, the team implemented light structural guardrails to ensure balanced participation. For example, a visible timer was used to help stay on schedule. Participants were also encouraged to offer intuition grounded in their field experience even if they were not deeply familiar with a given technology. This approach enabled the team to gather both expert insights and informed practitioner intuition, which is critical for technologies still emerging or not yet widely deployed.



Source: AAPTP

Figure 9. Impact and Feasibility Definitions and Matrix

Post-Session Surveys for Quantitative Ratings

While focus groups prioritized qualitative insights and open dialogue, the team collected quantitative impact and feasibility ratings through follow-up surveys sent to each group. The survey also asked participants to prioritize key industry gaps, as established earlier in this report. This dual approach, qualitative depth followed by quantitative rating, ensures both richness of expert insights and consistency for comparative evaluation across technologies.

Step 5: Scoring Technologies

The findings from the AI-assisted literature synthesis are used to score technologies on a 5-point scale using the following dimensions: (1) performance, (2) ROI, (3) safety, (4) efficiency, (5) sustainability, (6) readiness, (7) technical barriers, (8) upfront cost, (9) regulatory/operational hurdles, and (10) stakeholder acceptance. A brief description of each dimension is provided below:

- Performance: How well the technology fulfills its intended technical function relative to current practice.
- ROI: How well the technology delivers economic value relative to its total lifecycle cost (equipment, labor, downtime, maintenance).
- Safety: How much the technology reduces risk exposure or incidents for workers and users compared to current methods.

- Efficiency: How much the technology improves operational throughput, time, or resource use, without considering cost directly.
- Sustainability: How the technology supports environmental goals relative to current practice.
- Readiness: Reflects the maturity of the technology's development and deployment.
- Technical Barriers: How challenging it is to engineer, integrate, or operate the technology within existing systems.
- Upfront Cost: How financially accessible the technology is, regardless of ROI.
- Regulatory/Operational Hurdles: How well the technology fits within current standards and regulations.
- Stakeholder Acceptance: How ready and willing key stakeholders (owners, engineers, contractors, regulators, crews) are to adopt it.

The evaluation uses a 5-point ordinal rating scale to assess each technology relative to current practice, as shown in Table 9. The scale is directional ("higher is better"), and each score level is explicitly defined to ensure consistent interpretation.

Table 9. Definition of the 5-Point Scale Used to Evaluate the Technologies

Score	Interpretation
1	Clearly worse than current practice or introduces meaningful new risk, burden, or inefficiency.
2	Somewhat inferior or offers limited benefit relative to current practice.
3	Comparable to current practice, or evidence is unclear/inconsistent.
4	Noticeably better than current practice with documented advantages.
5	Clearly superior to current practice, with quantified, replicated gains across multiple case studies.

The scoring instructions were designed to keep each rating bound to documented evidence rather than model assumption. For every technology, the AI was restricted to the assembled document corpus and prohibited from introducing outside knowledge, inferring values, or extrapolating beyond the cited text. Information had to be traceable to specific cited evidence, and airfield-specific evidence (runway, taxiway, and apron applications) was prioritized over roadway-only evidence. To counter the tendency of language models toward positive framing, the instructions placed the model in a deliberately skeptical posture in which each score began at the lowest level and was raised only on the basis of direct, cited evidence. A separate AI evaluation step, configured as an evaluator with correction loops, screened each draft for factual accuracy, tone neutrality, completeness, and technical depth, and was tuned to flag unsupported claims, promotional language, and omitted limitations.

These scores were treated as a structured first pass rather than final results. Every score was reviewed and, where warranted, revised by the team. The team reviewed factual claims and challenged whether each assigned score was genuinely supported by the

source evidence. The evaluation architecture itself was shaped through multiple rounds of human QA, iterative redesign, and external review.

Following the initial team scoring based on the AI-assisted literature synthesis, the results were revisited after the focus group sessions. The discussion provided an opportunity to reflect on how the technologies are perceived and experienced in practice. Where appropriate, refinements were made to certain dimensions to better align the scores with practitioner insight and contextual considerations raised during the conversation. In some cases, the transcript offered direct support for adjustment; in others, revisions reflected the overall tenor of the discussion rather than a single explicit statement.

These refinements were applied selectively and conservatively. Each change was documented with a brief explanation to clarify how the final score evolved. This iterative approach ensures that the evaluation reflects both structured evidence synthesis and stakeholder insights.

Phase 3: Recommendations

Step 6: Assessing Impact and Feasibility

Each technology is evaluated using a multi-criteria scoring matrix (shown in Table 10). The matrix consolidates findings from the AI-assisted literature synthesis and the focus groups into three core numerical indicators: Impact Score, Feasibility Score, and Gap Alignment. These indicators feed into a weighted Total Score (0–100), ensuring that high-impact, high-feasibility technologies rise to the top while still reflecting stakeholder priorities and identified gaps. All weights reported in Table 10 were determined by polling the project panelists.

The Impact Score (1–5) summarizes how strongly a technology can improve pavement practice when implemented successfully. It is calculated as a weighted average of the benefits dimensions (performance, cost, safety, efficiency, and sustainability) derived primarily from the literature, with focus-group insights used to contextualize or adjust emphasis.

The Feasibility Score (1–5) reflects how realistic it is to adopt the technology in airfield projects, calculated as a weighted average of readiness, technical and cost barriers, regulatory/operational hurdles, and stakeholder acceptance, again informed by both documentary evidence and stakeholder input.

Two additional indicators directly link the scoring system back to the gap and stakeholder priorities identified earlier. Gap Alignment (0–3) measures the degree to which a technology addresses one or more of the identified gaps from the industry survey and focus-group discussions; technologies that directly target multiple high-priority gaps receive the highest values.

These three indicators are combined into a Total Score (0–100) using the weighting scheme shown in Table 10. All components of the Total Score are normalized to a 0–1 scale before weighting to ensure comparable contribution despite different raw scales.

Table 10. Scoring Structure and Criteria Used to Evaluate Each Technology

Description	Type/Range	How to Populate
Impact Score	Numeric (1–5)	0.34 × Performance Score + 0.19 × ROI Score + 0.26 × Safety Score + 0.10 × Efficiency Score + 0.11 × Sustainability Score
Feasibility Score	Numeric (1–5)	0.24 × Readiness Score + 0.18 × Technical Barriers Score + 0.21 × Upfront Cost Score + 0.25 × Regulatory/Operational Hurdles Score + 0.13 × Stakeholder Acceptance Issues Score
Gap Alignment	Numeric (0–3)	0 = Addresses no gaps 1 = Addresses low-priority gaps 2 = Addresses medium-priority gaps 3 = Addresses high-priority gaps
Total Score	Numeric (0–100)	0.38 × Impact Score + 0.35 × Feasibility Score + 0.26 × Gap Alignment

Step 7: Gap Analysis

A structured gap analysis was conducted to ensure that technology prioritization reflects the industry's most pressing challenges rather than technical evidence alone. Six industry gaps were identified based on the survey. The following gaps were identified:

- **Need to Modernize Specifications and Criteria:** Existing specifications, such as P-401, do not fully reflect current best practices in materials design and performance testing. Updating specifications to include Superpave, BMD, and performance-based testing would allow more innovative mixtures (e.g., high RAP, recycled materials) to be evaluated and approved based on actual performance rather than prescriptive limits.
- **Innovation and Change Management:** The industry relies heavily on long-standing, proven methods, which can make the adoption of new technologies and practices slow or unsupported. While traditional approaches offer reliability, this resistance to change often limits innovation and the advancement of more efficient or modern solutions.
- **Construction Quality:** Even the best materials and designs cannot compensate for poor construction practices. Achieving high-quality pavement relies on proper techniques, trained crews, and timely feedback. Real-time quality monitoring is

especially needed to detect issues during construction rather than after problems appear.

- **Workforce and Training:** There is a growing need for better-trained inspectors, engineers, and field personnel who understand current specifications, testing methods, and on-site operations. Inadequate training can lead to inconsistent enforcement of standards and reduced pavement performance.
- **Budget:** Agencies often face a mismatch between what is needed for high-quality, long-lasting pavements and the budgets available to deliver them. Limited funding leads to choosing either overly robust (and costly) designs or minimalistic solutions that may be insufficient, ultimately affecting pavement longevity and performance.
- **Design Tools and Analysis:** Airfield pavement design using FAARFIELD still relies on simplified models that do not fully integrate material performance properties, leading to missed opportunities for better design and more accurate predictions of performance and lifecycle cost. Incorporating mechanistic properties and nuanced analytical methods would improve reliability and allow more cost-effective, long-term solutions.

The focus group participants were asked to identify the three gaps that would generate the greatest impact if addressed first. The results of the focus group polling on industry gaps are shown in Table 11. The results were used to assign high-medium-low priority status to each gap.

Each technology is then evaluated against these prioritized gaps using the structured scoring rubric shown in Table 10. Technologies receive a Gap Score of 3 only if they directly address a high-priority gap, 2 for medium-priority gaps, 1 for low-priority gaps, and 0 if they address no identified gap. The three indicators (Impact, Feasibility, and Gap Alignment scores) are combined into a Total Score (0–100) using the weighting scheme shown in Table 10. All components of the Total Score are normalized to a 0–1 scale before weighting to ensure comparable contribution despite different raw scales. All weights reported in Table 10 were determined by polling the project panelists. Gap Alignment is weighted at 26 percent of the Total Score.

Table 11. Percentage of Focus Group Respondents Selecting Each Industry Gap as a Top-Three Priority

Gap	Percent of Focus Group Selection	Priority Designation
Need to Modernize Specifications and Criteria	91%	High
Innovation and Change Management	55%	High
Construction Quality	46%	Medium
Workforce and Training	46%	Medium
Budget Constraints	32%	Low
Design Tools and Analysis	27%	Low

Gap Alignment scoring requires that the technology itself provides a concrete mechanism to address the gap. Five scoring principles govern the scoring:

- High-Priority Gap Principles:
  - Need to Modernize Specifications and Criteria: A technology must drive specification modernization by providing a framework, method, or tool that enables specifications to be updated, standardized, and aligned with current best practices. For example, BMD provides the testing framework that replaces prescriptive volumetric criteria; it is a specification-modernizing tool. HiMA is not currently explicitly allowed according to P-401 and would benefit from specification change, but it does not cause it.
  - Innovation and Change Management: A technology must provide a concrete mechanism to de-risk adoption of other technologies, not simply be innovative itself. For example, M-E Pavement Design tools enable simulation of novel materials within realistic pavement structures to predict service life before field trials.
- Medium-Priority Gap Principles:
  - Construction Quality: A technology must provide a concrete quality improvement mechanism: measurement tools (e.g., continuous friction measurement equipment [CFME]), real-time process monitoring (e.g., infrared thermal profiling [IRTP]), automated data collection (e.g., sUAS, computer vision/AI), digital QA workflows (e.g., electronic ticketing [e-Ticketing]), construction methods with measurably better outcomes through process control (e.g., 3D machine control), or post-construction condition assessment technologies that improve evaluation data quality over manual approaches (e.g., traffic-speed deflectometer [TSD]).
- Low-Priority Gap Principles:
  - Budget: Technologies must demonstrate documented, quantified cost savings, not just lifecycle payback. Material reuse (RAP, full-depth reclamation [FDR], CIR) qualifies through direct recycling cost reductions.
  - Design Tools and Analysis: A technology must provide analytical capability that improves the reliability of airfield pavement design beyond current empirical or simplified methods. For example, M-E Pavement Design enables mechanistic analysis of pavement structures, and BIM/digital twins extend analytical infrastructure by integrating design, construction, and performance data across the pavement lifecycle.

Findings

This section presents the findings from the multi-criteria technology evaluation. A total of 51 technologies were assessed across 10 dimensions (Performance, ROI, Safety, Efficiency, Sustainability, Readiness, Technical Barriers, Cost, Regulatory/Operational Hurdles, and Acceptance). These dimensions were used to calculate composite Impact and Feasibility scores based on the weighted average approach detailed in Table 10.

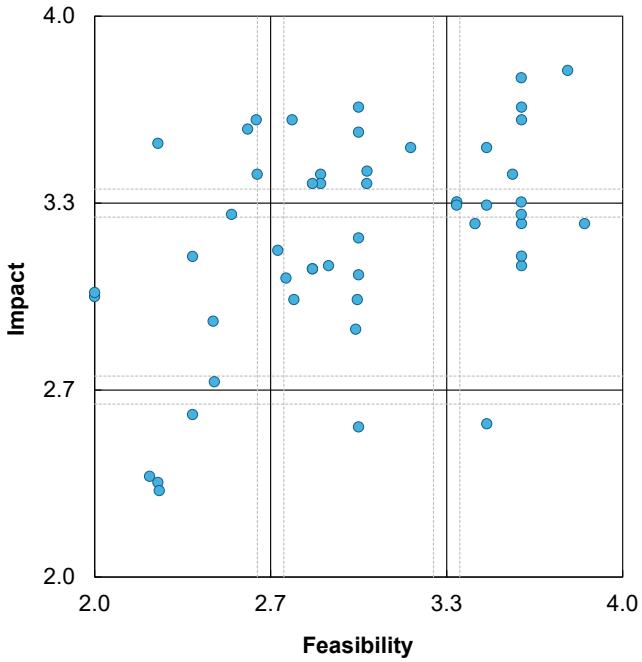


Figure 10. Two-Dimensional Impact vs. Feasibility Matrix for All Technologies

Figure 10 presents the consolidated Impact–Feasibility scatter plot for all 51 technologies. Each point represents a technology's composite scores, which reconcile scores from literature synthesis with expert focus group judgment across the 10 scoring dimensions. Technologies in the upper-right quadrant exhibit both high impact potential and high implementation feasibility, representing the strongest candidates for near-term advancement. Technologies toward the lower-left are those with lower scores on both dimensions, indicating limited demonstrated benefits and significant adoption barriers.

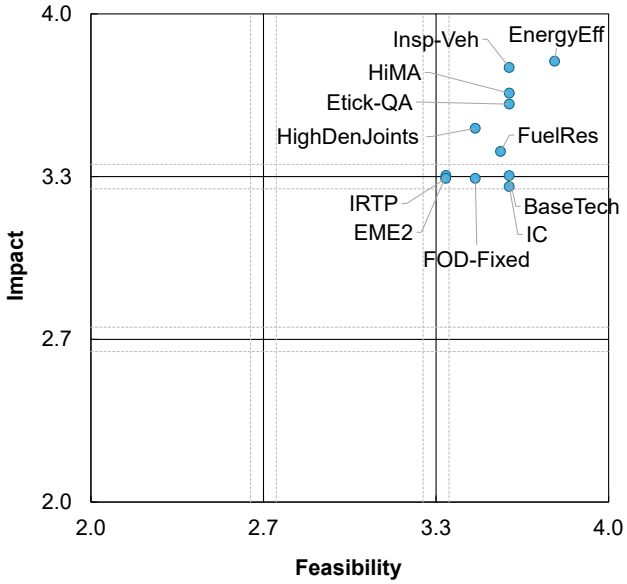
The technologies were grouped into seven priority tiers based on their Impact–Feasibility score, as follows:

- Cell 1: High Impact/High Feasibility
- Cell 2: High Impact/Medium Feasibility
- Cell 3: High Impact/Low Feasibility
- Cell 4: Medium Impact/High Feasibility
- Cell 5: Medium Impact/Medium Feasibility
- Cell 6: Medium Impact/Low Feasibility
- Cells 7–9: Low Impact/High-Medium-Low Feasibility

The following sections present each priority tier, including the technologies assigned to them, the documented evidence regarding performance and sustainability, and applicable regulatory considerations.

Cell 1: High Impact/ High Feasibility Technologies

Figure 11 presents the Impact–Feasibility scatter plot for the 11 technologies classified in Cell 1. These technologies have demonstrated performance benefits with manageable implementation pathways. Many are either already in use in some airfield applications or have mature roadway precedents that support a structured deployment pathway. Dimension scores for each technology are presented in Table 12 and Table 13.



Source: AAPTP

Figure 11. Impact vs. Feasibility Matrix for Technologies Classified as High Impact/High Feasibility

Table 12. Impact Dimension Scores for High Impact/High Feasibility Technologies

Technology Name	Performance	ROI	Safety	Efficiency	Sustainability	Impact Score
Highly Polymer Modified Asphalt (HiMA)	5	3	3	3	3	3.7
High-Modulus Asphalt (EME2)	4	3	3	3	3	3.3
Fuel-Resistant Asphalt Mixtures	4	3	3	4	3	3.4
e-Ticketing & Digital QA	4	4	3	4	3	3.6
Fixed Systems for FOD Detection	4	3	4	4	4	3.8
Vehicle-Mounted Systems for Pavement Inspection	4	3	3	4	2	3.3
Infrared Thermal Profiling (IRTP)	4	4	4	4	2	3.8
Intelligent Compaction (IC)	4	3	3	4	2	3.3
Airfield Base and Subbase Tech.	3	4	3	4	3	3.3
High-Density Longitudinal Joints	4	3	3	3	3	3.3

Table 13. Feasibility Dimension Scores for High Impact/High Feasibility Technologies

Technology Name	Readiness Level	Technical Issues	Upfront Cost	Regulatory Hurdles	Stakeholder Acceptance	Feasibility Score
Highly Polymer Modified Asphalt (HiMA)	3	3	4	4	3	3.6
High-Modulus Asphalt (EME2)	3	3	3	4	3	3.4
Fuel-Resistant Asphalt Mixtures	4	2	4	4	4	3.6
e-Ticketing & Digital QA	3	3	4	4	3	3.6
Fixed Systems for FOD Detection	4	3	4	4	4	3.8
Vehicle-Mounted Systems for Pavement Inspection	3	3	4	3	3	3.5
Infrared Thermal Profiling (IRTP)	3	3	4	4	3	3.6
Intelligent Compaction (IC)	3	3	3	4	3	3.4
Airfield Base and Subbase Tech.	3	3	4	4	3	3.6
High-Density Longitudinal Joints	3	3	4	4	3	3.6

Highly Polymer Modified Asphalt (HiMA)

HiMA is an asphalt binder formulated with approximately 7–8 percent polymer by weight, roughly double the 2.5–3.5 percent typical of conventional polymer-modified asphalt (PMA), such that the polymer-rich phase becomes structurally continuous and governs mechanical response (Rivera et al., 2021). Produced almost exclusively with styrene–butadiene–styrene (SBS) elastomer, HiMA achieves phase inversion that yields high elastic return and increased strain tolerance (Złotowska et al., 2021). A specialized high-vinyl SBS variant addresses viscosity and storage-stability challenges, enabling mixing temperatures limited to approximately 160–170 °C (Porot et al., 2019).

Regulatory Context: FAA Item P-401 specifies performance graded (PG) binder per ASTM D6373, with standard PG grade tables listing grades up to PG 82 (FAA Advisory Circular [AC] 150/5370-10H). HiMA-relevant grades (PG 82+) may not be listed and may require engineering justification and/or a Modification of Standards (MOS) (FAA Order 5300.1G). FAARFIELD presents two structural design limitations: (1) fixed modulus inputs (200,000 psi surface; 400,000 psi stabilized base) provide no design credit for HiMA's enhanced

stiffness regardless of binder modification (AC 150/5320-6G); and (2) the layered elastic framework lacks constitutive damage models to capture fatigue life extension and damage tolerance, which are HiMA's primary performance benefits. Mixing temperatures for HiMA-relevant grades (PG 82+) (160–170 °C) approach the P-401 maximum of ~177 °C.

Key Evidence from Literature:

- In Florida, HiMA sections exhibited rut depths of 2.7–3.0 mm versus 5.1 mm for PG 76-22 PMA controls after 100,000 Heavy Vehicle Simulator (HVS) passes at 50 °C, with 35- to 40-percent lower tensile strains and approximately 3.5 times greater predicted fatigue life (Kwon et al., 2020).
- The inclusion of a HiMA-based stress-relieving asphalt mixture interlayer yielded 12.2 percent cracked area after 29 months versus 48.1 percent for a standard overlay, with 3.9 times slower crack propagation (Gaspar et al., 2017).
- Binder characterization showed Jnr of 0.04 versus 0.09 kPa^{-1} and percent recovery of 93.8 percent versus 70.5 percent relative to PMA (Rivera et al., 2021).
- Due to the enhanced mechanical properties of HiMA, mechanistic analyses estimate 46–54 percent asphalt thickness reductions at equivalent fatigue performance (Habbouche et al., 2018).
- Material cost premiums are +$20–$25/ton (dense-graded) compared to PG 76-22, with an estimated 10-month break-even (Vargas-Nordcbeck & Musselman, 2021).
- Elevated viscosity requires strict storage temperature/time controls and prompt compaction (Vargas-Nordcbeck & Musselman, 2021).
- Benzene/toluene extraction can alter HiMA indices (e.g., C=O, S=O), complicating recovered-binder chemistry (Devulapalli et al., 2023).

Stakeholder Perspectives: A contractor participant described HiMA as a practical near-term improvement: "I'm personally very interested in looking at highly polymerized modified asphalt mixes, especially if we're trying to look at like a P401 spec and try to improve performance. Simply plugging in a new liquid and maybe bringing the air voids down some would be an easy lift." Virginia already implements HiMA, stone mastic asphalt (SMA), and EME2 base mixes, noting they "can perform extremely well" but cautioning that quality control must extend through production and construction, "it doesn't end at the plant." Lastly, a materials researcher placed HiMA alongside SMA and EME2 as "very rational things to be doing" and noted that international airfield operators are already using high polymer modified mixes and rejuvenators with BMD approaches.

High-Modulus Asphalt (EME2)

A French-origin, high-modulus asphalt mix design method (Enrobé à Module Élevé, Class 2) or EME2 uses a hard paving-grade bitumen at relatively high binder content and low in-place air voids (AV) to achieve high stiffness, rut resistance, and satisfactory fatigue resistance compared to conventional asphalt base mixtures with unmodified binders

(Valenzuela & Latter, 2018). EME2 acceptance is verified by performance tests rather than solely volumetric criteria; the framework includes a minimum dynamic modulus of 14,000 MPa at 15 °C and 10 Hz per EN 12697-26 and fatigue characterization via bending or indirect tensile tests according to EN 12697-24 (Petho & Denneman, 2013, Petho & Denneman 2016). In European practice, EME2 has been used for base layers on roads subject to heavy traffic and on airports, establishing direct airfield relevance for runway, taxiway, and apron base/binder applications (Valenzuela & Latter, 2018).

Regulatory Context: FAARFIELD assigns fixed modulus values of 200,000 psi (surface) and 400,000 psi (stabilized base), and the variable stabilized flexible base option caps at 400,000 psi, meaning EME2's high modulus may not be used to generate thinner pavement design, which eliminates the technology's primary cost benefit within the current design framework (AC 150/5320-6G). P-401's standard Marshall/Gyratory acceptance framework was not designed for EME2's performance-specified approach, which targets low in-place AV and uses stiffness/fatigue thresholds (≥14,000 MPa at 15 °C) rather than solely volumetric criteria. Adoption may therefore require an MOS to adjust P-401 acceptance thresholds (FAA Order 5300.1G).

Key Evidence from Literature:

- Australian EME2 acceptance limits include AV at 100 gyrations ≤ 6.0 percent, wheel-tracking at 60 °C ≤ 4.0 mm at 30,000 cycles and ≤ 2.0 mm at 5,000 cycles, minimum stiffness 14,000 MPa at 15 °C /10 Hz, and minimum fatigue 150 microstrains at 20 °C /10 Hz at 10^6 cycles (Dias et al., 2017).
- Airport-specific analyses using the LEDFAA design program with measured high-modulus inputs showed base thickness reductions at warmer average temperatures across multiple departure levels and subgrade supports, with smaller reductions at lower average temperatures (Espersson, 2014).
- The cost of high-modulus asphalt concrete variants with crumb rubber and RAP was found to be comparable or lower in $/ton versus a Superpave control, with modeled thickness reductions in binder courses (Mousa et al., 2021).

Stakeholder Perspectives: A materials researcher grouped EME2 alongside HiMA and SMA as "*very rational things to be doing*," noting that under different names these approaches "*are being done already in airfields.*" A State DOT representative confirmed that their "*standard base mix is basically the EME2*," and that these mixes "*can perform extremely well, or they can perform extremely poorly if something goes wrong. Understanding exactly what can go wrong and accounting for it in terms of both design and production and construction*" is essential.

Fuel-Resistant Asphalt Mixtures

Asphalt mixtures that are designed to withstand softening, dissolution, and loss of aggregate–binder adhesion when exposed to hydrocarbon fuels typical of airfield operations, reducing distress and the risk of foreign object debris (FOD) on runways, taxiways, and aprons (Irfan et al., 2017; White, 2018). Three principal technical approaches appear in the literature. First, polymer-modified binders react with asphalt to form a cross-linked "polymer-linked" network that limits mass loss and supports higher modulus after jet fuel exposure (Irfan et al., 2017). Fuel-resistant PMA formulations typically contain up to 7.5 percent polymer by weight and lose less than 1 percent of their mass after 24-hr immersion in jet fuel (Corun, 2023). Second, semi-flexible pavements impregnate a highly flowable cementitious grout into an open-graded asphalt layer to produce a rigid–flexible composite with elevated load capacity and fuel-spillage resistance suitable for airport aprons (Hassani et al., 2020; Khan et al., 2021). Third, epoxy asphalt binder systems form a thermoset, cross-linked network that provides chemical resistance to aircraft fuels and lubricants with historical deployments on taxiways, terminal aprons, hangars, and fueling areas tolerating jet exhaust heating to 426 °C (Lu and Bors, 2015; Cong et al., 2019).

Regulatory Context: FAA Item P-404 in AC 150/5370-10H is the existing specification for fuel-resistant asphalt mix pavement. P-404 was revised in 10H and no longer requires coal tar—it now specifies polymer-modified asphalt binder PG 82-28 or PG 88-22 per ASTM D6373, with fuel resistance achieved through high polymer modification and mix design (low AV, high density). P-404 is used in conjunction with P-401. All in all, the regulatory framework for fuel-resistant pavements already exists through P-404, which may make updating the specification to accommodate modern alternatives a more straightforward path.

Key Evidence from Literature:

- An FAA #3 surface mix with PG 94-22 fuel-resistant (FR) binder outperformed mixtures with PG 64-22, PG 76-22, and PG 82-22 binders in repeated load testing, with all three FR specimens reaching flow number (FN) > 20,000 cycles at 140 °F and 25 psi; the FR binder accumulated half the APA rutting of the PG 64-22 (Maher & Bennert, 2006).
- Epoxy hot mix asphalt (HMA) tested for the George Washington Bridge also achieved FN > 20,000 and exhibited fatigue life 2–3 orders of magnitude greater than a PG 76-22 I-5 mix, though it was flagged for unpredictable set-up/curing times (Maher & Bennert, 2006).
- A P-601 (now P-404) 9.5 mm FR mix demonstrated an FN advantage over a standard Logan Airport 12.5 mm P-401 mix, a better APA rut depth, and 9–10.6 times greater flexural beam fatigue life. In the Overlay Tester, the FR mix achieved 4,134 cycles

(short-term oven aging) and 102 cycles (long-term oven aging) versus 745 and 6 for the P-401 (Bennert et al., 2017).

- P-404 mix costs approximately 20–25 percent more than P-401 mix (driven by 2–3 times more polymer and ~1 percent more liquid asphalt), but because the cost increase affects only the surface layer, the total project cost increase is typically 5–7 percent (Corun, 2023).
- FAA P-404 has been deployed at numerous airports including LaGuardia (2002), Logan (2004+), Charlotte Douglas (2006), Portland Jetport (2015), BWI Marshall (2016), Bob Hope/Burbank (2019), Toronto International (2020), and multiple Georgia airports. Hurlburt Field (2018) in Florida was the first DOD project; DOD has since adopted an FR specification (UFGS 32 12 17.19) almost identical to FAA P-404 (Corun, 2023).

Stakeholder Perspectives: A consultant emphasized that FR mixtures offer HiMA-level performance with added fuel resistance, noting their expanding use: "We're seeing now more usage away from just aprons. We're looking at taxiways. We're actually looking at some runways." Another stakeholder endorsed the technology, stating it's "always a good thing in airport conditions for sure," and a research panelist rated it high impact/high feasibility given clear paths for broader adoption based on local experience.

e-Ticketing & Digital Quality Assurance

Electronic ticketing (e-Ticketing) digitizes the creation, transfer, and archiving of construction material delivery data, replacing paper weight tickets. It links each asphalt load to time and location via Global Positioning System (GPS)-equipped trucks that cross virtual geofences at the plant, scale, jobsite, and paver, generating time-stamped records streamed to web-based maps and inspector tablets in real time (Sturgill et al., 2019). Digital QA extends this into continuous, geospatially referenced construction data streams through paver-mounted thermal profiling (PMTP), IC, and continuous density estimation via dielectric measurements (Chang et al., 2018; Wang et al., 2019). A Material Delivery Management System (MDMS) standardizes data and pushes it via APIs to a cloud database for near real-time visualization, with an American Association of State Highway and Transportation Officials (AASHTO) provisional practice (MDM-1-UL) drafted to support consistent use (Embacher, 2021).

Regulatory Context: FAA Item C-100 (AC 150/5370-10H) requires the Contractor to maintain and make available QC records but is format-neutral. It does not explicitly prohibit electronic records. No FAA AC or Engineering Brief currently establishes e-Ticketing requirements for airport construction, yet because e-Ticketing does not modify physical design, materials, or construction methods, it may not be subject to MOS per FAA Order 5300.1G. Digital records must still satisfy Federal retention and audit standards under Airport Improvement Program (AIP) Grant Assurance 13 (Order 5100.38D).

Key Evidence from Literature:

- An e-Ticketing system recorded GPS-based truck movements across geofences at plant/scale/site/paver, streaming full digital ticket fields and daily pay summaries, while field awareness of truck locations allowed production adjustments to avoid paver stops when trucks were delayed (Sturgill et al., 2019).
- MDMS/Veta integration overlays dump locations with IC/PMTP/dielectric profiling system (DPS) data to link QA tests and acceptance decisions to specific loads, stationing, thermal patterns, and pass counts, supporting timely remove-and-replace decisions and workmanship troubleshooting (Embacher, 2021).
- e-Ticketing reduced inspector exposure to hazardous jobsite conditions by eliminating paper ticket handoffs near haul trucks and active equipment (Subramanya & Kermanshachi, 2022).
- Connectivity constraints at plants and jobsites, geofence configuration errors (especially with material transfer vehicles), GPS offsets, vendor interoperability, and data ownership/records retention challenges were identified as principal technical and operational limitations (Sturgill et al., 2019; Wang et al., 2019).

Stakeholder Perspectives: A panelist valued the ability to "tie that information with long-term performance to make better decisions for the next project moving forward." A materials engineer noted packages are "available now and being used" with "an impact on our quality literally almost immediately," while a contractor called it "the easiest to implement."

Energy-Efficient Asphalt Plant Technologies

Energy-efficient asphalt plant technologies are production-facility upgrades that reduce burner fuel use, electricity intensity, and cradle-to-gate greenhouse gas (GHG) emissions during asphalt mixture manufacturing while maintaining mixture quality (Milad et al., 2022; Young, 2023). These upgrades target the dominant plant-stage energy drivers, especially aggregate drying and heating in rotary dryers, which account for approximately 60 percent of plant energy use and 67+ percent of production carbon emissions (Milad et al., 2022). Key measures include warm mix asphalt (WMA) temperature reductions (110–140 °C versus 150–180 °C for HMA), burner and dryer optimization, aggregate moisture management, variable frequency drives on large motors, insulation and heat-recovery improvements, and fuel-flexible burners (Milad et al., 2022; Young, 2008).

Regulatory Context: FAA Item P-401 (AC 150/5370-10H) specifies asphalt plant requirements per ASTM D995, requiring plants to produce mix within JMF-approved temperature ranges with temperature indication and recording at discharge. Equipment upgrades that produce conforming mix may not require an MOS. WMA production temperatures (~250 °F) may require verification against temperature limits (≤325 °F for unmodified binders and ≤350 °F for polymer-modified binders). Energy efficiency

improvements are eligible for AIP funding under 49 USC §47110(b)(7) and Order 5100.38D §3-70, though this applies to airport-owned infrastructure, whereas most asphalt plants are contractor-owned and off-airport, which may limit AIP applicability (AC 150/5370-10H; Order 5100.38D).

Key Evidence from Literature:

- Lowering mixing temperature from 180 °C to 125 °C for a foamed WMA reduced plant-measured energy consumption by 35 percent, CO_2 by 35 percent, SO_2 by 25 percent, NO_x by 60 percent, and dust by 25–30 percent in an Italian plant study (Hassan, 2010).
- Enclosing fine aggregate stockpiles reduced drying energy by 10.4–14.3 percent and increased dryer throughput by 15–21 percent when stockpile moisture was lowered from 7 to 4 percent (Young, 2008).
- A burner changeout to enable fuel switching (No. 2 diesel to natural gas) recovered an investment of approximately $8,000 (~$10,000 installed) in under 6 months; increasing tank insulation from 3 to 6 inches saved ~1,296 gal/year of diesel with a 1-year payback (Young, 2008).
- A practical production-strategy bundle for temperature reductions and dryer/heater tuning yielded fuel reductions of 8–15 percent for 40–50 °F lower final mix temperature, with an additional 3–5 percent from exit-gas reductions after flighting optimization (Young, 2023).

Stakeholder Perspectives: A contractor participant rated these technologies high impact and high feasibility: “a lot of that is already being done, just needs to be done more … it’s low cost and that’s an easy sell.” Another participant agreed that “the really good contractors are already paying attention to this.” However, participants flagged that on federally funded projects, “sometimes you start talking about true warm mix production temperatures, and some folks get really nervous,” thus, the cost-savings case is clearest for direct plant retrofits (variable frequency drives , insulation, moisture control), where “the payback is direct and it’s a pretty short-term return on investment.”

Fixed Systems for FOD Detection

Fixed FOD detection systems are permanently installed sensor networks that continuously monitor runway, taxiway, and apron pavements to detect, locate, and alert on hazardous objects during routine airport operations using performance benchmarks derived from AC 150/5220-24 (Herricks et al., 2012a). Fielded systems follow two principal approaches: electro-optical (EO) video sensing and millimeter-wave radar sensing (Herricks et al., 2012a; Herricks et al., 2011b).

Regulatory Context: Current practice relies on manual visual inspections per 14 CFR §139.327 (daily inspections) and §139.305(a)(4) (prompt FOD removal). AC 150/5210-24A

establishes the FOD management program framework and recognizes in §4.3.2.2.1 that advanced technologies are "now available for improved FOD detection, including capabilities for continuous detection," while AC 150/5220-24 provides detailed procurement performance specifications. Fixed automated systems are thus fully specified within the FAA framework and do not require an MOS. AIP funding is available per Order 5100.38D Appendix L (Table L-2, items j/k) but only for large-hub airports at 50-percent Federal share.

Key Evidence from Literature:

- A hybrid installation at Boston Logan International Airport (BOS) mounted 10 Surface Detection Units, each integrating a 76–77 GHz radar unit and an EO sensor with near-infrared illumination, on runway edge light positions to scan the full runway width and deliver fused radar-image detections to an operator interface (Herricks et al., 2012b). The hybrid EO/radar system met the basic functions and detection requirements in AC 150/5220-24, achieving 94 percent daylight/dry detection that increased to 98 percent after hybrid record review, with average time to detection of 35 s and average location accuracy of 5.02 ft versus the AC threshold of 16 ft (Herricks et al., 2012a).
- EO performance under variable conditions included 97–98 percent near-dawn/dusk detection, 83 percent wet-pavement detection at Chicago O'Hare International Airport (ORD), 96 percent on snow/ice taxiway, and 90 percent total nighttime detection across combined ORD locations (Herricks et al., 2012a).
- At Providence T. F. Green International Airport (PVD), the fixed radar achieved 100-percent observed detection of aircraft object-set items placed ≥1,000 ft from the sensor, with 3.0 ft average location error and typical scan under 1 min; a heavy-rain squall caused 2–3 min of detection loss with full recovery within 9 min; winter tests documented 87–93 percent detection depending on target reflectivity (Herricks et al., 2011b).
- A cost-benefit analysis for a standard high-activity airport estimated representative initial cost of $5.75M and average annual operations and maintenance of $275K ($9.39M undiscounted over 12 years), yielding a direct-only benefit–cost ratio of 1.22 (net present value [NPV] $2.1M, break-even Year 9), rising to a benefit/cost (B/C) 2.64 (NPV $15.4M, break-even Year 3) when 1× indirect costs and partial wildlife fringe benefits are included (Hilburn & Pesmen, 2023).
- An improved YOLOv8 model for FOD imagery achieved mAP at 0.5–0.95 of 93.8 percent at 90 FPS on the FOD-A dataset, with reduced performance on real runway images versus curated dataset tests (Farooq et al., 2024; Munyer et al., 2022).

Stakeholder Perspectives: Participants viewed fixed FOD detection as practical and mature. One noted fixed systems provide "pretty good, geotagged alert operations" useful for airfield surveillance, while another flagged range limitations for long runways,

prompting discussion of mix-and-match approaches (i.e., fixed systems for runways with alternative technologies for taxiways/aprons). Panelists emphasized that manual inspections may miss debris at speed, underscoring the value of continuous automated sensing. They also noted fixed systems could verify contractors haven't left equipment/debris post-construction.

Vehicle-Mounted Systems for Pavement Inspection

Vehicle-mounted systems for pavement inspection integrate nondestructive sensors on moving platforms (e.g., survey vans) to observe surface and subsurface conditions at driving speeds, producing georeferenced data for condition assessment while minimizing intrusive testing and on-foot exposure (Elseicy et al., 2022). Common configurations combine LiDAR/mobile laser scanning with global navigation satellite system (GNSS) and an inertial measurement unit for dense three-dimensional point clouds; GPR for subsurface layer thickness and dielectric characterization; and road surface profilers, which pair an inertial unit, laser height sensor, and distance measuring instrument, for roughness indices (Elseicy et al., 2022; Guan et al., 2015). Additional payloads documented in roadway studies include video cameras for surface imaging, optical sensors for distance measurement, ultrasonic sensors for rut detection, and accelerometers for roughness (Koch et al., 2013; Chen et al., 2016).

Regulatory Context: Current FAA pavement condition assessment relies on visual Pavement Condition Index (PCI) surveys per ASTM D5340 as recommended by AC 150/5320-17A and AC 150/5380-6C, falling weight deflectometer (FWD)/heavy weight deflectometer (HWD) structural evaluation per AC 150/5370-11B, and continuous friction measurement equipment (CFME) per AC 150/5200-30D Appendix D/E. Automated systems may need to produce data compatible with the ASTM D5340 PCI methodology to be accepted for Airport Pavement Management Systems (APMS). Survey vehicles are subject to standard 14 CFR §139.329 movement-area access procedures.

Key Evidence from Literature:

- A low-cost in-vehicle system (video camera, laser line generators, dual-band GPS with post-processed kinematic [PPK] positioning) was compared against on-foot visual inspection on the 3,000- by 45-m runway of Amílcar Cabral International Airport. PCI values from the two methods yielded R^2 = 0.90 with a standard error of 3.64 PCI points; section-level PCI differences were ≤2 points. The in-vehicle method inspected the full 270 sampling units in 3 days versus 3 weeks for 43 sampling units on foot. Image spatial resolution was <0.003 m/pixel at center; positioning error was <0.05 m via PPK-GNSS. The system could not reliably identify low-severity depressions and showed a bias toward classifying distresses at higher severity levels (Santos et al., 2020; Lima et al., 2019).

- A multifunctional vehicle with laser scanning cameras captured 4,096 points per 4-m-wide section on a 2,200-m runway, parallel taxiway, and five exit taxiways, computing PCI, International Roughness Index (IRI), rutting (RUT), macrotexture (ETD), and straightedge index from a single survey campaign. HWD-derived aircraft classification number/pavement classification number (ACN/PCN), IRI, RUT, ETD, and PCI data were merged to prioritize structural and functional rehabilitation, with works phased to limit total airport closure to 15 consecutive days. IRI thresholds and RUT thresholds were applied per International Civil Aviation Organisation (ICAO) and ASTM standards (Di Mascio & Moretti, 2019).
- A profiler-class LiDAR mobile mapping system deployed on runways resolved tining on the order of 3–5 mm and detected shallow features on the order of 1–2 cm, with automated depth/area/volume estimation for surface anomalies and debris (Ravi et al., 2020).
- RGB-D sensor arrays achieved a design scanning speed of ~97 km/h with lane-width coverage but reported better imaging quality below ~48 km/h without extensive strobing; approximate procurement cost of ~$150,000 per commercial camera/laser vehicle was cited, with lower-cost RGB-D alternatives proposed (Chen et al., 2016).
- Air-launched GPR was collected at an average of 37 mph on roadways, reducing the need for lane closures and on-foot exposure (Khamzin et al., 2017).
- On a runway, air-coupled GPR (2 GHz) measured construction layer thicknesses validated by coring, and a road surface profiler classified runway roughness as low quality but acceptable for continued use in that case (Elseicy et al., 2022).

Stakeholder Perspectives: One participant stated, “vehicle monitor right now we’re still using it as the ground truth values right now just for comparison with the drone data or the smartphone data.” Another noted that these systems “improve safety 100 percent because you don’t have people going out and doing physical surveys unless absolutely necessary.” One participant also stated, “I would say that vehicle mounted systems are high in feasibility,” while expressing more cautious feasibility assessments for competing methods such as drones and AI-based approaches.

Infrared Thermal Profiling (IRTP)

IRTP uses infrared thermography integrated with the paving train to continuously measure and map asphalt mat surface temperatures during placement (Sebesta et al., 2012a). A PMTP, an infrared sensor bar with GPS referencing, produces georeferenced, color-coded temperature profiles in real time on 1- by 1-ft grids evaluated over 150-ft segments (Von Quintus et al., 2023). Thermal-differential groupings classify temperature differentials as low (<25 °F), medium (25–50 °F), or high (>50 °F) severity to screen for zones at risk of nonuniform density (Sebesta et al., 2012a). AASHTO PP 80-20 or AASHTO R 110-22 is used to compute and classify temperature differentials, with many specifications excluding

paver stops from calculations (Chang et al., 2020; Sebesta et al., 2024). FHWA places PMTP between field pilot/first application and specification-development stages for QA deployment (Von Quintus et al., 2023).

Regulatory Context: Temperature monitoring is traditional (spot checks at the plant and at the job site per §401-5.3e), not continuous profiling. AC 150/5370-11B references infrared (IR) thermography for delamination detection. The Airport Asphalt Pavement Technology Program (AAPTP) Asphalt Paving Handbook references the use of IRTP and identifies a 25 °F thermal-segregation differential.

Key Evidence from Literature:

- IR imaging and GPR provided essentially 100 percent coverage of new HMA surfaces in demonstrations; IR color-coded maps highlighted colder placement-temperature zones that became higher AV locations after compaction (Sebesta et al., 2012b).
- Measuring temperature segregation just before breakdown rolling yielded stronger correlations with AV and laboratory properties than measurements immediately behind the paver (Kim et al., 2017).
- A documented case integrating IC and PMTP showed large reductions in "Severe" segregation when a material transfer vehicle was introduced between paving days (Chang et al., 2018).
- A program synthesis reported that a higher coefficient of variation (COV) of mat temperature was associated with a higher COV of mat density, and that using the thermal profiler to guide corrective actions reduced AV variability (Sebesta et al., 2024).
- One field study defined four segregation levels: no segregation ≤10 °C; low-level 11–16 °C; medium-level 17–21 °C; high-level ≥21 °C (Dhakal & Elseifi, 2015). A WMA study reported corresponding thresholds of <3 °C, 3–8 °C, 8–18 °C, and >18 °C (Li et al., 2017).

Stakeholder Perspectives: Focus group participants viewed thermal profiling positively, though they noted a clear gap between highway and airport adoption. One contractor described running thermal profilers regularly on DOT projects but less so at airports, explaining that "runway paving, airport paving's a little different than mainline highway," with weather sensitivity and late-season paving cited as conditions where the technology proves particularly useful.

Intelligent Compaction (IC)

IC equips vibratory rollers with accelerometers, GNSS/GPS positioning, infrared temperature sensors, and an onboard computer to produce color-coded, real-time maps of pass counts, mat surface temperatures, and a roller-derived stiffness index—the intelligent compaction measurement value (ICMV), across the entirety of the compacted

area (Xu et al., 2012). ICMV is a generic umbrella for vendor-specific indices (CMV, CCV, HMV, Evib) computed from drum acceleration responses (Sivagnanasuntharam et al., 2021). ICMV reflects the multilayer system response within the roller's depth of influence rather than a single HMA lift, and is influenced by mixture temperature, underlying layer stiffness, roller amplitude/frequency, and travel speed (Xu et al., 2012; Sivagnanasuntharam et al., 2021).

Regulatory Context: P-401 requires compaction by rolling with steel-wheel, pneumatic-tire, and vibratory rollers, with the sequence and type at the Contractor's discretion (§401-4.13). Acceptance density is determined from cores via the percent within limits (PWL) method (C-110, §401-5.5). A nuclear density gauge (ASTM D2950) may be used for Contractor QC monitoring (§401-5.3f). If IC is used solely as supplementary process control alongside existing core-based acceptance, an MOS may not be triggered. However, if IC data modify or replace QC/acceptance criteria, an MOS may be required under both "new construction methods" and "quality control or acceptance criteria." The AAPTP Asphalt Paving Handbook, section 8.3.7, documents IC technology including ICMV levels, roller GPS/accelerometer/IR instrumentation, and real-time compaction mapping. Engineering Brief 56 defines the PWL acceptance framework (acceptable quality level=90, rejectable quality level=55, sublot sampling n=4); IC data are supplementary within that framework.

Key Evidence from Literature:

- Systematic analysis of eight HMA projects used semivariograms and compaction curves to determine optimum passes and target ICMVs; uniformity increased from subbase to HMA base and surface (Xu et al., 2012).
- Cross-study summaries show ICMVs correlate well with FWD and portable seismic pavement analyzer stiffness measures but poorly/inconsistently with density via nuclear/non-nuclear gauges and cores (Sivagnanasuntharam et al., 2021).
- In a Vermont demonstration, establishing a target ICMV at fixed vibration settings and targeted re-rolling increased average nuclear gauge density at five locations from 125.5 lb/ft^3 to 128.4 lb/ft^3 (Foroutan & Ghazanfari, 2019).
- An economic analysis estimated a 37-percent construction cost reduction per 1.6 lane-km for thick overlays (assuming 30-percent compaction-time reduction), 54.4-percent construction cycle cost reduction for new construction at 4.8 km/h, and annualized savings of $15,385 per lane-mile from improved uniformity (Savan et al., 2015).
- Roller–asphalt interaction modeling shows sensitivity to temperature, base stiffness, layer thickness, and loading frequency, requiring fixed parameters during correlation (Imran et al., 2017).
- FHWA characterizes IC for asphalt mats as at the "field demonstration" stage with evolving verification requirements for acceptance (Von Quintus et al., 2023).

AASHTO PP 81-18 and Veta provide provisional geospatial QA data workflows (Chang et al., 2022).

Stakeholder Perspectives: Participants described IC as routine in current highway practice. One contractor noted, "Intelligent compaction is kind of being used on pretty much everything." Another stated, "Intelligent compaction, 3D, and infrared [profiling], they're all tools that help build a better product, so the contractors are starting to naturally adopt them just to perform better," and reported using IC on "a good majority of airports." A third panelist offered a counterpoint: "I'm not really sure if it is necessarily helping them outside of if you had a very good QC program, and there's people that produce exactly the same quality if their crews and their QC is on point."

Airfield Base and Subbase Technology

Pavement base and subbase are engineered foundation layers beneath the asphalt surface that distribute aircraft loads, provide a stable construction platform, control grade and elevation, deliver drainage, and protect against frost damage (Uzarowski & Rizvi, 2014). In typical flexible airfield pavements, an HMA surface course overlies a crushed aggregate base and granular subbase, with most section thickness in the base/subbase to reduce stresses to levels the subgrade can sustain (Brown et al., 2008). Stabilized base variants include cement-treated base (CTB, P-304), lean concrete base (P-306), soil-cement (P-301), and cement-treated permeable base (P-307, new in 10H) (AC 150/5370-10H; AC 150/5320-6G). Recycled concrete aggregate is specified under Item P-219 for base/subbase reuse (AC 150/5320-6G). Paver-placed granular base uses an asphalt paver as a mechanical spreader to place granular base in a controlled, uniform layer, improving uniformity and reducing segregation relative to grader placement (Brown et al., 2008).

Regulatory Context: AC 150/5370-10H defines complete specifications for seven base/subbase items: P-154 (Subbase), P-208 (Aggregate Base), P-209 (Crushed Aggregate Base), P-219 (Recycled Concrete Aggregate), P-304 (Cement-Treated Base), P-306 (Lean Concrete Base), and P-307 (Cement Treated Permeable Base). AC 150/5320-6G §3.13.3.2 states: "If aircraft in the design traffic mix have gross loads of 100,000 pounds or more then use of a stabilized base is required." Engineering Brief 66 (Feb 2004) creates Item P-215 for rubblized Portland cement concrete (PCC) base on a case-by-case basis, requiring MOS. AC 150/5370-11B Table 21 (p. 75) assigns fixed FAARFIELD modulus values. These caps mean superior base performance beyond the assigned range may not receive any additional FAARFIELD design credit.

Key Evidence from Literature:

- Laboratory screening/field trials for a recycled cement-bound taxiway base identified 4 percent cement and 8 percent water as optimal. An asphalt paver placed the layer at 4.0 m/min; a 15-ton single-drum roller achieved optimal

compaction in six passes. Dynamic modulus reached ~85 percent of maximum at 24 h. The 60,000 m^2 taxiway opened to air traffic 7 days after surface placement with average PCN 120 by FWD. Cradle-to-gate emissions: 51.6 kg CO_2e/m^2 (recycled) versus 78.4 kg CO_2e/m^2 (standard), an ~35-percent reduction attributed to shorter hauls and on-airport recycled aggregate sourcing (Giustozzi et al., 2012).

- Unbound recycled concrete aggregate compacted to 98 percent modified Proctor showed higher resilient modulus and smaller permanent strain than typical natural granular subbases at lower moisture ratios; stiffness decreased and permanent strains increased at higher moisture ratios (Arulrajah et al., 2012).
- An airport rebuild used a track asphalt paver with Trimble PCS900/SPS930 3D control to place ~6,600 yd^3 P-209 base from borrow to design grade, meeting FAA grade tolerance of ±0.5 inches and 16-ft straightedge smoothness with no remedial work. Paving was completed in 17 days versus ≥25 days estimated without 3D technology (For Construction Pros, 2013).
- **Stakeholder Perspectives:** A participant noted that stabilized bases are already mandated for heavy aircraft. Regional availability of quality aggregate affects adoption of stabilized alternatives: “In Mississippi, where we don’t have good aggregates, they’re used a lot. In Colorado, where there’s plenty of good aggregate rock… they don’t use them as much because it’s real cheap for them to buy a lot of rock.” The participant characterized the technology area as “low-hanging fruit” and “underused.” A key barrier cited was the absence of material characterization inputs in ME design software: “right now, there’s no way in that guidance to even use a recycled concrete aggregate because it doesn’t have that option. It doesn’t have the option for several of these. So, you would have to be creative in how to try to use that with the current methodology.”

High-Density Longitudinal Joints

High-density longitudinal joint construction encompasses materials, layout, and compaction practices that raise in-place density and lower permeability at the seam where adjacent asphalt lanes meet (Williams, 2011). Joint areas typically exhibit higher AV and lower density than the mat interior because one lane edge is unconfined and cools faster (Akentuna & Salari, 2023). Constructible methods include notched wedge geometry, IR heating of the cold edge, edge restraint devices, joint stabilizers/adhesives, and cutting wheels to re-establish a vertical face (Williams, 2011). Statistically significant improvements in density and permeability were reported for the joint heater, the notched wedge, and a joint stabilizer in comparative roadway field evaluations (Williams, 2011).

Regulatory Context: AC 150/5370-10H (P-401, §401-4.12) requires “the joint in the surface top course shall be at the centerline of crowned pavements.” According to §401-4.14, joints exposed for more than 4 hr or cooled below 175 °F (80 °C) must be cut back (max 3 inches) to a clean vertical face and tack-coated per P-603 before new material is placed. P-401

does not prescribe specific joint density techniques (notched wedge, joint heaters, echelon paving, or other advanced methods), though P-401 Engineer's Notes mention hot joint construction to provide additional joint density QC. Joint density acceptance is evaluated via cores using the PWL method (P-401 Table 5: Joint density L=90.5 percent; C-110 provides the PWL framework). Engineering Brief 56 recognizes joints as "historically the poorest performing portion of pavements."

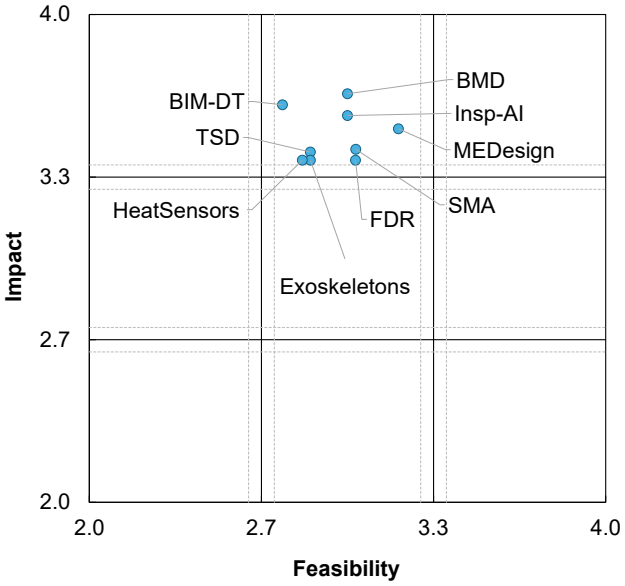
Key Evidence from Literature:

- In Tennessee roadway comparisons, IR joint heating yielded the lowest joint AV and permeability and the highest indirect tensile (IDT) strength among evaluated techniques; X-ray computed tomography confirmed improved compaction extending into the cold-side mat (Huang et al., 2010).
- Full-scale roadway trials of microwave joint heating reported the highest compaction degree for wearing course joints and best-class semi-circular bending (SCB) ultimate stress in mid-temperature testing (Maliszewski et al., 2021).
- At Yakutat Airport, echelon paving and IR joint heaters eliminated approximately 600 m^3 (21,000 ft^3) of wasted asphalt and helped meet FAA density requirements on runway and taxiway paving (Chitnis et al., 2024).
- IR joint heater cost was approximately $0.12 per linear ft; rubberized joint adhesive approximately $0.25/lf (Williams, 2011). Joint stabilizer application was reported at $0.36–$0.57/lf (Chitnis et al., 2024).
- Infrared heating improved rutting resistance but reduced fracture resistance due to binder stiffening in laboratory comparisons, indicating a performance trade-off requiring precise temperature control (Chitnis et al., 2024).

Stakeholder Perspectives: Participants endorsed longitudinal joint quality as critical for airports, with one panelist stating: "Longitudinal joints are very important at airports, and there's always ways people are trying to maximize those. We've done the notch wedge… a ton of people asking when the spec for being able to do that and not have to cut is going to take place. We've used VRAM, not by spec, just to help with joint density on airport projects." Another panelist agreed that "anything you can do to improve the centerline joint works well" when done correctly. However, perspectives on specific techniques diverged. One practitioner reported that Illinois DOT "tried the notched wedge, we got rid of it. We tried the heater, got rid of it, tried stabilizers, got rid of it," favoring VRAM and echelon paving instead, adding that "if you've got a good paving crew, you don't need anything." A researcher noted that restrained edge with high-tech coat "is working great compared to the others" but cautioned that infrared preheating "affects the binder properties… in the long run, it affects the cracking properties." Panelists called notch wedge and VRAM "pretty low cost for the impact you get."

Cell 2: High Impact/ Medium Feasibility Technologies

Figure 12 presents the Impact–Feasibility scatter plot for the nine technologies classified in Cell 2. These technologies have demonstrated performance benefits with more implementation barriers than those in Cell 1. Several have well-established roadway precedents that provide a foundation for structured adoption. Additional groundwork such as airport-scale validation or specification updates may be needed. Dimension scores for each technology are presented in Table 14 and Table 15.



Source: AAPTP

Figure 12. Impact vs. Feasibility Matrix for Technologies Classified as High Impact/Medium Feasibility

Table 14. Impact Dimension Scores for High Impact/Medium Feasibility Technologies

Technology Name	Performance	ROI	Safety	Efficiency	Sustainability	Impact Score
Balanced Mixture Design (BMD)	5	3	3	3	3	3.7
Stone Mastic Asphalt (SMA)	4	3	3	3	4	3.4
Mechanistic-Empirical (M-E) Pavement Design	4	4	3	3	3	3.5
Building Information Modelling and Pavement Digital Twins	4	4	3	4	3	3.6
Computer Vision/AI Methods for Remote Sensing	4	3	4	4	2	3.6
Traffic-Speed Deflectometer (TSD)	4	3	3	4	3	3.4
Full-Depth Reclamation (FDR)	3	4	3	4	4	3.4

Technology Name	Performance	ROI	Safety	Efficiency	Sustainability	Impact Score
Wearable Back-Support Exoskeletons for Construction Workers	4	2	4	3	3	3.4
Wearable Heat-Stress Monitoring for Construction Workers	4	2	4	3	3	3.4

Table 15. Feasibility Dimension Scores for High Impact/Medium Feasibility Technologies

Technology Name	Readiness Level	Technical Issues	Upfront Cost	Regulatory Hurdles	Stakeholder Acceptance	Feasibility Score
Balanced Mixture Design (BMD)	3	3	3	3	3	3.0
Stone Mastic Asphalt (SMA)	4	3	2	3	3	3.0
Mechanistic-Empirical (M-E) Pavement Design	4	2	3	3	4	3.2
Building Information Modelling and Pavement Digital Twins	3	2	2	3	4	2.7
Computer Vision/AI Methods for Remote Sensing	3	3	3	3	3	3.0
Traffic-Speed Deflectometer (TSD)	4	2	2	3	3	2.9
Full-Depth Reclamation (FDR)	4	3	2	3	3	3.0
Wearable Back-Support Exoskeletons for Construction Workers	4	2	2	3	3	2.9
Wearable Heat-Stress Monitoring for Construction Workers	3	2	3	3	3	2.8

Balanced Mixture Design (BMD)

BMD is an asphalt mixture design approach that uses performance tests on appropriately conditioned laboratory specimens to ensure that a selected mixture simultaneously meets rutting and cracking targets while considering mixture aging, traffic, climate, and location within the pavement structure (Yin et al., 2020). There are three general BMD approaches: 1) volumetric design with performance verification, 2) performance-modified volumetric design, and 3) performance design. Rutting and moisture damage are typically assessed using wheel-tracking devices such as the Hamburg Wheel-Tracking Test (HWTT) and Asphalt Pavement Analyzer (APA), while cracking resistance is characterized at intermediate temperatures via the Indirect Tensile Cracking Test (IDT-CT) or Illinois Flexibility Index Test (I-FIT) and at low temperatures via the Disk-shaped Compact Tension (DCT) or Semi-Circular Bend (SCB). FHWA has also developed mechanistic approaches using the Asphalt Mixture Performance Tester (AMPT), including cyclic fatigue and the stress-sweep rutting tests, together with Flex Suite tools (FlexMAT, FlexPAVE, PASSFlex) to translate mixture index values into structural distress predictions and tie them to performance-related specifications.

Regulatory Context: P-401 in AC 150/5370-10H mandates Marshall or Gyratory (Superpave) mix design with specific stability, flow, voids in mineral aggregate (VMA), and AV targets (3.5 percent). The APA may be used in lieu of Marshall stability/flow testing, creating the closest existing link to performance testing. Because BMD constitutes a new construction method/material specification, approval may be required from the FAA Director of Airport Safety and Standards (FAA Order 5300.1G §10.a). The applicant must certify that the proposed mix "will perform for its intended design life, based on historical data" (Order 5300.1G §11.a). FAARFIELD assigns a fixed modulus of 200,000 psi (surface) or 400,000 psi (stabilized base) to P-401 HMA regardless of actual performance; a BMD mix cannot receive structural design credit for superior properties.

Key Evidence from Literature:

- NCAT Test Track sections designed using BMD accumulated approximately 6.4 million equivalent single axle loads (ESALs) with 0–0.8-percent lane-area cracking and 0.2–5.5 mm rut depth under accelerated conditions (Yin et al., 2020).
- Idaho BMD thresholds for dense-graded mixes included IDT-CT-Index classes (good if >73.7, moderate 26.4–73.7, poor if <26.4), and HWTT maximum rut depth of 10 mm at 15,000 passes or 12.5 mm at 20,000 passes (Kassem et al., 2023).
- A Missouri I-155 demonstration used BMD acceptance criteria of CT-Index ≥45 for dense-graded mixes, CT-Index ≥160 for SMA, and HWTT maximum rut depth of 12.5 mm at 15,000 passes (Buttlar et al., 2024).
- For one 70-percent RAP series, raising the binder by 0.5 percent yielded CT-Index 72 at $33/ton versus CT-Index 23 at ~$29/ton for the control, representing a 7-percent

cost increase; cost reductions up to 14.8 percent were reported at 25-percent RAP with improved CT-Index using a tall-oil rejuvenator (Kassem et al., 2023).

- Oregon's BMD development documented a case where the balanced target binder content was below the volumetric target, indicating potential mixture-level materials cost reduction (Coleri et al., 2020).
- Laboratory recreation of mixtures within allowable binder/gradation tolerances showed that design-balanced mixtures sometimes failed cracking/durability thresholds under simulated production, recommending performance-based QC/QA to detect drift (Bowers et al., 2023).
- Loose-mix aging procedures significantly influence cracking indices; validation work emphasizes aligning laboratory aging to field targets (Yin et al., 2020).

Stakeholder Perspectives: Participants broadly rated BMD as highly impactful. One panelist stated: "I think BMD has a lot to offer to improve performance in any asphalt mix, whether it's an airport or not." Another noted: "I think that you're going to see the impacts from an innovation standpoint. So, I think that's all pretty high," while cautioning that extensive benchmarking is needed first: "we have to benchmark where we are to know where we need to go." A third panelist observed that international operators already use BMD approaches on runways with high RAP and rejuvenators. However, panelists consistently flagged regionality of criteria as a challenge: "BMD tends to be very specific to a region, to an area, as far as like establishing those criteria… that might be a challenge when you're trying to develop a nationwide spec."

Stone Mastic Asphalt (SMA)

Stone mastic asphalt (SMA), also called stone matrix asphalt in the United States, is a gap-graded HMA engineered to develop a coarse aggregate skeleton with "stone-on-stone" contact that carries load (Alderson, 2013). A binder-rich mastic of asphalt binder, mineral filler, and stabilizing fibers (or polymers) fills the remaining voids to provide durability (Alderson, 2013). SMA designers verify the skeleton by volumetric checks such as voids in the coarse aggregate (VCA) and VMA, using procedures including dry-rodding to confirm that VCAmix (VCA of the compacted mixture) is less than or equal to VCADRC (VCA of the coarse fraction in the dry-rodded condition), indicating stone-on-stone interlock (Brown et al., 1997). The mastic is characterized by filler–binder ratio, Rigden voids-based fixed/free binder fractions, and rheological properties (Alderson, 2013). Coarser gradations that reduce wheel-tracking depths can become permeable, requiring careful control of gradation and mastic stiffness (Alderson, 2013). SMA requires specialized production controls (e.g., fiber feeders, temperature management) to control binder drain-down (Liu et al., 2019).

Regulatory Context: SMA is not a defined item in AC 150/5370-10H. P-401 and P-403 are exclusively dense-graded. SMA is not referenced in AC 150/5320-6G, and FAARFIELD

contains no SMA layer type. As a mix type absent from current specifications, SMA may require an MOS per FAA Order 5300.1G §11.a.

Key Evidence from Literature:

- At the NCAT Test Track, a 12.5-mm SMA with granite aggregate (containing 28 percent flat and elongated particles) recorded less than 5 mm total rutting after more than 10 million ESALs with no cracking observed over a 2-year loading cycle (West et al., 2012; West et al., 2018).
- NCAT Test Track paired comparisons between SMA and Superpave dense-graded sections using the same PG 76-22 SBS-modified binder showed SMA had, on average, 0.24 mm higher macrotexture depth and higher skid number SN40R than the Superpave section (Yin & West, 2018).
- A national survey across 16 agencies found 5-year weighted average bid prices for SMA exceeding polymer-modified Superpave dense-graded mixtures by $6–$31/ton. Specifically, the premium averaged approximately $17/ton where RAP/recycled asphalt shingles (RAS) were allowed in SMA versus approximately $21/ton where they were not (Yin & West, 2018).
- At least 18 State DOTs routinely use SMA on high-traffic routes, based on an FHWA/NCAT survey and market analysis data (Yin & West, 2018).
- The U.S. Department of Defense (DOD) has developed a formal SMA specification for military airfields (UFGS-SMA 32 13 17) (Jamieson & White, 2020).
- A Johannesburg Airport runway touchdown zone trial showed that the SMA GripTester friction value increased from 0.64 initially to 0.71 after 5 months of aircraft traffic conditioning; macrotexture decreased from 1.33 mm initially to 0.9 mm after 5 months. SMA surface properties were reported as better than all compared test mixes, and the conventional asphalt pavement reference section required grooving to meet texture requirements (Blazejowski, 2011).
- SMA can meet the ICAO minimum runway surface texture recommendation of 1 mm without post-construction grooving when properly designed and delivered (Jamieson & White, 2020).
- Early Sydney Airport taxiway SMA trial experienced surface finish and raveling issues attributed to construction and plant difficulties (Jamieson & White, 2020).
- Edwards Air Force Base SMA overlay experienced wheel-path bleeding (fat spotting) attributed to excessive fines passing the 4.75 mm sieve, very low in-place AV (~1 percent), and finer-than-specified gradation and higher asphalt content found in pavement cores, but no measurable rutting (Brown et al., 2018).

Stakeholder Perspectives: Participants recognized SMA as a proven highway mix with direct airport relevance. One panelist called SMA “a great mix” but cautioned: “if you’re in a state where it’s not typically used, and a contractor is not used to using it, it can be a disaster,” citing a Boston airport project where inexperienced contractors “did not go well at

all." Virginia already uses SMA alongside HiMA and EME2 base mixes, with a participant stating they "can perform extremely well, or they can perform extremely poorly if something goes wrong," emphasizing that quality control "doesn't end at the plant." A contractor flagged aggregate sourcing as a barrier: "our closest source for SMA aggregates is four hours from our closest plant, so costs go up exponentially."

Mechanistic-Empirical (M-E) Pavement Design

M-E pavement design involves predicting rutting, cracking, and long-term roughness by first computing mechanistic pavement responses (stresses, strains, and deflections under traffic and climate) and then applying empirically calibrated transfer functions to convert those responses into distress and IRI predictions at a specified reliability (AASHTO, 2008). This approach allows designers to iterate layer thicknesses and materials until performance targets are met rather than prescribing structures directly. M-E methods require inputs describing traffic spectra, wheel loads, climate histories, structural configuration, and material properties. Mechanistic response calculation can range from traditional layered elastic analysis to full 3D viscoelastic moving-load simulation. Climate inputs, processed through the Enhanced Integrated Climatic Model, produce hourly temperature and moisture profiles that drive time-varying material behavior. Distresses are then predicted using empirical cracking, rutting, and roughness models or through mechanistic fatigue and permanent-strain damage models.

Regulatory Context: AC 150/5320-6G §3.2 requires that "the structural design of pavements on federally funded projects must be completed using FAARFIELD," which implements layered elastic analysis (flexible) and 3D finite element analysis (FEA) (rigid). FAARFIELD assigns fixed modulus values to P-401 HMA layers per Table 3-2: 200,000 psi (surface) and 400,000 psi (stabilized base). The variable stabilized flexible base option permits 150,000–400,000 psi (§3.13.3.3). These fixed values mean FAARFIELD provides no structural design credit for material property differences between standard and advanced asphalt mixtures. If enhanced M-E analysis produces non-standard pavement sections, an MOS may apply per FAA Order 5300.1G. FAARFIELD enhancements require FAA internal approval and software development cycles calibrated against full-scale test data from the National Airport Pavement Test Facility (NAPTF).

Key Evidence from Literature:

- A national survey of implementing agencies documented one quantified cost savings case of approximately $10 million per year attributed to Mechanistic-Empirical Pavement Design Guide (MEPDG)-based design decisions compared with designs using the AASHTO 1993 Guide, based on design comparisons across project portfolios; this is the only monetized ROI figure in the reviewed corpus (Pierce & McGovern, 2014).

- Numerous U.S. State DOTs have undertaken formal MEPDG/AASHTOWare Pavement ME Design (PMED) implementation programs, including Missouri, Ohio, Connecticut, South Dakota, Virginia, Georgia, New Hampshire, Iowa, Tennessee, and Indiana (Titus-Glover et al., 2020; Titus-Glover & Mallela, 2009; Yut & Mahoney, 2014; Yut et al., 2017; Cetin et al., 2015; Apeagyei & Diefenderfer, 2011; Kim et al., 2019; Daniel et al., 2013; Gopisetti et al., 2021; Onyango et al., 2019; Jiang et al., 2008; Pierce & McGovern, 2014; Robbins et al., 2014).
- Virginia evaluated PMED inputs for SMA and polymer-modified dense-graded mixtures, finding that dynamic modulus (|E*|) alone may not fully explain measured rutting differences between mix types; rutting k-coefficients in PMED may require mixture-appropriate values (Nair & Saha, 2021; Apeagyei & Diefenderfer, 2011).
- FlexPAVE predicted rankings and damage values, including differentiation of top-down versus bottom-up cracking, showed agreement with field measurements across the FHWA Accelerated Load Facility, the NCAT Test Track, the Korea Expressway Corporation test road, and Manitoba Infrastructure and Transportation RAP and WMA roadway sections (Wang et al., 2018; Kim et al., 2022; Wang, 2019).
- Both MEPDG/PMED and FlexPAVE require project- or region-specific calibration before reliable distress magnitude predictions can be made (Tran et al., 2024; Williams & Shaidur, 2013; Tarefder & Rodriguez-Ruiz, 2013; Wang et al., 2018; Wang, 2019).

Stakeholder Perspectives: Participants viewed M-E pavement design as high-impact for airfields but with moderate feasibility due to calibration data gaps. One panelist stated: “this would have a very high impact on how we’ve done pavement design, roadways, airfields, historically using, you know, mainly empirical techniques.” However, the same panelist cautioned that “for airfields, that’s where I think some data might be lacking. And there probably needs to be more time for collecting the data to calibrate the transfer functions.” Another panelist endorsed the direction: “certainly anything that can build upon that and advance that approach would be tremendously impactful,” while noting that in practice, “when you have an airfield and you have a standard pavement design for that airfield, we tend to stick with that.” Another participant expressed a preference for “a higher emphasis on the mechanistic part than the empirical part. A bigger M and a smaller E,” and observed that staffing and expertise constraints may limit adoption without automation.

Building Information Modelling and Pavement Digital Twins

A pavement digital twin is a virtual representation of a physical pavement that remains connected to measured and historical data so stakeholders can analyze, predict, and act across design, construction, operations, and maintenance phases (Wang et al., 2024). BIM serves as the information backbone; FEA provides the physics engine for structural decision support (Wang et al., 2024; Pacios Alvarez et al., 2021). The literature describes a combined stack of BIM, the Internet of Things (IoT), and Geographic Information Systems

(GIS), where BIM provides the authoritative model, IoT provides sensor data, and GIS contributes spatial context (Wang et al., 2024; Chang et al., 2024). Technical approaches include semi-analytical finite element (FE) formulations computing 3D viscoelastic responses under moving loads (Shen & Wang, 2024), BIM-to-FEA automated workflows (Huang et al., 2025), Infrastructure-BIM (I-BIM) "smart objects" computing condition indices from survey attributes (Bosurgi et al., 2022), and federated data storage using Exdir/HDF5 with authenticated streaming via IOTA/MAM (Pacios Alvarez et al., 2021). Airport-oriented examples in the literature include BIM plus WebGL visualization of airport pavement quality and a SysML-based airport digital twin platform (Chang et al., 2024).

Regulatory Context: BIM and digital twins are not referenced in any FAA AC, order, or regulation for airport pavement applications. As project management and data tools, not physical design or construction modifications, they may not be subject to the MOS process per FAA Order 5300.1G. AC 150/5370-10H C-100 §100-9 states that "when QC inspection and test results are recorded and transmitted electronically, the results must be archived," acknowledging electronic records within an otherwise paper-oriented documentation framework. AC 150/5300-13B §1.8 establishes airport data management requirements including GIS and geospatial survey standards (referencing AC 150/5300-18).

Key Evidence from Literature:

- A semi-analytical finite element method (SAFEM) digital twin for asphalt pavements, developed with partial AAPTP support, uses Fourier-indexed 2D subproblems and CPU/GPU parallelization to compute temperature-dependent viscoelastic responses under moving loads with realistic three-directional tire contact stresses. Field validation against an instrumented Long-Term Pavement Performance (LTPP) Program section showed relative differences at deeper sensors lower than near-surface; near-surface predictions were more sensitive to unmeasured tire contact stress distributions (Shen & Wang, 2024).
- A BIM-finite element method (FEM) workflow integrating Revit/Civil 3D with ABAQUS reported rutting deformation of 19.51 mm (3.12-percent error versus theoretical), temperature field error within 4.2 percent of field tests, and a modeling efficiency improvement of approximately 68.66 percent with end-to-end simulation under 1 hr (Huang et al., 2025).
- BIM automation was used to generate large sets of asphalt pavement FEM simulations for rutting and fatigue, serving as inputs to a CNN-TCN-Attention deep learning surrogate for multi-objective structural design optimization (Huang et al., 2025).
- A comprehensive transportation DT survey reports that predictive maintenance supported by digital twins "significantly reduces emergency repairs and service interruptions, thereby reducing costs and enhancing safety and stability" (Wu et al., 2025).

- The same survey identifies "interoperability, data quality/accuracy needs, and privacy/security" as persistent challenges, and notes that full-scale predictive maintenance systems "require substantial investments in sensors, processing infrastructure, and human resources" (Wu et al., 2025).
- An airport-focused BIM Execution Plan aligned with the APMS defined "Coordination 3D" to reduce interference and "Planification 4D" linking schedules bi-directionally with planning systems during airfield works, with federated storage of encrypted BIM models, FEA models, and sensor data in an HDF5-compatible Exdir structure (Pacios Alvarez et al., 2021).

Stakeholder Perspectives: Participants described BIM/digital twins as highly impactful for pavement operations and asset management. A Federal agency participant noted that FHWA "continue[s] to have an emphasis in our advancing efforts and still have grant programs around BIM for infrastructure moving towards digital twins," describing the 5-year Advanced Digital Construction Management Systems (ADCMS) grant program focused on "lifecycle data management so that all that information from planning to design, the materials information, the testing information, the certification information, all gets preserved and appended to the model." An airport operator participant stated BIM/digital twins "would be something that would be extremely useful to us should we implement that" from an operations and maintenance perspective, while acknowledging that airport BIM adoption "has been focused on the building side. We haven't really done anything at all on the civil side from a BIM perspective." Another panelist cautioned that "generating things for practical day-to-day use may be a little bit an issue more on terms of a short term," rating the technology as high impact with moderate feasibility.

Computer Vision/AI Methods for Remote Sensing

Computer vision applies algorithms to 2D images and 3D surface data to detect, segment, and quantify pavement distresses and texture, automating activities that have traditionally depended on manual visual surveys (Sun et al., 2022). Deep learning, specifically Convolutional Neural Networks (CNNs), is a widely used approach for pixel-level crack segmentation; it learns hierarchical features directly from imagery and reduces sensitivity to background clutter compared with traditional thresholding or morphology pipelines (Sun et al., 2022). Technical variants include DMA-Net, an encoder–decoder architecture building on DeepLabv3+ with multi-scale attention, demonstrated on runway/taxiway imagery from the Fitchburg Municipal Airport (FMA) dataset (Sun et al., 2022). Another variant is transformer-based segmentation using a Swin-Transformer encoder (Guo et al., 2023); the Laser Crack Measurement System (LCMS), a full-lane 3D transverse profiling system producing macrotexture indices such as mean profile depth and digital mean texture depth (Laurent et al., 2017); and RGB-D cameras pairing color with depth to create point clouds for distress geometry estimation (Lin et al., 2023).

Regulatory Context: AC 150/5320-17A Appendices A and B contain the PASER Manuals, which describe types and causes of distress and provide a rating system to visually rate pavement condition on a scale ranging from excellent to failed. ASTM D5340 PCI is the standard quantitative survey method. AC 150/5220-24 Table 1 (p. 5) recognizes "Electro-Optical" systems that use video technology and image processing data as the primary means to detect FOD on runways and Air Operations Area (AOA) surfaces, establishing an FAA precedent for image-processing technology on airfield surfaces, though limited to FOD detection.

Key Evidence from Literature:

- YOLO v3 and Faster R-CNN matched Iowa DOT manual QA/QC labels at 97.56 percent and 96.9-percent accuracy on 3D asphalt and concrete images, with inference at 0.01 s/frame and 0.09 s/frame, respectively (Ghosh & Smadi, 2021).
- An LCMS full-lane 3D texture workflow on five Georgia DOT highway routes achieved raveling severity classification accuracy of 90.8 percent, with precision and recall exceeding 85 percent across all four severity levels (L0–L3), using a combined macrotexture-plus-deep-feature model (Hsieh & Tsai, 2021).
- A digital image processing technique applied to airport runway photographs correlated 2D image-derived macrotexture with mean texture depth from the sand patch method (ASTM E965-15) at $R^2 = 0.754$ and $R^2 = 0.761$ across 132 images at 33 stations on two runways (Ghaderi & Abedini, 2021).
- PaveSAM, a fine-tuned "Segment Anything" model, achieved zero-shot-like pavement distress segmentation using bounding-box prompts after fine-tuning on only 180 labeled images, reducing pixel-level annotation requirements for new pavement contexts (Owora et al., 2024).
- DMA-Net (enhanced DeepLabv3+ with multi-scale attention) trained and tested on the Fitchburg Municipal Airport (FMA) runway dataset showed dice/mIoU improving from 67.9/53.6 percent (baseline) to 69.9/55.9 percent with dilated ResNet-101, dice loss, and multi-scale attention (Sun et al., 2022).
- A hybrid-window attentive vision transformer (CrackFormer) achieved precision = 0.9376, recall = 0.9352, and F1 = 0.9364 across seven roadway crack datasets, though large, annotated datasets were required (Xiao et al., 2023).
- A YOLOv5 distress detection pipeline with IoA-based post-processing reduced false positives by 20.5 percent and delivered geotagged Automated Pavement Surface Distress Index values; validated on RDD2022 and CPRI, with noted sensitivity to perspective and zoom (Cano-Ortiz et al., 2024).
- A Crack Transformer using a Swin-Transformer encoder and MLP decoder demonstrated improved mF1, mPrecision, and mRecall on CFD, Crack500, and a custom shadow/foliage dataset, outperforming CNN baselines under challenging conditions (Guo et al., 2023).

Stakeholder Perspectives: One participant noted that "computer vision and remote sensing we cannot talk about them separately. They are integrated and the feasibility is also like I feel it's mature now to use remote sensing and computer vision models for identifying the pavement condition," citing the emergence of zero-shot learning models such as SAM3 that reduce training data requirements. Another participant stated that "these topics are high impact" but placed feasibility "in the medium like category," noting that "there's some feasibility issues that need to be figured out but I think they've come a long way." Participants affirmed safety benefits: "they improve safety 100 percent because you don't have people going out and doing physical surveys unless absolutely necessary," and it "puts people out of harm's way." One panelist cautioned that "AI models must be trained locally" because "a general system doesn't work everywhere" and that users should be "careful not using that as a black box." Another agreed, noting that "sometimes it gives you slightly skewed data."

Traffic-Speed Deflectometer (TSD)

A TSD is a nondestructive pavement evaluation system that measures the vertical deflection velocity of the pavement surface at traffic speed using Doppler lasers (Shrestha et al., 2019). It computes deflection slope by dividing measured vertical velocity by survey speed, then numerically integrates the slope profile to reconstruct a surface deflection basin for structural assessment (Shrestha et al., 2019). Unlike the FWD, which applies a stationary impulse load and measures vertical deflection, the TSD applies a rolling dual-tire axle load and measures deflection slope, requiring device-specific processing to relate outputs to FWD-based indicators (Elseifi et al., 2019; Nasimifar et al., 2018). Documented roadway configurations include six Doppler sensors positioned near 4, 8, 12, 24, 36, and 60 inches from the loaded axle with a forward reference laser (Katicha et al., 2022). Reconstructed deflection-basin indices, D0 (center deflection), SCI_12, and D60, are interpreted as indicators of overall structural capacity, asphalt-layer response, and subgrade response, respectively, when normalized for load, speed, and temperature (Huang et al., 2022).

Regulatory Context: AC 150/5370-11B Table 1 lists nondestructive testing (NDT) device categories as static (Benkelman Beam, La Croix Deflectograph), vibratory (Dynaflect, Road Rater), and impulse (FWD/HWD); TSD is not listed. However, §15 states the FAA "does not have an approved list of deflection measuring equipment," which implies that Table 1 is descriptive, not exclusionary. FAA backcalculation programs (BAKFAA, MODULUS, and five others per Table 15) assume impulse-load deflection basins using multilayer elastic theory, not continuous velocity data. Movement of a TSD truck on airport surfaces may require compliance with 14 CFR §139.329 vehicle access procedures.

Key Evidence from Literature:

- A review with 26-State pooled-fund participation concluded TSD is adequate for network-level pavement management, with remaining gaps in data collection protocols, calibration standards, and PMS implementation guidelines (Katicha et al., 2022).
- An FHWA/LTRC study (Elseifi and Zihan, 2018) deployed TSD in Louisiana and at MnROAD at up to 60 mph/1,000 Hz, and subsequent work produced an artificial neural network-based tool to convert TSD basins to FWD-equivalent inputs for standard backcalculation software (Zihan et al., 2020).
- SHRP 2 reported TSD survey costs of approximately $25–$40 per mile (collection) and $75–$90 per mile (with processing) (Flintsch et al., 2013).
- Another study processed ~950 miles across eight South Carolina routes over 4 days, establishing SCI12 thresholds of good (<1.6 mils), fair (1.6–3.3 mils), and poor (>3.3 mils) at 0.1-mile segments; SCI12 showed low correlation with Pavement Quality Index, confirming structural and functional condition are independent (Huynh et al., 2021).
- A Texas A&M/TxDOT study integrated TSD indices with GPR-derived thickness and surface condition filters via a PaveCheck platform for 4-year treatment planning and reported a quantified benefit–cost ratio from substituting TSD for FWD surveys (Scullion et al., 2025).
- At Copenhagen Airport, TSD surveyed 189 km of two runways in 4 hours at ~80 km/h, discriminating stiff/very stiff zones on an asphalt runway and detecting slab joint movement through an asphalt overlay on composite runway (Nielsen & Jensen, 2022).
- The Copenhagen Airport campaign included viscoelastic backcalculation of layer moduli from TSD slopes, SCI300 agreement against prior HWD data, and quantification of joint movement on the composite runway (Nielsen & Jensen, 2022).
- On a regional-airport taxiway, higher IRI values correlated with lower TSD D0–FWD agreement, indicating pavement roughness adversely affects TSD–FWD comparability and must be addressed in QC (Austroads, 2014).
- On the 518-mile East Idaho Loop Corridor, a TSD plus GPR plus selective FWD workflow produced continuous structural number, pavement and subgrade moduli, and remaining life at 10-m intervals stored in a spatial geodatabase for network and project-level scoping (Maser et al., 2017).
- A test-track study at 70 km/h showed the AASHTO D0 temperature correction applies to TSD, and that TSD deflections are more sensitive to temperature than to speed, making temperature normalization the more critical step for multi-trip comparability (Zhang et al., 2023).

Stakeholder Perspectives: One participant noted that technologies such as GPR and the TSD have been promoted for years and are considered "high impact," but wider adoption depends on "the specifiers… allowing them and acceptance of them." Another emphasized the multi-function capability of modern systems, explaining that the equipment "not only measures deflection, but also… shows and classifies cracks," allowing agencies to collect the needed information "in one pass." A panelist also suggested that "the acceptance issues will be solved in the near future," citing recent work by the Minnesota and Michigan DOTs. However, concerns were raised about mobilization costs, noting that "for very short distances… it will be a little expensive," even though the technology is already available.

Full-Depth Reclamation (FDR)

FDR is an in-place rehabilitation process that pulverizes the existing asphalt pavement together with a predetermined portion of the underlying base, subbase, and/or subgrade, blends in a stabilizing agent, and compacts the mixture to form a stabilized base for a new surface course (Reeder et al., 2017). Stabilization approaches are grouped as mechanical (e.g., aggregate addition), chemical (e.g., Portland cement, lime, fly ash), and bituminous (e.g., emulsified asphalt, foamed asphalt), with selection tied to materials, laboratory mix design, and project needs (Morian et al., 2012; Shuler, 2015). Acceptance practices for cement-stabilized FDR emphasize unconfined compressive strength (UCS) targets, compaction moisture control, pulverization/thickness verification, and curing windows (Morian et al., 2012; Scullion et al., 2012). FDR does not correct saturated subgrades or inadequate drainage systems on its own (Reeder et al., 2017).

Regulatory Context: Item P-207 in AC 150/5370-10H provides a complete specification covering materials, equipment, construction methods, and compaction (95-percent ASTM D1557 requirement) and may be used as base course under flexible and rigid pavements. AC 150/5320-6G §4.1.1 states that on federally funded projects, recycled materials other than P-219 require an MOS per FAA Order 5100.1 "due to variability of recycling materials and methods"; however, P-207 is an established FAA specification item, so standard FDR use should not trigger this requirement. In FAARFIELD, AC 150/5320-6G §4.11.2.1.3 directs that the FDR layer be modeled as a User Defined layer with recommended modulus of 25,000–50,000 psi; AC 150/5370-11B Table 21 and Table 22 provide modulus ranges and equivalency factors for base layers.

Key Evidence from Literature:

- A Federal Highway Administration (FHWA) multi-stabilizer FDR mix-design guide (FHWA-HIF-12-015) documented standardized lab procedures for Portland cement (PC), fly ash (FA), asphalt emulsion (AE), and foamed asphalt plus PC stabilization, including Superpave gyratory compactor compaction, indirect tensile strength/ tensile strength ratio (TSR) per AASHTO T283 for AE/foamed mixes, and UCS plus tube suction for PC/FA mixes (Bang et al., 2011).

- National Cooperative Highway Research Program (NCHRP) Report 863 found FDR mixtures generally exhibit less temperature dependency and higher stiffness at low reduced frequencies than CIR and cold central plant recycling (CCPR); chemical additives (cement, lime) consistently increased |E*| and reduced temperature susceptibility; cement also reduced permanent deformation relative to mixtures without additives (Schwartz et al., 2017).
- HVS testing with identical 60 mm surfacing showed in dry loading, FDR-FA reached 5.8-mm rut after 34M ESALs, FDR-PC reached 2.1 mm after 43M ESALs, both stopped before terminal criteria with no cracking; wet loading showed that FDR-NS reached 13-mm terminal rut at ~215,000 ESALs, while FDR-PC had only 3.2-mm rut after more than 17M ESALs (Jones et al., 2016).
- A Colorado statewide probabilistic LCCA (CDOT-2024-07) reported average 10-year agency costs of $576,312/lane-mile for FDR versus $754,555 for overlays. Initial construction cost was 82 percent higher for FDR ($617K versus $338K/lane-mile), but lower maintenance drove the lifecycle advantage (Torres-Machi et al., 2024).
- An LCA found FDR produced 51-percent lower GHG emissions and 64-percent lower energy consumption than mill-and-fill at the base-rehabilitation stage; asphalt-plant heating alone accounted for 53 percent of mill-and-fill GHG; using a low-clinker hydraulic road binder reduced FDR emissions further (Souza et al., 2024).
- At Friedman Memorial Airport (Hailey, ID), FDR with PC for a single-runway rehabilitation was estimated to take ~30 days versus 45–50 days for remove-and-replace; the project eliminated ~4,000 truck trips, recycled 73,440 yd^2 in place, reduced construction cost by more than $1,000,000, and was completed within the 30-day closure (Reeder et al., 2017).
- A multi-State practitioner survey found airports are the least utilized pavement type for FDR among all surveyed categories (Owino et al., 2022).

Stakeholder Perspectives: One participant with direct experience stated: “Full depth, we do quite a bit of that in the Dakotas and all over, just as a way for not having to do full remove and replace… we’ve had great luck.” Another participant with airport project experience emphasized execution sensitivity: “I have used that on airport projects, two paving projects. And when done well, it results in national-winning project award pavements. Done improperly or by people that don’t completely understand the technology… it ends up in disaster.”

Wearable Back-Support Exoskeletons for Construction Workers

Wearable back-support exoskeletons are body-worn mechanical devices that apply assistive moments around the hip and lower back to reduce physical demands during lifting, bending, and manual material handling tasks associated with work-related musculoskeletal disorders in construction (Kermavnar et al., 2021). Devices are grouped by actuation: active systems use powered actuators and control to deliver torque, while

passive systems rely on mechanical elements such as springs to store and return energy without external power (Poliero et al., 2022; Crea et al., 2021).

Regulatory Context: AC 150/5370-10H Section 70-06 requires compliance with "applicable federal, state, and local requirements for health, safety and sanitary provisions." Section 70-08 requires work in accordance with an approved Construction Safety and Phasing Plan (CSPP) per AC 150/5370-2G. Worker safety equipment falls under OSHA jurisdiction (29 CFR 1926). Any equipment worn in the AOA must not create FOD risk or interfere with airport operations per the CSPP.

Key Evidence from Literature:

- An eight-worker concrete task field study (4 h, BackX™): workers cited finishing, rebar tying, and raking as potential application areas; barriers reported included bulk, chest/thigh pressure, movement restriction, and interference with safety harnesses and tool belts; modifications requested included integrated harness/tool-strap systems and improved cushioning (Gonsalves et al., 2024).
- A direct active-versus-passive lab comparison (XoTrunk active versus Laevo v2.56 passive) found overall lumbar extensor median activation reductions in the 8- to 41-percent range across static and dynamic tasks; the active device (XoTrunk) achieved more than twice the reduction of the passive device in the dynamic task (Poliero et al., 2022).
- A systematic review reported significant reductions in L5/S1 moments and estimated spinal compression forces across studies, with larger reductions for active designs (up to ~22 percent) than passive designs (~14 percent) in lifting tasks (Kermavnar et al., 2021).
- Using a back-support exoskeleton increased workers' cognitive load by 33 percent during material handling tasks that required frequent setting adjustments, measured via EEG (multi-channel headset) and EDA (wristband) signals processed with a machine-learning framework (Liu et al., 2024).
- In a static stoop task with BackX™, averaged median EMG activity was reduced by approximately 75 percent in the thoracic erector spinae and 56 percent in the lumbar erector spinae across 8 subjects relative to no-device baseline (Kazerooni et al., 2019).

Stakeholder Perspectives: Participants noted that back-support devices are used on an on-request basis in the field: "most of the time, that is by request. If anybody on the crew is outfitted with it, it's just purely by request on what their duties are." Another participant expressed interest but flagged cost: "The exoskeleton sounds interesting… depending on the person, you know, if there's a guy that's out there carrying a lot all day long and don't know that he needs an exoskeleton. Upfront costs sounds like a lot."

Wearable Heat-Stress Monitoring for Construction Workers

Wearable heat-stress monitoring uses body-worn sensors and connected software to continuously measure workers' physiological responses and local thermal conditions for early recognition of heat strain during active construction work (Pancardo et al., 2015; Hwang & Lee, 2017). Wrist-worn devices capture photoplethysmography (PPG), electrodermal activity , and skin temperature without interrupting work (Jebelli et al., 2019). Supervisory decision tools fuse personal signals with environmental indices such as Wet Bulb Globe Temperature (WBGT) to classify heat-risk states and deliver actionable alerts (Pancardo et al., 2015). Core body temperature can be estimated from heart-rate time series via Kalman filtering or compact thermophysiological models implemented on wearable platforms (Buller et al., 2010; Hirata et al., 2021). Work-rest assessment frameworks use individualized indicators such as percentage of heart rate reserve (%HRR) to quantify cardiovascular load (Hwang & Lee, 2017).

Regulatory Context: AC 150/5370-10H Section 70-06 requires compliance with "applicable federal, state, and local requirements for health, safety and sanitary provisions." Section 70-08 requires work in accordance with an approved CSPP per AC 150/5370-2G. Worker safety equipment falls under OSHA jurisdiction (29 CFR 1926). Any equipment worn in the AOA must not create FOD risk or interfere with airport operations per the CSPP. P-401 §401-4.8 specifies maximum binder temperatures of 325 °F (unmodified) and 350 °F (modified) when added to aggregate, creating inherent radiated-heat exposure during asphalt operations.

Key Evidence from Literature:

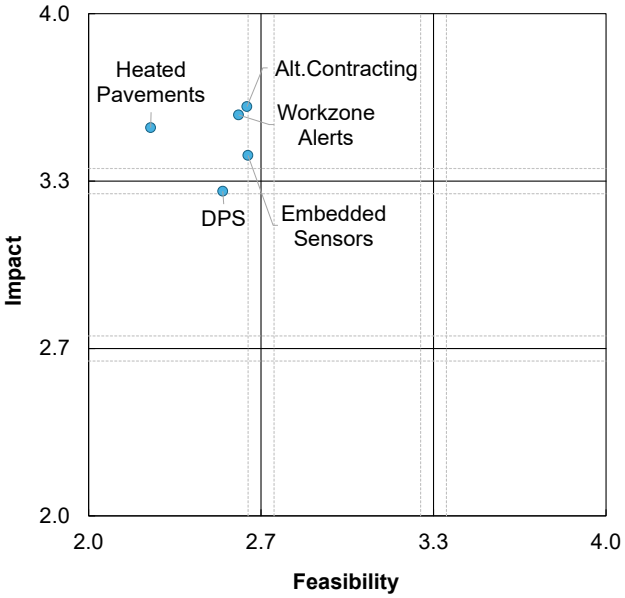
- A wristband platform (PPG, skin temperature, accelerometry) showed <1 percent error versus a clinical graded-exercise reference (n=3, indoor) and 95.7 percent agreement with a reference heartrate monitor outdoors. An 18-worker, 3-month summer pilot on a roadway construction project in South Korea used LoRa telemetry direct to a web/smartphone dashboard; field managers reported satisfaction with individual risk determination (Kim et al., 2020).
- A real-time personalized heat-stress monitoring system explicitly lists "asphalt work" as a primary target scenario under "artificially heated" environments (Pancardo et al., 2015).
- In an asphalt road paving field study (n=7, Seoul), on-body temperature averaged 30.7 °C during working hours versus 27.9 °C from 54 municipal weather stations, a gap of up to 5.4 °C on a single day. High heat strain (≥40-percent heart rate reserve) occurred on 9 dates while official heatwave alarms were issued on only 4. Three workers reached extreme heat strain thresholds (HR > 180 − age bpm for ≥4 min) on 2 dates. Notably, affected workers reported feeling comfortable at the time, demonstrating a perception–physiology mismatch (Kim & Yoo, 2023).

- Mortality from exertional heat illness can fall from 80 to near 0 percent when core body temperature is detected early and reduced below 40 °C within 30 min, providing the primary clinical rationale for continuous wearable monitoring (Dolson et al., 2022).
- ISO 7243 (WBGT-based action limits) and ISO 9886 (HR threshold: 180 − 0.65 × age) provide the standards framework most commonly applied in construction heat-stress monitoring. ISO 7243 is characterized in the literature as conservative in tropical conditions and unable to capture worker-specific microclimates, the gap that individualized wearable monitoring is intended to fill (Kakamu et al., 2021; Pancardo et al., 2015).

Stakeholder Perspectives: Participants with direct deployment experience described active use of wearable heat-stress monitors during summer paving in hot climates. One panelist noted: “We will have our crews out there, especially when we see that temperature’s going to spike. We will make sure that the crew is outfitted to monitor where they’re at, as an alert to see if anybody is nearing a heat stroke issue.” The same participant observed behavioral modification: “When they’re wearing it, you notice that they hydrate more, that they’re covered more… it does actually modify a little bit of their behaviors, because they know that they’re being watched.” Participants also emphasized device personalization: “They get assigned sensors, so that it’s theirs, and we benchmark them. If you have a naturally high heart rate, you’d hate to be always on alert.” Another participant noted that sensors are “not super expensive” but flagged field adoption challenges: “We’ve caught a lot of people taking them off… there’s a love-hate relationship with them right now. The safety and the environmental people love them. The field, not so much.” The environmental context was also highlighted: “It’s really hard to expect someone to stand next to a 300-plus degree pavement all day in close to 100 degree weather.”

Cell 3: High Impact/Low Feasibility Technologies

Figure 13 presents the Impact–Feasibility scatter plot for the five technologies classified in Cell 3. These technologies offer substantial performance and safety benefits but face considerable implementation barriers that limit near-term airfield deployment. Technologies in this cell are either constrained by FAA regulatory requirements, high installation and operational costs, durability concerns, limited airfield-scale validation, or significant institutional resistance to adoption. Dimension scores for each technology are presented in Table 16 and Table 17.



Source: AAPTP

Figure 13. Impact vs. Feasibility Matrix for Technologies Classified as High Impact/Low Feasibility

Table 16. Impact Dimension Scores for High Impact/Low Feasibility Technologies

Technology Name	Performance	ROI	Safety	Efficiency	Sustainability	Impact Score
Progressive & Alternative Contracting Methods	4	4	3	4	3	3.63
Embedded Pavement Sensors	4	3	3	4	3	3.44
Heated Airport Pavements	4	3	3	4	4	3.55
Dielectric Profiling System (DPS)	3	4	3	4	3	3.29
Embedded Electromagnetic Work-Zone Alerts	4	3	4	3	3	3.60

Table 17. Feasibility Dimension Scores for High Impact/Low Feasibility Technologies

Technology Name	Readiness Level	Technical Issues	Upfront Cost	Regulatory Hurdles	Stakeholder Acceptance	Feasibility Score
Progressive & Alternative Contracting Methods	4	2	2	2	3	2.61

Technology Name	Readiness Level	Technical Issues	Upfront Cost	Regulatory Hurdles	Stakeholder Acceptance	Feasibility Score
Embedded Pavement Sensors	3	2	2	3	3	2.62
Heated Airport Pavements	3	2	2	2	2	2.24
Dielectric Profiling System (DPS)	3	1	3	3	2	2.52
Embedded Electromagnetic Work-Zone Alerts	3	2	3	2	3	2.58

Progressive and Alternative Contracting Methods

Progressive and alternative contracting methods are procurement and delivery approaches that rebalance team selection, price negotiation, and risk allocation to influence asset outcomes beyond prescriptive "methods-and-materials" specifications (Anastasopoulos et al., 2010). Commonly cited mechanisms include performance-based contracting (PBC), incentive/disincentive provisions, cost-plus-time (A+B) bidding, warranties, and delivery frameworks such as design–build (DB), construction manager/general contractor (CM/GC), and progressive design–build (PDB) (Anastasopoulos et al., 2010; Gajurel, 2014). In PDB, the owner selects a design-builder on qualifications, advances design collaboratively and negotiates a guaranteed maximum price (GMP) via open-book procedures, with an off-ramp to design-bid-build (DBB) if no agreement is reached (Gransberg & Molenaar, 2019). In CM/GC, the owner engages a constructor during design for preconstruction services and later negotiates construction packages when design definition supports pricing (Antoine et al., 2019). DB consolidates design and construction under one entity, procured as low-bid or best-value (Antoine et al., 2019). PBC frameworks tie compensation to measurable in-service outcomes such as IRI, rutting, cracking, friction, and response times; performance-related specifications (PRS) extend this concept by linking acceptance quality characteristics measured at construction to mechanistic performance prediction models and life-cycle cost differentials to determine rational pay adjustments (Karlaftis & Kepaptsoglou, 2012; Gajurel, 2014; West et al., 2023).

Regulatory Context: Sealed bidding is "the preferred method for procuring construction" under 2 CFR §200.320(c) (Order 5100.38D, p. U-13). DB, construction manager-at-risk (CMAR), and other alternative delivery methods are permitted but classified as "competitive proposals," which may require Airports District Office (ADO) pre-review and concurrence (Order 5100.38D §3-43, p. 3-37; Table U-9(3), p. U-17). DB is explicitly authorized under 49 USC §47142, which requires that "three or more bids must be submitted'" (Table U-9(3)). For CMAR, "the sponsor selects a construction manager-at-risk

(CMAR) based on qualifications and price early in the design phase" (Table U-9(3), p. U-17). Grant Assurance 32 mandates Brooks Act qualification-based selection for professional services. Value engineering is encouraged per 2 CFR §200.318(g) (Order 5100.38D §3-54, p. 3-44).

Key Evidence from Literature:

- For $10–$50M highway projects, mean total durations were 2,106 days (DBB), 662 days (CM/GC), and 1,420 days (DB/BV); CM/GC was significantly shorter than both DBB and DB/best-value (BV) (Antoine et al., 2019).
- Projects procured using qualifications-based selection had significantly less severe claims (cost) than open bid; BV selection increased the likelihood of fewer claims, lower schedule growth, and higher overall success in empirical highway analysis (Hasanzadeh et al., 2018).
- PDB is reported as widely used in airport projects, indicating sector familiarity with qualifications-based selection, open-book GMP negotiation, and early design-builder engagement in permitting (Gransberg & Molenaar, 2019).
- Fairbanks International Airport and Memphis airport CMAR cases document defined QC/QA role allocations and progressive GMP administration aligned with airfield stakeholders (Gransberg & Shane, 2010).
- The first I-15 marking warranty letting failed due to high bids under perceived risk and partial payment structures; the project was rebid with Interstate Maintenance funds and adjusted risk/payment terms to facilitate award, signaling higher initial costs and administrative complexity to structure workable allocations (Zlatkovic & Porter 2013).
- A study of 12 completed North American design-build-finance-operate-maintain highway projects ($90M–$1,100M) reported an average construction cost change of 0.81 percent and an average schedule change of −0.3 percent; 10 of 12 projects had no construction cost increases, and 11 of 12 had no schedule increase or finished early (Chasey & Bansal, 2012).

Stakeholder Perspectives: One panelist stated: "From an FAA's perspective, they do allow those, but they're on a case-by-case basis. They do require special approval, but certainly high feasible, high impact, especially working in an airfield environment and the flexibility that those tend to offer versus the traditional design to build." Another noted: "I think it would have high feasibility if the owner, FAA on airfields, would accept it… because of all the work done related to highways on implementing alternate contracting methods and the cost effectiveness that's been reported." A panelist observed that CM/GC "is gaining in use, certainly that engaged interaction between all the parties and working towards common goals and having that open communication is a big part of the advantage." However, a defense-agency participant cautioned that procurement departments are "quite risk-averse and pretty much rooted in traditional contracting methods," characterizing

feasibility for airfield paving as low from that perspective. Another panelist noted design-build has "kind of a pushback right now" because firms feel "the owner agencies have been putting too much risk on them."

Embedded Pavement Sensors

Embedded pavement sensors combine distributed fiber-optic sensing (DFOS) and embedded point-sensor networks (e.g., temperature, moisture, strain, pressure probes; micro-electro-mechanical systems (MEMS); time-domain reflectometry (TDR)) to provide continuous or event-triggered subsurface condition data for runways, taxiways, and aprons (Hauswirth et al., 2020; Ceylan et al., 2016). DFOS uses an optical fiber as a continuous sensor to measure strain and/or temperature along its length via Brillouin (BOTDA) or Rayleigh (SWI) scattering (Bao et al., 2016; Xiang & Wang, 2018). Embedded environmental networks place sensing elements within pavement layers to continuously measure temperature, relative humidity, moisture content, and dynamic response (Ceylan et al., 2016).

Regulatory Context: AC 150/5200-30D §3.3.1 references in-pavement Runway Surface Condition Sensors providing "site-specific pavement and air temperature trends, dew point temperature, chemical strength" per SAE Aerospace Recommended Practice 5533.

Key Evidence from Literature:

- At Denver International Airport (DIA), 460 sensors (strain gauges, thermocouples, and TDRs) were embedded across 16 runway slabs to monitor aircraft wheel and environmental loading, with data transferred to a centralized FAA-managed database (Ceylan et al., 2016; Yang et al., 2014).
- At Zurich Airport, armored fiber-optic cables were embedded in HMA at 4 cm and 13.5 cm depths, survived placement at ~140 °C and heavy compaction and captured distributed strain fields beneath an A330-300 aircraft's main gear (Hauswirth et al., 2020).
- The FAA NAPTF embedded over 1,000 sensors across instrumented test sections divided into static (hourly temperature, moisture, crack status) and dynamic groups; many sensors were damaged and sections replaced on an ~18-month cycle under accelerated testing (Ceylan et al., 2016).
- A military runway structural health monitoring system design specified eight instrumented sections with embedded thermometers, strain gauges, and pressure cells, using trigger-based acquisition during aircraft passes only and comparing responses against FEM thresholds for anomaly detection within an APMS framework (Bruno et al., 2021).
- Point capacitive ice sensors were tested in a 36-day field observation adjacent to a runway at Turin-Caselle airport, successfully identifying dry, wet, and icy surface states (Troiano et al., 2011).

Stakeholder Perspectives: Participants recognized embedded sensors as a practical monitoring tool, with one panelist stating: “I think embedded sensors are actually relatively inexpensive. Some of those, the fiber optic strains are a little bit more expensive, but I can see where using some of these embedded sensors would help engineers over time look at that data and see if they’re noticing a problem in an area.” However, panelists raised durability and data concerns: “The problem with the sensors are, there are a couple of challenges. They have a limited life and then accuracy of these sensors. Sometimes, it changes by time.” Data volume was flagged as a barrier: “it generates lots of data and analyzing the data, it could be a challenge, which the AI, actually, that we talked before, can be incorporated to handling this data and analyzing this data.” Participants also emphasized coordination between sensor installation and pavement rehabilitation cycles: “it should be coordinated with the life of the pavement and how much is the life of the remaining pavement that you have.” A contractor noted that embedded items complicate asphalt milling and recycling. Participants emphasized that gaining FAA specification acceptance and convincing airports and contractors of feasibility are sequential barriers, and that “closure is not the easiest thing to do at the airport,” adding complexity to any instrumented study.

Heated Airport Pavements

Heated airport pavements are engineered runway, taxiway, and apron surfaces that actively prevent or remove snow and ice by maintaining surface temperatures at or above freezing using embedded heating systems (Ceylan et al., 2014). Two families are documented for airfields: hydronic heated pavement systems (HHPS), which circulate heated fluid through embedded pipes, and electrically heated pavement systems, which generate heat via resistive elements or by energizing an electrically conductive paving layer (ECON) through joule heating (Abdualla et al., 2023; Abdualla et al., 2016). A third approach embeds near-surface nickel–chromium (NiCr-80/20) heat wires to concentrate heat at the surface (Daniels et al., 2019).

Regulatory Context: Order 5100.38D §3-78 explicitly names heated airfield pavement as AIP-eligible under AC 150/5370-17, Airside Use of Heated Pavement Systems, conditional on a positive benefit-cost analysis. The ADO must remove heated pavement area from snow removal equipment calculations. AC 150/5200-30D §3.3 establishes that pavement temperature, not air temperature, determines ice formation. §4.5.1 states that “preventing a bond is always preferred over removal.” §4.7 notes chemicals become ineffective near their eutectic temperature. §4.6.3.1 describes chemical deicers causing a “large drop in dissolved oxygen levels of receiving waters,” and §4.6.3.2 addresses PCC scaling from chemical use. §4.4.1 references snow melters as existing thermal equipment precedent. Table 1-1 specifies clearance time targets: 1/2-hr for airports with ≥40,000 annual operations; 1 hr for 10,000–40,000; 1-1/2 hr for 6,000–10,000; and 2 hr for <6,000.

Key Evidence from Literature:

- At Chicago O'Hare International Airport (ORD), a 697 m^2 conductive asphalt pavement system was installed on a taxiway with copper cables cast in a 5-cm graphite-infused layer that met P-401 specifications; the system consistently produced a power density of 484 W/m^2 over a 3.5-year evaluation and withstood 200,000 aircraft passes without significant cracking; however, the estimated operating cost was approximately $2,400/hr for a 10,000-ft runway (Anand et al., 2017; Ceylan et al., 2014).
- Oslo Airport Gardermoen operates HHPS across 35,700 m^2 of apron sites at a design-heating performance of 248 W/m^2; operators characterized heated stands as necessary for aircraft turnaround and safety; stand construction costs were $275,000–$375,000 per stand with annual operating costs of approximately $16,500 per stand (Anand et al., 2017; Ceylan et al., 2014).
- The Greater Binghamton Airport (BGM) hydronic-geothermal prototype comprised 3,200 ft^2 of apron with 20 closed vertical wells at 500 ft depth; the system operated successfully during monitored winter events and reversed in spring–fall to assist terminal cooling, but experienced controller failures and required continued plowing across the heated apron (Ziegler & Nixon, 2023).
- The first U.S. airport ECON installation at DSM generated 300–350 W/m^2 and effectively melted ice and snow across multiple winter events; surface current measured 0.4 mA during 210 V AC operation, which the authors reported as below the 1-mA human perception threshold (Sassani et al., 2018).
- A benefit-cost ratio (BCR) analysis for HHPS across three U.S. airports found BCR and median BCR values of: Minneapolis–St. Paul International Airport (MSP) 2.05 (median 1.61), John Glenn Columbus International Airport (CMH) 1.35 (median 1.20), and Des Moines International Airport (DSM) 1.20 (median 1.14); heating only 20 percent of an apron area increased BCRs to 3.78 (MSP), 2.75 (CMH), and 2.25 (DSM), indicating that targeted area selection substantially improves economic viability; a base HHPS installation cost of $35/$ft^2$ with sensitivity from $15–$45/ft^2 was used in the airport analyses (Anand et al., 2017).

Stakeholder Perspectives: Participants recognized heated pavements as a high-impact concept for northern operations but expressed feasibility concerns. One participant noted: "the hydronic pipes, if you're talking about pavement, you don't want to break those and then you shut down the whole system," while highlighting conductive pavement with carbon fibers as an alternative that "would drastically decrease the use of chemicals and snow removal equipment." A researcher with geothermal bridge deck experience characterized the technology as "important impact" but assessed it as "still probably at the research level." A contractor participant raised rehabilitation concerns: "when you're putting something in the pavement, you know, if you're milling up, you have those

concerns." Another panelist identified the primary feasibility barriers as "the maintenance side of those systems … and the cost" and observed that embedded systems "change how we think about our pavements in general, which I think is a challenge for a lot of pavement engineers." One panelist also recalled a European airport deployment and noted the technology "has been worked on for some time," but cited "limited case studies" as a constraint on widespread adoption.

Dielectric Profiling System (DPS)

A DPS is a GPR configuration that measures the asphalt surface dielectric constant and correlates those measurements to in-place mat density or AV content for QC/QA decisions (Von Quintus et al., 2023). Air-coupled GPR antennas transmit electromagnetic pulses toward the pavement and analyze the reflected signal at the air–asphalt interface; the computed surface dielectric is related to density via project-specific calibration to field cores (Diefenderfer & Nair, 2025). The dielectric constant varies with asphalt constituents and AV, supporting regression or mixing-model relationships to bulk specific gravity (Gmb) (Chang et al., 2011). Field implementations include push-cart units with integrated GPS/distance measuring instrument and vehicle-mounted antenna arrays for transverse coverage (Von Quintus et al., 2023; Hoegh et al., 2015). A laboratory dielectric measurement system procedure computes G_{mb} from specimen dielectric within 8–10 min per specimen after aggregate dielectric is established (Sias & Dave, 2023).

Regulatory Context: P-401 §401-5.5 specifies that QA acceptance density is determined from cores analyzed under the C-110 PWL method (AC 150/5370-10H). P-401 §401-5.3f states: "A nuclear gauge may be used to monitor the pavement density in accordance with ASTM D2950." Using DPS for QC monitoring as a supplement to nuclear gauges may not require MOS (it does not modify acceptance criteria), but using DPS for density acceptance may require MOS.

Key Evidence from Literature:

- The DPS procedure requires a project-specific correlation between measured dielectric and mat density using field cores or lab-compacted pucks for every project, because lift thickness, moisture, aggregate type, and underlying layers all influence the relationship (Von Quintus et al., 2023).
- Across nine roadway projects, DPS dielectric versus core-based percent maximum density correlations (R^2) ranged from 0.52 to 0.98; the lowest value (0.52) was for a 25-mm nominal maximum aggregate size (NMAS) mixture attributed to surface texture influence; the Virginia Transportation Research Council (VTRC) concluded DPS is promising for process control but premature for density acceptance pending further study of mixture effects (Diefenderfer & Nair, 2025).
- At Helsinki-Vantaa Airport, a 900-m by 60-m area (eight lanes) was surveyed in approximately 3 hr at 50–70 km/h using air-launched GPR; AV were calculated at 5

m means; the authors concluded that GPR provided a functioning QC method for runways with advantages of speed and spatial coverage (Leng, 2011).

- For non-slag asphalt mixtures, a GPR-predicted density error was reported at 0.5–1.1 percent (using two calibration cores), while nuclear gauge errors were 1.2–3.1 percent under the same conditions (Leng, 2011).
- The Alaska Department of Transportation & Public Facilities revised density pay factors to "percent conforming" with factors ranging from 0.80 to 1.05 under DPS-based assessments; Ohio DOT reported that rolling density meter measurements and estimated densities were more reliable for entire lots than sparse cores, used nine cores for a linear calibration curve, and required daily verification with ongoing pilots to finalize procedures (Von Quintus et al., 2023; Wilson et al., 2019).

Stakeholder Perspectives: Participants described DPS as a technology that works but faces significant practical barriers. One practitioner with direct DPS ownership stated: "I own a dielectric profiling system, I use it as a QC tool, but it's not really feasible right now as a technology. It is starting to get mounted in smaller applications to rollers for real-time density, so I think its feasibility's starting to prove itself." Another panelist noted calibration complexity and aggregate sensitivity: "it's a huge piece of equipment that sits on these rollers, and you have to calibrate it, and you may get some odd dielectric signals from things like slag, different aggregates that aren't necessarily normal." A third participant concluded: "The DPS systems just… I think they need more time. There's more development that is necessary."

Embedded Electromagnetic Work-Zone Alerts

Electromagnetic (EM) work-zone alerts are systems that use EM mechanisms either to generate and deliver alert signals or to self-power warning devices located at or near the pavement surface (Duarte & Ferreira, 2016). Three implementation families exist. First, in-pavement energy harvesters convert traffic-induced motion into electricity to activate local warning devices (e.g., flashing markers) without grid connections; outputs range from milliwatt to watt scale (Zabihi & Saafi, 2020; Heller et al., 2023). Second, wireless proximity warning systems use Bluetooth Low Energy (BLE) radio signals from equipment-mounted beacons and worker-carried devices to issue hazardous-proximity alerts on active jobsites (Kim et al., 2022). Third, a connected-vehicle approach uses dedicated short-range communications in Vehicle-to-Infrastructure (V2I) architectures to broadcast work-zone messages (Zeng et al., 2012; Hallmark et al., 2019).

Regulatory Context: AC 150/5370-2G governs work-zone delineation, specifying physical barricades, lighted barricades, cones, and signs for construction areas adjacent to active aircraft areas. AC 150/5370-10H §70-08 requires contractors to work in accordance with an approved CSPP developed per AC 150/5370-2G, which includes marking and barricading plans. AC 150/5340-1M and AC 150/5345-55A cover standard airport marking and lighting

requirements. FAA Order 6750.16E governs siting criteria for electronic equipment near airports; any EM system on the airfield must demonstrate compatibility with NAVAIDS, airport communications, and aircraft electronics. Embedded components must not create FOD, damage aircraft tires, or compromise pavement integrity. AC 150/5370-2G's requirement for "prominent, comprehensible warning indicators" (§2.20.1) could potentially accommodate electromagnetic alerts as a supplement. Novel safety technologies can be incorporated into a project-specific CSPP. Alerts are classified as operational safety equipment and therefore may not be subject to the MOS process under FAA Order 5300.1G.

Key Evidence from Literature:

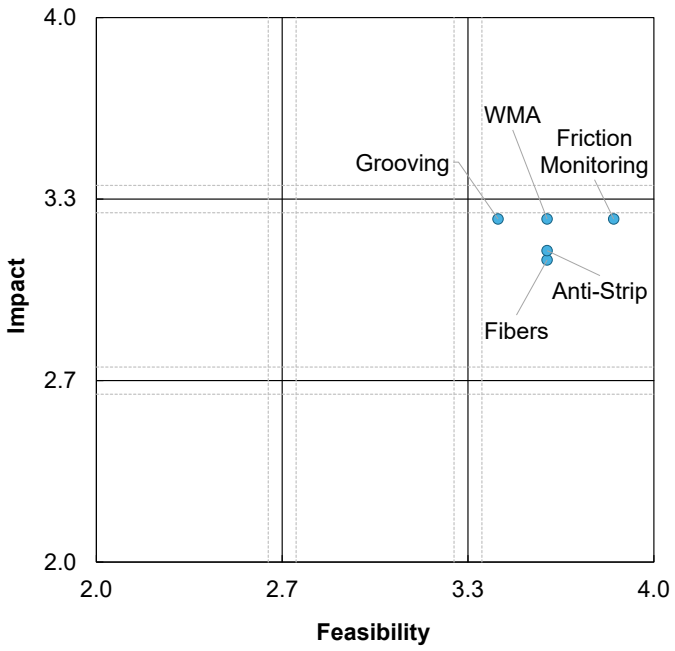
- An Illinois Center for Transportation laboratory pilot tested eight scenarios varying EM-strip spacing (1 ft and 2 ft) and inclination angles (45°, 60°, 90°, and 120°); repeatable detection was achieved at a minimum spacing of approximately 2 ft for slower speeds, and diagonal-strip configurations (45°–120°) reliably determined left- or right-merge requirements from the captured magnetometer signature sequence, establishing proof-of-concept for a passive, infrastructure-side V2I alert with no active power source required in the strip itself (Sakulneya & Roesler, 2023).
- An IoT system using equipment-mounted equipment protection units, worker-carried personal protection units, and fixed BLE beacons achieved a recall of 97.45 percent and an F1-score of 0.931 in its fourth of four progressive evaluation tests on active roadway paving and maintenance sites (Kim et al., 2022).
- A BLE-based proximity sensing study on roadway work zones applied a parameter adjustment function that reduced alert-distance deviation from a 10-m setting from 5.54 m to 0.03 m for a truck, and from 0.88 m to 0.37 m for a wheel loader, across 160 trials per equipment type; without calibration, inter-equipment variability was substantial, confirming the need for equipment-specific parameter adjustment (Park et al., 2017).
- Field trials of a tactile-based wearable system transmitted three simultaneous pieces of hazard information with approximately 95-percent perception accuracy; complete alert signal profiles were transmitted in under 250 ms per unit cycle, demonstrating that multi-modal, rapid alert delivery is technically achievable in the noisy, obstructed-sightline environment typical of active work zones (Sakhakarmi et al., 2021).

Stakeholder Perspectives: Participants described firsthand experience with geofence-based electromagnetic work-zone alerts. One practitioner reported that the system "actually worked really, really well" and "probably saved a couple guys their lives, to be honest, because it did go off, and the sirens went off, and there was a person flying through the work zone." Another panelist noted growing adoption: "that's becoming quite a bit more

popular, and I think the impact is high, and it's not really too expensive, so if you could save one life, obviously, that's massive."

Cell 4: Medium Impact/ High Feasibility Technologies

Figure 14 presents the Impact–Feasibility scatter plot for the five technologies classified in Cell 4. These technologies offer meaningful performance benefits and face relatively few barriers to airfield deployment. Technologies in this cell are generally well-supported by existing FAA specifications, have established roadway or airfield precedents, and are familiar to contractors and agency personnel. Dimension scores for each technology are presented in Table 18 and Table 19.



Source: AAPTP

Figure 14. Impact vs. Feasibility Matrix for Technologies Classified as Medium Impact/High Feasibility

Table 18. Impact Dimension Scores for Medium Impact/High Feasibility Technologies

Technology Name	Performance	ROI	Safety	Efficiency	Sustainability	Impact Score
Warm Mix Asphalt (WMA)	3	3	4	3	3	3.26
Fiber-Reinforced Asphalt Concrete	3	3	3	3	4	3.11
Anti-Strip/Moisture Additives	4	2	3	3	3	3.14
Runway Texture and Friction Monitoring	3	3	4	3	3	3.26
Runway Grooving	3	3	4	3	3	3.26

Table 19. Feasibility Dimension Scores for Medium Impact/High Feasibility Technologies

Technology Name	Readiness Level	Technical Issues	Upfront Cost	Regulatory Hurdles	Stakeholder Acceptance	Feasibility Score
Warm Mix Asphalt (WMA)	4	3	3	4	4	3.62

Technology Name	Readiness Level	Technical Issues	Upfront Cost	Regulatory Hurdles	Stakeholder Acceptance	Feasibility Score
Fiber-Reinforced Asphalt Concrete	4	3	3	4	4	3.62
Anti-Strip/ Moisture Additives	4	3	3	4	4	3.62
Runway Texture and Friction Monitoring	5	3	3	4	4	3.86
Runway Grooving	4	2	3	4	4	3.44

Warm Mix Asphalt (WMA)

WMA is a family of asphalt mixture production and placement technologies that lower mixing and compaction temperatures relative to conventional HMA by modifying binder rheology or binder–aggregate interactions. Three principal approaches exist: water-based foaming (direct water injection or zeolites releasing steam in hot binder), chemical packages (surfactants/adhesion promoters that reduce interfacial friction), and organic wax additives (e.g., Fischer–Tropsch waxes) that reduce viscosity at mixing/compaction temperatures and crystallize on cooling to increase stiffness at service temperatures (Diab et al., 2016).

Regulatory Context: P-401 contains no WMA-specific provisions; DOD UFGS 32-12-15.16 and U.S. Air Force Engineering Technical Letter 11-3 provide military airfield WMA guidance pathways. P-401 §401-4.8 specifies that unmodified binder shall not exceed 325 °F (160 °C) when added to the aggregate and modified binder shall not exceed 350 °F (175 °C). FAA Order 5300.1G requires MOS approval for new construction methods: §3 (p. 3) states airports must submit a request "when it results in cost savings or greater efficiency without sacrificing safety or useful life."

Key Evidence from Literature:

- The U.S. Army Engineer Research and Development Center (ERDC) conducted full-scale Accelerated Pavement Test using a Heavy Vehicle Simulator for Airports (HVS-A) applying a single F-15E wheel load of approximately 35,500 lb at 325 psi tire pressure, with a target effective pavement temperature of 109 °F (43 °C), across four identical pavement structures differing only in surface mixture; results showed rutting performance of WMA was slightly poorer than that of HMA across all three WMA technologies, but still recommended WMA as a viable alternative to HMA for airfield wearing surfaces and called for monitored trial sections on active airfields (Mejías-Santiago et al., 2014).

- At Boston Logan International Airport, a 19-mm NMAS intermediate course and fuel-resistant surface course were produced approximately 40 °F (22 °C) below normal HMA temperatures using Sasobit, meeting the FAA 24-hr intermediate-lift window and 6-hr surface-course window and completing work in 3 days instead of a typical 5, under ambient conditions of approximately 38 °F (3 °C) and ~25 mph winds (Bennert, 2012; Mejías-Santiago et al., 2012). Bennert (2012) recommended limiting temperature reductions using flow number or equivalent performance tests to control the rutting–fatigue trade-off for airfield applications.
- A ~52 °F (29 °C) production temperature reduction corresponded to ~21-percent fuel savings and ~20-percent CO_2 reduction. Across 14 U.S. roadway field projects (2006–2011), WMA production temperatures averaged 48 °F (27 °C) lower than companion HMA under controlled steady-state monitoring (West et al., 2014).
- Worker breathing-zone Total Organic Matter (TOM) exposure averaged 36 percent lower across WMA technologies, and all nine polycyclic aromatic compounds were below detection limits in the highest-TOM samples screened (West et al., 2014).
- Additive costs for chemical WMA technologies range from approximately $2.00–$3.50/ton of mix as a recurring production cost; capital costs for mechanical foaming system retrofits range from approximately $50,000–$75,000 (Chowdhury & Button, 2008; McCarthy et al., 2012).

Stakeholder Perspectives: Participants described WMA as a high-feasibility technology with a clear adoption path. One participant noted that “the FAA tech center up there in Atlantic City did do a study on warm mix and found that the performance was equal to hot mix.” Another observed that climate-specific restrictions apply “if we’re in any type of a cold weather situation, we actually don’t allow foaming. It is only the chemical additives” and noted that some chemical WMA additives also provide anti-strip capabilities, “getting a double bang for your buck.”

Fiber-Reinforced Asphalt Concrete

Fiber-reinforced asphalt concrete (FRAC) adds discrete fibers to HMA to increase stiffness, cracking resistance, and deformation resistance relative to unreinforced mixes (Stempihar et al., 2012). Fibers fall into two functional categories: fibers to stop or mitigate draindown in SMA mixtures (cellulose or mineral, typically ~0.3 percent by mix mass), and fibers to stabilize the mix and inhibit rutting, cracking, and shoving (polyester, polypropylene, aramid, or combinations) (Buncher et al., 2025).

Regulatory Context: Fibers are not referenced in AC 150/5370-10H for HMA applications. P-401 mix design criteria (Marshall or Gyratory) are based on conventional aggregate-binder systems without fiber reinforcement. FAARFIELD assigns fixed modulus values to P-401 layers regardless of additives/modification, providing no structural design credit for any

fiber reinforcement. An MOS may be required to enable the addition of fibers into existing asphalt mixture items per FAA Order 5300.1G.

Key Evidence from Literature:

- FAA P-402 porous friction course (PFC), 1 inch thick, was placed on Runway 1-19 at Jackson Hole Airport using a blend of aramid and polypropylene fibers to address raveling, snow plowing, high tire pressures, and heavy aircraft loads, placed over 11–17 inches of asphalt base layers. Confined dynamic modulus testing at 10 Hz (≈100 mph runway speed) and 1 Hz (≈20 mph taxiway speed) indicated the FRAC mixture was "considerably stronger" at higher temperatures for both frequencies; four-point bending beam fatigue at 40 °F showed longer life at lower strain levels (Stempihar et al., 2012).
- Bid tabulations for Jackson Hole Airport and Sheridan County Airport showed that adding fibers increased unit cost per ton of P-402 by approximately 11 percent for FRAC. An equivalent uniform annual cost analysis indicated that extending service life by approximately 0.9 years beyond an 8-year baseline achieves break-even on the cost premium, while more than 1.1 years beyond a 10-year baseline are needed to justify the premium (Stempihar et al., 2012).
- In a laboratory program using FAA P-401 surface-course mixtures, carbon, basalt, and fiberglass fibers were evaluated at 0.15 percent and 0.30 percent by total mix weight using IDT-CT and APA with binder content controlled to isolate fiber effects. At 5.6-percent binder, CT-Index values were 266 (control), 324 (carbon at 0.15 percent), and 484 (carbon at 0.30 percent); basalt at 0.30 percent improved only at optimum binder content; fiberglass showed no statistically significant improvement. However, all fibers at 0.30 percent increased APA rut depth (average approximately 6.6 mm versus approximately 4.4 mm for the control), and optimum binder content increased 0.6–0.8 percent depending on fiber type, with the rutting penalty not resolved by reducing binder content alone (Alfalah et al., 2021).
- In a Virginia DOT/VTRC study, for most mixtures evaluated, fiber addition did not improve BMD test results compared with controls because production binder contents were reduced from design levels. CT-Index, mass loss, and ITS appeared most influenced by effective binder content and film thickness rather than fiber content. The Virginia DOT recommended designing fiber-modified mixtures using performance criteria with long-term field evaluation (Diefenderfer & Nair, 2025).
- In a plant-produced Idaho highway overlay, fiber clumping was directly observed during plant feeding; fibers "clumped and were blown as balls into the feeder" (Bayomy et al., 2016).
- Plant-produced FRAC with low aramid dispersion state ratio (ADSR) (poorly dispersed fibers) showed substantially lower FN than high-ADSR mixes and

approached control mix FN values. Fiber length increases improved FN but simultaneously reduced ADSR (Noorvand et al., 2018; Noorvand et al., 2022).

Stakeholder Perspectives: Participants described fibers as "pretty well suited to an airfield type application and certain pavements in an airfield," noting they could be "complementary to some of the technologies" in other mix categories and could provide "real toughening, strengthening" but "would require a balanced mix design type of approach."

Anti-Strip/Moisture Additives

Anti-strip additives (ASA) are materials introduced into the asphalt system to strengthen binder–aggregate adhesion and preserve binder cohesion under water and freeze–thaw exposure, thereby limiting stripping and wet-condition strength loss (Abuawad et al., 2015). Reported additive classes include (i) traditional liquid additives, (ii) metal ion surfactants, (iii) hydrated lime and Portland cement, (iv) silane coupling agents, and (v) silicone (Behiry, 2013). Common families include amine-based liquid anti-strip agents added at low dosage to binder, hydrated lime and cementitious mineral fillers, and organosilane chemistries (e.g., Zycotherm/Zycosoil) that form hydrophobic linkages with siliceous aggregates (Abuawad et al., 2015; Sengöz et al., 2013; Khani Sanij et al., 2019). Performance is typically evaluated using AASHTO T 283 for TSR, HWTT (AASHTO T 324) for stripping/rutting, and surface free energy frameworks for adhesion thermodynamics (Abuawad et al., 2015; Hamedi, 2016; Ghabchi et al., 2019).

Regulatory Context: Anti-stripping is directly addressed in current FAA specifications. P-401 §401-2.4 (AC 150/5370-10H) states that any anti-stripping agent "shall be heat stable and shall not change the asphalt binder grade beyond specifications." P-401 §401-2.4 further requires that anti-strip "shall be an approved material of the Department of Transportation of the State in which the project is located." P-401 Table 1 (p. 270) sets an 80 percent minimum TSR per ASTM D4867 as a mix design criterion. P-403 includes similar anti-stripping provisions. Engineering Brief 102 (Asphalt Treated Permeable Base Course) §407-3.1 mandates a minimum 0.5 percent anti-strip, and §407-2.4 requires the same State DOT approval and heat-stability provisions as P-401.

Key Evidence from Literature:

- A 13-mixture study (PG 67-22 and PG 70-22, three aggregate types) evaluated amine-based liquid ASA and a chemical WMA additive using HWTT (AASHTO T 324), Modified Lottman (AASHTO T 283), MiST (ASTM D7870 at 7,000 cycles), and binder bond strength pull-off under two conditioning severities (freeze-thaw (FT)-3; MiST 7,000). PG 70-22 with amine-based ASA showed no stripping failure in HWTT across all conditioning types, and higher ITS and TSR than WMA and control under MiST 7,000. Under PG 67-22, the amine ASA avoided stripping under FT-3 while the WMA

additive alone showed stripping onset. The study recommends incorporating moisture pre-conditioning into AASHTO T 324 prior to wheel-tracking to address documented precision limitations of the standard Modified Lottman/TSR protocol (Mohammad et al., 2025).

- A national survey reported 82 percent of State DOTs require anti-strip treatment in HMA (56 percent using liquid anti-strips only, 15 percent liquid or lime, 29 percent lime only) (Kim et al., 2012).
- Pull-off TSR for PG 64-22 after 48-hr conditioning increased from 37 percent (control) to 76 percent with hydrated lime and 65 percent with Class C fly ash. PG 70-28 with high-quality aggregates showed limited sensitivity to additive type under the same conditioning, indicating diminishing returns when polymer-modified binders and premium aggregates are already specified (Kim et al., 2012).
- Under simulated HMA plant production conditions, the anti-stripping effectiveness of liquid amine-based agents was effectively removed after one day of prolonged high-temperature storage/production (Hesami & Mehdizadeh, 2017).
- Amine anti-strip agents are reported to decompose and release irritant gas at high temperature (Min et al., 2015).
- HWTT in water at 50 °C for up to 20,000 passes (AASHTO T 324) showed no indication of moisture-induced damage, while TSR testing on the same mixes indicated possible moisture susceptibility (Ghabchi et al., 2019).

Stakeholder Perspectives: Participants described anti-strip as a high-feasibility technology with an established regulatory path. One panelist noted that a major airport authority "has added systems in the last couple of years to really bring this into their airfield systems and approve them. And I think it's worked just fine." Another participant cautioned that ASA "are expensive. So when they're needed, they're amazing. But if they're not needed, you know, it's just one more thing," noting their value is conditional on the presence of moisture-sensitive aggregates.

Runway Texture and Friction Monitoring Technology

Runway friction management encompasses the design, measurement, and maintenance practices needed to preserve aircraft braking and directional control on asphalt-surfaced runways in dry, wet, and contaminated conditions. Microtexture at the aggregate scale supports adhesion; macrotexture promotes drainage and governs hysteresis (White, 2017). Macrotexture is commonly provided by transverse grooving (square saw-cuts 6 mm in width by 6 mm depth at 38 mm spacing) on dense-graded asphalt (White, 2017). Airports monitor surface condition using CFME with self-wetting at defined speeds and offsets (White, 2017). Friction is further assessed through paired macrotexture and spot-friction devices (mean profile depth from a Circular Track Meter, laser profilography, and a Dynamic Friction Tester) (Pullen et al., 2014; Ward et al., 2019). Complementary deceleration-based tools (e.g., calibrated Bowmonk accelerometers) have demonstrated

correlation with CFME and can serve as contingency methods when CFME is unavailable (Ward et al., 2019).

Regulatory Context: AC 150/5320-12C is the primary FAA document governing runway friction evaluation. The document specifies friction survey frequency by traffic volume (Table 3-1: e.g., >210 daily turbojet landings = weekly surveys) and friction level classifications by device and speed (Table 3-2: e.g., Mu Meter minimum 0.42 at 40 mph, 0.26 at 60 mph). Corrective action thresholds state: below Maintenance Planning Level for 1,000+ ft requires extensive evaluation; below Minimum Friction Level for 500 ft with adjacent segments below Maintenance Planning requires immediate corrective action (§3-20). Texture depth thresholds are newly constructed recommended average 0.045 inches (1.14 mm); below 0.030 inches requires correction within one year; below 0.010 inches requires correction within two months (§3-23). Table 2 lists approved CFME devices. All approved CFME operate per ASTM E1960. FAA Order 5100.38D Table M-1e confirms friction measuring equipment is AIP-eligible for Part 139-certificated airports with scheduled turbojet operations.

Key Evidence from Literature:

- An aviation manager at Hartsfield–Jackson Atlanta International Airport emphasized using friction surveys combined with surface texture assessments to define treatment extent and type (Pullen et al., 2014).
- An ERDC program developed deceleration-based contingency runway friction measurement methods to complement CFME, which is identified as expensive, labor-intensive, and requiring multiple technicians. The Bowmonk AFM2 Mk3 decelerometer showed high repeatability and strong linear correlation to the Mk2 GripTester CFME at 25 mph under controlled procedures. Smartphone accelerometer techniques showed high correlation to both the Bowmonk and Mk2 GripTester at 25 mph when mounting and vehicle controls were enforced but exhibited poor reproducibility across manufacturers without strict controls. Recommendations call for further smartphone testing on rubber-contaminated surfaces before adoption as routine friction-change indicators (Ward et al., 2019).
- The NASA-led Joint Winter Runway Friction Measurement Program integrated instrumented aircraft and multiple ground friction devices across airport sites to harmonize measurements and relate ground friction to aircraft stopping performance on contaminated surfaces. The program established the Canadian Runway Friction Index and International Runway Friction Index, subsequently standardized as ASTM E 2100 for winter surfaces (Yager, 1996; Howell et al., 2003; Wambold et al., 2003).
- An explainable machine-learning system using XGBoost was trained on 200,508 landings at Oslo Airport, using weather and runway reports with friction signals estimated from flight data, and identified slippery runway conditions with an ROC

AUC (standard machine learning performance metric) of 0.95 (strong performance) and predicted friction with a mean absolute error (MAE) of 0.0254. The system uses continuously available data, enabling condition assessment without the runway closures required for CFME surveys (Midtfjord et al., 2022).

- Wet or contaminated runways were cited as leading factors in runway excursions, accounting for approximately 40 percent of European overrun accidents and 75 percent globally, with braking distance identified as the prime determinant of landing distance. An empirical–mechanistic model developed from multi-year CFME data at an operational runway linked Grip Number (GN) at restart of traffic after de-rubberizing (GNrestart) to cumulative landing weight (CLWy), enabling separation of recoverable rubber masking from non-recoverable texture consumption and data-driven scheduling of de-rubberizing events (Biancardo et al., 2020).

Stakeholder Perspectives: A participant with direct CFME research experience stated, "we routinely run CFMEs on our runways today." The same participant stated that friction monitoring "is focused towards targeting maintenance limits and safety" but "doesn't really help you understand a lot about your infrastructure," adding that, "we're not seeing a lot of skidding off the runway" given other mitigations like extra runway length requirements. The key research gap is interpretation: "When you measure this number, what does that mean to the user community?" The DOD uses the Grip Tester routinely: "it's small, it's portable … easy to calibrate, easy to run." The same participant added that a smartphone deceleration app performs "as good as the Bowmonk," a free tool versus ~$20,000 equipment. Separately, a panelist noted via post-session correspondence that "there are no specific and clear testing procedures and requirements for asphalt and concrete pavement surface friction during the mix design and construction phases," and that "with the increasing use of non-conventional additives, recycled materials, fibers, and PMA, it is essential to incorporate laboratory testing and requirements into the mix design process for airports," citing the Vancouver airport expansion project where the British Pendulum test had to be specifically requested to evaluate friction impact of fiber in the mix.

Runway Grooving

Runway grooving is the practice of saw-cutting regularly spaced, shallow, transverse channels into runway pavement to provide macrotexture and ensure rapid water escape paths at the tire–pavement interface, maintaining contact and reducing hydroplaning risk during wet conditions (Pasindu & Fwa, 2015). The FAA standard configuration is transverse grooving, square saw-cuts 1/4 inch wide by 1/4 inch deep at 1-1/2 inches center-to-center spacing, perpendicular to the centerline on dense-graded asphalt (White, 2017; Pasindu & Fwa, 2015). An alternative trapezoidal groove, 1/4 inch deep, 1/2 inch top width, 1/4 inch bottom width at 2-1/4 inch spacing, maintains equal cross-sectional area but widens the inlet and reduces wetted perimeter relative to the square groove (Pasindu & Fwa, 2015).

Some airfields have adopted SMA to achieve ≥1 mm macrotexture and compliant wet friction without grooving (Jamieson & White, 2020; White, 2017). Buildup of rubber deposits in pavement grooves will reduce the effectiveness of the grooves and increase the likelihood of hydroplaning. Ultra-high-pressure water "water cutting" has been used to remove rubber accumulation with minimal asphalt erosion and reduced water volume compared with conventional water blasting (White & Rodway, 2014).

Regulatory Context: AC 150/5370-10H Item P-621 provides the complete specification for groove dimensions, spacing, equipment, and orientation. AC 150/5320-12C §2-21 prescribes the FAA standard groove configuration as mandatory text: 1/4 inch (±1/16 inch) depth by 1/4 inch (+1/16 inch, −0 inch) width by 1-1/2 inch (−1/8 inch, +0 inch) center-to-center spacing, with 60 percent or more of grooves not less than 1/4 inch deep, continuous for the entire runway length and transverse to operations. §3-5 triggers corrective action when 40 percent of the grooves are equal to or less than 1/8 inches in depth/width for 1,500 ft. Grooving is also a Congressional priority per 49 USC §47101(f). Order 5100.38D Table G-5b specifies AIP eligibility: stand-alone at commercial service airports; at non-commercial airports, eligibility depends on runway length. Alternative patterns, spacings, or orientations may require an MOS per FAA Order 5300.1G.

Key Evidence from Literature:

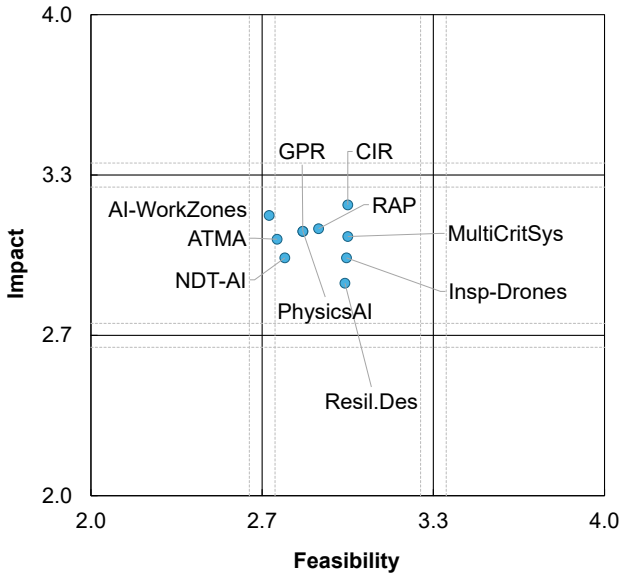
- A study at NAPTF and two in-service runways concluded that trapezoidal-shaped grooves (1/4 inch deep, 1/2 inch wide at top, 1/4 inch wide at bottom, 2-1/4 inch center-to-center) offered improved water dispersion capability, greater resistance to rubber contamination, better groove integrity under heavy loads, and improved longevity, while friction values were comparable to standard grooves (Patterson, 2012).
- Under 10,362 passes at 75,000 lb wheel load, trapezoidal grooves lost 43 percent of height versus 54 percent for standard grooves (Patterson, 2012).
- At Marine Corps Air Facility Quantico, the airport manager reported rubber removal could be delayed by almost nine months with trapezoidal grooves (Patterson, 2012).
- Trapezoidal cutting costs were 15–25 percent higher at both MCAF Quantico and Chicago O'Hare (ORD) airports ($1.50/yd^2 versus ~$1.10/yd^2 at ORD; $1.75/yd^2 versus ~$1.25/yd^2 at MCAF), with the differential expected to decrease with large-scale blade production. The study concluded the trapezoidal groove "should be considered an acceptable option for pavement grooving on airports." (Patterson, 2012)
- On a dense-graded asphalt wearing course with a polymer-modified PG 82-22 binder, skid number improved from 62 pre-grooving to approximately 70 post-grooving and rubber removal. Under rubber accumulation, outflow meter tests showed trapezoidal grooves draining in 15–20 s versus 22–30 s for square grooves (Pasindu & Fwa, 2015).

- An ungrooved SMA runway surface at Emerald Airport delivered CFME friction 18–38 percent higher than dense-graded asphalt (DGA) at 65 and 95 km/hr on Days 1 and 17 of service, and exceeded expected grooved-DGA friction even when a 5–15 percent post-grooving friction increase was assumed for DGA (White & Almutairi, 2022).

Stakeholder Perspectives: One participant stated that "there's a certain amount of grooving that you can't do, because the grooves collapse on normal polymerized type hot mix surface" and that "SMA doesn't groove well. OGFCs don't groove well. But if you can put enough polymer in there, and use HiMA binder like Florida has, you can groove that, and it works really well." The same participant described trapezoidal grooving as "fairly new technology. I don't think we're there yet" and cautioned that "you have to be careful, because if not, the grooves will collapse."

Cell 5: Medium Impact/ Medium Feasibility Technologies

Figure 15 presents the Impact–Feasibility scatter plot for the 10 technologies classified in Cell 5. These technologies offer meaningful performance, safety, or sustainability benefits but face moderate implementation barriers that require additional groundwork before widespread airfield adoption. Technologies in this cell are generally supported by a growing body of roadway or research evidence but face varying combinations of regulatory gaps, limited airfield-scale validation, data interpretation challenges, and institutional or procurement barriers. Dimension scores for each technology are presented in Table 20 and Table 21.



Source: AAPTP

Figure 15. Impact vs. Feasibility Matrix for Technologies Classified as Medium Impact/Medium Feasibility

Table 20. Impact Dimension Scores for Medium Impact/Medium Feasibility Technologies

Technology Name	Performance	ROI	Safety	Efficiency	Sustainability	Impact Score
Reclaimed Asphalt Pavements (RAP)	3	3	3	3	4	3.11
Multi-Criteria Decision Support Tools	4	3	2	3	3	3.08

Technology Name	Performance	ROI	Safety	Efficiency	Sustainability	Impact Score
Physics-Informed AI for Pavement Performance Prediction	3	3	3	4	3	3.10
Resilient Pavement Design	4	2	2	3	3	2.88
Small Unmanned Aircraft Systems (sUAS) for Pavement Inspection	3	3	3	4	2	2.99
Ground-Penetrating Radar (GPR)	3	3	3	4	3	3.10
Machine Learning/AI Methods for NDT Data Interpretation	3	3	3	4	2	2.99
Cold In-Place Recycling (CIR)	3	3	3	4	4	3.21
Autonomous Truck-Mounted Attenuators (ATMA)	3	2	4	3	3	3.07
AI Vision Alerts for Work Zones	3	2	4	4	3	3.17

Table 21. Feasibility Dimension Scores for Medium Impact/Medium Feasibility Technologies

Technology Name	Readiness Level	Technical Issues	Upfront Cost	Regulatory Hurdles	Stakeholder Acceptance	Feasibility Score
Reclaimed Asphalt Pavements (RAP)	3	3	3	2	4	2.89
Multi-Criteria Decision Support Tools	3	3	3	3	3	3.00
Physics-Informed AI for Pavement Performance Prediction	3	2	3	3	3	2.83
Resilient Pavement Design	4	2	2	3	4	2.99
Small Unmanned Aircraft Systems (sUAS) for Pavement Inspection	4	3	3	2	3	3.00

Technology Name	Readiness Level	Technical Issues	Upfront Cost	Regulatory Hurdles	Stakeholder Acceptance	Feasibility Score
Ground-Penetrating Radar (GPR)	3	2	3	3	3	2.83
Machine Learning/AI Methods for NDT Data Interpretation	3	3	3	2	3	2.76
Cold In-Place Recycling (CIR)	3	3	3	3	3	3.00
Autonomous Truck-Mounted Attenuators (ATMA)	4	2	2	3	2	2.73
AI Vision Alerts for Work Zones	3	2	3	3	2	2.69

Reclaimed Asphalt Pavements (RAP)

RAP is asphalt material milled or excavated from existing pavements and reused in new asphalt mixtures, providing both mineral aggregate and aged asphalt binder that partially replace virgin materials (Copeland, 2011). When RAP is incorporated into HMA, the aged binder interacts with the virgin binder such that the blended binder's grade and the mixture's stiffness change with RAP content, affecting rutting and cracking performance and requiring deliberate binder selection, mixture design, and verification testing (Copeland, 2011).

Regulatory Context: P-401 §401-3.4 states that RAP "shall only be used for shoulder surface course mixes and for any intermediate courses," with a note capping the maximum at 30 percent and requiring a one-grade softer binder when RAP exceeds 20 percent. RAP is prohibited on airfield surface courses. On federally funded projects, "due to the variability of recycling materials and methods," the use of recycled materials other than those meeting P-219, may require an MOS in accordance with FAA Order 5300.1G.

Key Evidence from Literature:

- U.S. Air Force and Portugal airfield overlays (8-12 years old) with 35- to 60-percent RAP and rejuvenators showed PCI ratings of 37–80 at inspection, with lower-severity block cracking as the dominant distress and overall performance similar to virgin pavements under the same environment; a 5-year-old California airfield with a 50-percent RAP overlay achieved PCI >75 and TSR = 87 percent, while a 5-year-old

North Dakota airfield with 70 percent RAP achieved PCI >75 but TSR = 25–35 percent, with climate identified as the primary distress driver (Leiva et al., 2018).

- Japan's National Institute for Land and Infrastructure Management reported 70-percent RAP suitable for airport surfaces, with 100-percent RAP plus rejuvenators performing nearly as well as virgin pavements in intensive laboratory testing; an Illinois municipal airfield used a 100-percent RAP unbound base beneath an HMA overlay and reported good condition at five years post-construction. (Leiva et al., 2018; Howard et al., 2009).
- According to NCAT Phase VI track (2015–2017), a surface mixture with 20-percent RAP + 5-percent RAS and a bio-based rejuvenator, paved without silo storage, developed slippage cracking at ~4 months (~1.8 million ESALs); forensic analysis attributed distress to incomplete rejuvenator–binder interaction leaving the virgin binder over-softened. Redesigning to 35-percent RAP-only with reduced rejuvenator dosage and a 2-hr silo hold eliminated prior slippage, with the redesigned section performing satisfactorily through ~7.5 million ESALs with cracking comparable to a 20-percent RAP control (West et al., 2019).
- NCHRP IDEA 236 established that RAP agglomerations ("black rocks") are the principal driver of partial binder contribution; a washed sieve analysis method produced recycled binder availability (RBA) results correlating with measured recycled binder contribution (RBC); availability-adjusted mix design (AAMD) accounts for unavailable binder volume in the aggregate structure; at 50-percent RAP, AAMD-designed mixtures met North Carolina DOT APA acceptance criteria while improving cracking tolerance index compared to current practice designs in laboratory evaluations (Castorena et al., 2024; Castorena et al., 2023).
- A 30-percent RAP overlay reduced energy up to 2.5-percent, GHG up to 2.8 percent, criteria air pollutants up to 13.8 percent, and life cycle costs by 7.8 percent compared to conventional HMA overlay (Lu & Xin, 2018).

Stakeholder Perspectives: Industry participants expressed strong interest in RAP adoption for airports but emphasized critical implementation requirements. One participant noted that RAP for airports "is probably a lot more of a control your source, control your stockpile type of setup than we normally would do," placing it in "a different box" from routine highway use. A contractor highlighted the significant regulatory opportunity: "Are we talking about going higher percentages of RAP than that's allowed for FAA designs, or allowing RAP at all for surface mix designs? Because right now, we're not allowed to use RAP in surface mixes. That could be a huge win." Multiple panelists agreed that combining RAP with BMD would be essential, with one stating: "using RAP in the surface mix and for the FAA to have confidence in that would require combining that with BMD for sure." A panelist familiar with implementation across multiple technologies observed that "RAP makes huge benefits, but you have to understand the drawbacks in

having design to account for that RAP and understanding RAP variability and RAP sourcing and all of the things that go with that."

Multi-Criteria Decision Support Tools

Multi-criteria decision support tools structure decisions by weighting and combining technical, economic, and environmental criteria, often measured in different units, to rank, select, or optimize treatments, materials, and multi-year programs (Bryce et al., 2014). Variants include the Analytic Hierarchy Process (AHP), which decomposes prioritization into goals–criteria–alternatives with pairwise comparisons and a consistency ratio check (Ahmed et al., 2017). Fuzzy AHP augments AHP with fuzzy membership functions and entropy weights to address subjectivity and uncertainty (Vyas et al., 2019). Compromise-ranking via AHP–VIKOR unifies life-cycle economic, environmental, and social dimensions (Zheng et al., 2020). Multi-objective optimization approaches compute Pareto-optimal programs under policy and budget constraints (Lu & Tolliver, 2013). LCCA with discounted cash-flow methods such as NPV provides the economic evaluation component (Gu & Tran, 2019). Airfield-specific indices—PCI, a Structural Condition Index (SCI), and a Foreign Object Debris (FOD) Index—together with FAA's PAVEAIR database distinguish structural needs from functional and FOD-related risks across runway, taxiway, and apron networks (Wang et al., 2019).

Regulatory Context: AC 150/5320-6G §1.3.3 requires LCCA for pavement type selection, using the most recent discount rate for cost-effectiveness analysis (AC 150/5320-6G §1.3.2). LCCA must include sensitivity analysis and may include probabilistic analysis (§1.3.3.4). Order 5100.38D §3-14 requires benefit-cost analysis (BCA) for discretionary capacity projects per 49 USC §47115(d). Order 5100.38D §3-8 establishes three-test project justification: actual need, most cost-effective option, and appropriate timing. 14 CFR §139.401-403 establishes the Safety Management System risk assessment framework, which multi-criteria tools naturally complement. AIP Grant Assurance 11 requires an effective pavement maintenance-management program. Decision support tools may not be subject to MOS per FAA Order 5300.1G, as they do not modify physical design, construction materials, or equipment standards.

Key Evidence from Literature:

- An entropy-based fuzzy AHP with hybrid SWOT mechanisms was demonstrated on an international airport asphalt runway divided into 12, 250-m sections (3.05 km total); the 5 prioritization criteria were pavement thickness (GPR), deflection (HWD), the ACN/PCN ratio as a structural index (backcalculated via Dynatest ELMOD 6), subgrade modulus, and PCI. Eight strategic maintenance and rehabilitation (M&R) policy alternatives were generated via hybrid SWOT mechanisms and ranked against technical feasibility, pavement durability, financial viability, and reliability; the top-ranked alternative prioritized maintenance for increased serviceability and reduced

operating costs, and rankings were stable under sensitivity analysis across different decision-maker optimism levels and confidence intervals (Vyas et al., 2019).

- Using FAA PAVEAIR data across up to 2,095 airport networks, survival analysis and Cox proportional hazard models showed that PCI-based service life was significantly longer than SCI- or FOD-based service life in general, meaning PCI-only trigger rules under-trigger early structural interventions and FOD-driven mitigations. Taxiway/apron interactions reduced SCI–PCI differences, and asphalt pavement surface interactions reversed the PCI–FOD comparison, implying surface- and branch-conditioned trigger rules are needed (Wang et al., 2019).
- A TxDOT web-based pavement management plan (PMP) tool converts Condition Score, Distress Score, Ride Score, traffic, and other factors to utilities, applies survey-elicited weights, and computes a composite priority index. The tool iterates performance projections, benefit calculations, life-cycle cost, and incremental benefit–cost analysis across a 4-year horizon to produce annual M&R programs and network dashboards (Gharaibeh et al., 2014).

Stakeholder Perspectives: One participant described the concept as "more of like a utility analysis" and confirmed direct experience: "I have been involved in some of the multi-criteria, using multi-criteria, if this is more like a utility analysis. And so I definitely think that's feasible." The same participant explained the approach as one "where you have weighting factors… various weighted indices for different parameters, like a group of safety factors, a group of economic factors, a group of performance factors… and you add them all up and see which one has the highest utility," noting use in Canadian projects to "provide a basis of backup on why decisions get made."

Physics-Informed AI for Pavement Performance Prediction

Physics-informed AI integrates mechanistic knowledge with machine learning by adding physics-based constraints to a model's loss function so predictions remain consistent with governing relationships while fitting observed data (Mondal & Chen, 2022; Pasupunuri et al., 2024). A physics-informed neural network (PINN) augments the data-fidelity loss with a physics-based term derived from mechanistic or mechanistic–empirical relationships (Pasupunuri et al., 2024).

Regulatory Context: AC 150/5320-6G §3.2 establishes FAARFIELD as mandatory for structural design of federally funded projects. FAARFIELD uses calibrated M-E failure models based on NAPTF full-scale test data; integration with FAARFIELD may require FAA internal approval and software development cycles.

Key Evidence from Literature:

- A PINN for jointed plain concrete pavement roughness was trained on 920 LTPP observations from 10 U.S. States and 48 sections using a combined loss function,

where the physics term applied a Huber penalty against the MEPDG IRI equation. After hyperparameter tuning, the model achieved testing MAE = 0.134 m/km and R^2 = 0.90 on the test set, with sensitivity analysis confirming physically consistent behavior (transverse cracking, spalling, patching, and faulting each produced higher predicted IRI, with initial IRI and transverse cracking exhibiting the largest rates of increase) (Pasupunuri et al., 2024).

- A PINN constrained by a fuzzy partial differential equation and a fatigue-cracking consistency term, with coefficients tuned via particle swarm optimization, was trained on nine years of highway data (2010–2018) from a 73 km, 12-lane section and tested on a held-out 2019 dataset; evaluated against backpropagation neural network (BPNN) and XGBoost on cross-direction and cross-year tests, the PINN achieved average R^2 improvements of +11.4 percent versus XGBoost and +20.9 percent versus BPNN, with MAE reductions of 4.1 percent and 13.1 percent respectively (Li et al., 2025).
- A PINN was developed to estimate the damage characteristic (C–S) curve relating pseudo-stiffness C to damage state S, and to predict fatigue life from limited pre-fatigue data. In a case study using asphalt mixture specimens tested at multiple temperatures, frequencies, and strain levels with three replicates per condition (18 loading conditions total), PINN-Asphalt Fatigue Prediction reported an average fatigue life prediction error of 5.2 percent across all 18 conditions and outperformed deep learning and statistical comparators on the test set (Han et al., 2024).
- A hybrid PINN solving transient one-dimensional heat conduction was formulated for multi-layer asphalt pavement temperature prediction, with interface continuity enforced via subdomain decomposition and a multi-output network enabling prediction at any depth and inversion of unknown boundary parameters from sparse embedded temperature observations. Validated against FEM benchmark temperature fields, the PINN achieved close agreement and optimal accuracy under a recommended architecture. With recommended loss weights (summer and winter configurations) and one fused observed data point, generalization performance was reported as $R^2 > 0.957$ across all depths (Quan et al., 2025).
- A deep learning surrogate model (ContactNet) was developed to predict three-dimensional tire–pavement contact stresses as a computationally efficient alternative to FE simulations. The model provided quick estimation of 3D contact stress distributions with low average errors in maximum stresses and contact area compared with FE ground-truth (Liu & Al-Qadi, 2021).
- A review of machine learning applications in road pavement management identified data quality, model interpretability, lack of standardized datasets, non-transparent pipelines, and limited independent validation as persistent barriers to adoption. Many implementations lack open code and data and full methodological detail, hindering replication. Results with lower accuracy but higher interpretability are

frequently preferred for agency decision-making, and explainable AI methods were recommended to increase acceptance (Tamagusko et al., 2024).

Stakeholder Perspectives: Participants held divided views on physics-informed AI. One participant stated that "advancing AI and leveraging AI capabilities government-wide is still a huge priority." Two panelists concurred, but another disagreed, citing poor experience with neural network outputs: "once you start getting close to your boundaries…you start getting these really weird results or unpractical results." Participants also noted that the emphasis should be "more on physics informed and kind of mechanistic part rather than whatever AI data analytics tool," and that the technology could "leapfrog over ME into something that's much more robust and able to be analyzed and used more commonly with less people, resources, staffing."

Resilient Pavement Design

Resilient pavement design frameworks integrate projected climate stressors (temperature, moisture, freeze–thaw, and extreme-event regimes) into materials selection, structural design, drainage, and life-cycle management so that pavements maintain performance under changing conditions (Qiao et al., 2020). Flexible pavements are climate-sensitive, meaning that temperature increases reduce asphalt stiffness and load-spreading capacity, which increases permanent deformation. Moisture increases result in a decrease of resilient modulus and shear strength of unbound layers at high saturation (Qiao et al., 2020). Resilient design measures include using stiffer PG binders for projected higher temperatures, inspectable drainage with reassessed culvert capacities, and fully permeable pavement systems designed with structural–hydraulic methods and drawdown criteria (Sias et al., 2025; Nemry & Demirel, 2012; Dawson, 2014; Jones et al., 2010).

Regulatory Context: P-401 includes a grade bumping mechanism per ASTM D6373 using a grade bumping table in §401-2.3, with grades available up to PG 82+. However, the bumping mechanism is calibrated to aircraft loading, not projected climate temperatures. FAARFIELD assigns a fixed modulus of 200,000 psi (surface) or 400,000 psi (base) regardless of binder grade, so stiffer binders receive no structural design credit. Specifying beyond the grade bumping table may require engineering justification and potentially MOS per Order 5300.1G. AC 150/5300-13B §6.3 requires airfield drainage systems and cross-references AC 150/5320-5 for design guidance. §6.3.2 mandates sub-drain systems to "preserve and prolong pavement performance." Permeable base course items exist: P-307 (CTPB, standard in 10H) and P-407 (asphalt treated permeable base). AC 150/5320-6G §3.12.14 requires designers to "consider the environmental conditions affecting the pavement during its construction and service life."

Key Evidence from Literature:

- AASHTOWare Pavement ME simulations across five U.S. locations using CMIP5 temperature-only projections showed 9–45-percent increases in asphalt rutting and 5–34-percent increases in total rutting at 20 years, while fatigue cracking increased by only 2–11 percent, indicating permanent deformation is the dominant climate-sensitive distress mode; a separate study using county-specific climate files versus interpolated MEPDG station files produced statistically significant differences in predicted asphalt pavement rutting, total rutting, transverse cracking, and IRI, confirming that climate input resolution materially alters ME design outputs (Gudipudi et al., 2017; Breakah et al., 2011).
- A Pavement Climate Sensitivity Catalog evaluating 70 combinations of temperature rise (0–5 °C) and groundwater rise (0–700 mm) for four gravel base thicknesses found that the required HMA thickness to maintain 85-percent reliability increased from 140 mm to 205 mm (+46 percent) at +5 °C for the 406 mm base, and required base thickness rose from 432 mm to 623 mm between 0 °C and +5 °C with steep increases above +3.5 °C (Knott et al., 2019).
- In a pavement LCA case study on a 26-km stretch of interstate highway near Boston using projections from 21 Global Climate Models under Representative Concentration Pathway 8.5 (RCP 8.5, the highest CMIP5 greenhouse gas concentration scenario), incorporating future climate projections into AASHTOWare Pavement ME instead of historical climate data increased M&R frequency from 4 to 6 mill-and-overlay cycles over the analysis period, increased agency NPV costs by 29.7 percent for the do-nothing-reconstruct alternative, while user operational costs decreased by approximately 2 percent, attributed to the pavement being restored to a smoother surface more frequently under the accelerated deterioration scenario (Haslett et al., 2021).

Stakeholder Perspectives: Participants expressed varying views. One participant noted that “resilience is still an okay word for us to use as an agency” and that the agency has ongoing resiliency efforts, but cautioned that feasibility “is going to really depend a lot about…the politics around things and the data you need in order to more accurately forecast into the future.” Another participant noted potential long-term value: “I think it would have a very beneficial impact down the road,” but rated feasibility as low to moderate because “I’m not sure the data is there yet from an airfield standpoint.” A third participant expressed skepticism: “if you really look at the life of the pavement…you’re not going to see such dramatic changes in temperature over the life of the pavement.”

Small Unmanned Aircraft Systems (sUAS) for Pavement Inspection

Drone-based pavement inspection uses small, unmanned aircraft systems (sUAS) to collect high-resolution RGB imagery, digital elevation models (DEMs), and stereo thermal

imagery for airport PMP inspections on runways, taxiways, and aprons consistent with PCI procedures under ASTM D5340 (Sourav et al., 2023). Mission planning uses close-range photogrammetry with forward and side overlap and surveyed ground control points (GCPs); georeferenced orthomosaics and DEMs are analyzed in GIS to identify and rate distresses per ASTM D5340 (Sourav et al., 2023). FAA-sponsored multi-airport research defined minimum specifications for platforms, sensors, data products, and processing workflows (Sourav et al., 2023).

Regulatory Context: Current standard practice relies on ground-based visual PCI surveys (ASTM D5340), FWD/HWD for structural evaluation (AC 150/5370-11B), and vehicle-mounted CFME for friction (AC 150/5200-30D). The use of drones does not yet exist as standard practice; however, the FAA Letter to Airport Sponsors explicitly names "Pavement Inspection" as a UAS research application and states that sUAS "cannot be used as a sole means of compliance with federal regulations and requirements and must be supplemented by traditional methods" until guidance is formalized. 14 CFR Part 107 governs sUAS operations: §107.12 requires a Part 107 remote pilot certificate, §107.31 requires visual line of sight (VLOS), §107.41 requires air traffic control authorization in controlled airspace, and §107.43 prohibits interference with airport operations. §107.200/205 provides a waiver pathway for these constraints. FAA Order JO 7200.23D §2-6 requires DroneZone submission (Low Altitude Authorization and Notification Capability cannot be used for on-airport operations), Air Traffic Manager coordination, and airport authority approval; §3-3 provides a multi-day authorization framework for pre-defined projects with set time frames; and §5-1 addresses beyond visual line of sight (BVLOS) waivers. The order also includes a mandatory High-Intensity Radiated Fields (HIRF) provision requiring operators to ensure sUAS can operate within the high-intensity radiated fields produced by airport radar, Instrument Landing System, and other systems, and to immediately terminate operations upon any indication of interference. AC 150/5300-13B §2.10.7 identifies UAS as "Emerging Entrants into the National Airspace System" and states: "The effect emerging entrant systems have on airport design will evolve over time. Stay current with technology advancements to understand impacts to airport design." It directs users to https://www.faa.gov/uas/ or the appropriate FAA Regional or ADO.

Key Evidence from Literature:

- Based on field deployments at six U.S. general aviation airports (ONZ, BNW, PRO, MTO, WWD, TTF), the recommended minimum sUAS image resolutions are 1.5 mm/pixel for RGB orthophotos, 6 mm/pixel for DEMs, and 30 mm/pixel or finer for thermal orthophotos; RGB orthophotos at 3.3 mm/pixel or better detected 13 of 14 PCC distress types and 6 of 9 asphalt pavement distress types observed at those sites, with DEMs primarily confirming elevation-change distresses (faulting, shoving, depression) and high severity distresses and stereo thermal emphasizing

crack-based features including cracks beneath pavement markings (Sourav et al., 2023; Sourav et al., 2022).

- Low-severity joint seal damage was unidentifiable in image-based interpretation; low-severity alkali–silica reaction, low-severity swell, and all-severity weathering/raveling showed no consistent detectable traits even in the highest-resolution imagery produced (Sourav et al., 2023).
- In a separate study across five airports (WWD, SAV, CVG, ONZ, TTF), three GSD thresholds were established: 2 mm GSD preferred for full PCI analysis; 3 mm GSD acceptable with minor caveats for global distresses and potential misses of some low-severity longitudinal and transverse cracking; and 4 mm GSD not acceptable for consistently identifying low-severity distresses; at 2 mm GSD, sUAS orthomosaics were judged better quality than digital survey vehicle imagery for distress interpretation (Valecha et al., 2023).
- sUAS cost per square yard ($0.10–$0.25) was comparable to a digital survey vehicle ($0.10–$0.25), with foot-on-ground (FOG) inspection at $0.08–$0.15 (Valecha et al., 2023).
- sUAS operations in the six-airport study operated under 14 CFR Part 107 with a minimum two-person crew plus a third for GCPs; non-data tasks were conducted outside the Runway Safety Area with stand-offs of 76.2 m from the runway centerline and 304.8 m from runway ends; NOTAM advisories were issued and Unicom radio monitored throughout; for WWD Runway 10/28 (~5,000 ft × 150 ft), estimated multirotor capture times were 2.25 hr at 2 mm GSD, 1.25 hr at 3 mm GSD, and 0.75 hr at 4 mm GSD (40/40 overlap, excluding battery changes and overhead), and processing 2,000–3,000 images at 45.7 MP typically required a minimum of two days on a single computer (Valecha et al., 2023; Sourav et al., 2022; Sourav et al., 2023).
- At Fitchburg Municipal Airport (FMA), a U-Net model trained on a hybrid dataset combining the public CRACK500 road-crack dataset with annotated runway tiles performed well on test images and outperformed a state-of-the-art model on CRACK500; crack details became difficult to see above approximately 120 ft Above Ground Level (AGL) with the test camera, and the study selected 50 ft AGL as the practical balance; approximately 2 passes versus approximately 10 passes at 10 ft AGL for a 150-ft-wide runway (Jiang et al., n.d.).
- A transportation literature review noted that UAS deployment benefits are sometimes oversimplified in publications, and that without public acceptance, large-scale UAS deployment will be slower; the review concluded that airspace regulatory constraints and battery limitations represent the primary barriers to wide-scale deployment (Outay et al., 2020).

Stakeholder Perspectives: Participants noted sUAS inspection is highly impactful but flagged feasibility concerns. One panelist observed that elevation model control “just isn’t

quite there in a lot of cases" and stressed the need for PPK-corrected positioning to achieve centimeter-level accuracy. Another panelist noted that "if there is an airport, we have to get clearance, that takes time," identifying airspace authorization as an operational bottleneck. Panelists emphasized multi-sensor fusion, combining drones, vehicle-mounted systems, smartphones, and potentially satellite imagery, for stronger interpretation reliability rather than relying on a single platform. One participant stated that current vehicle-mounted systems serve as "ground truth values right now just for comparison with the drone data."

Ground-Penetrating Radar (GPR)

GPR is a nondestructive testing (NDT) method that transmits short, high-frequency electromagnetic waves into pavements and records reflections at interfaces where dielectric properties change, allowing inference of subsurface structure and features in layered systems such as asphalt, base, and subgrade (Cheng et al., 2021). A single waveform is an A-scan; sequential A-scans along a survey path compose a B-scan; adjacent B-scans can be combined into a C-scan volume (Wang et al., 2022; Küçükdemirci & Sarris, 2022). Three-dimensional (3D) GPR systems use multi-channel antenna arrays with dense transverse spacing and high A-scan rates to achieve traffic-speed, lane-width coverage in roadway surveys (Liu et al., 2021). Field deployments commonly use multiple operating frequencies (e.g., 900 MHz (two orientations), 400 MHz, and 270 MHz) to balance depth and resolution (Cheng et al., 2021).

Regulatory Context: AC 150/5320-6G Appendix C (§C.4.1.3) directly references GPR as supplementary nondeflection NDT equipment for pavement evaluation (measuring layer thicknesses, detecting voids and excess water, locating utilities, and investigating delamination). AC 150/5370-11B also references GPR in its main body (§9b(1), §9, §37, Table 20, §42d) for the same purposes and identifies GPR as a common input source for existing layer thicknesses in FAARFIELD analysis. GPR equipment availability in the United States is governed by 47 CFR §15.509 (Subpart F, Ultra-Wideband Operation), which requires that "radiated emissions at or below 960 MHz…shall not exceed the emission levels in §15.209."

Key Evidence from Literature:

- In four field demonstrations across AASHTO Regions 1–4 (Texas, Florida, Minnesota, Maine), air-coupled GPR systems operating at 1 GHz and 2.2 GHz collected full-coverage dielectric profiles of newly compacted HMA overlays; after project-specific calibration to field cores using a logarithmic dielectric-to-air-void regression, both systems produced nearly identical geospatial AV maps at nearly 100-percent mat coverage, with the Region 2 (Florida) demonstration showing a statistically significant correlation between GPR-measured surface dielectric and laboratory core AV, and correctly identifying spatially coincident zones of elevated

AV (>12 percent) at locations where IR thermal differentials of 60–90 °F had been recorded during placement (Sebesta et al., 2012).

- GPR B-scan image processing for asphalt surface thickness achieved a mean relative error of 3.82 percent against 20 cores using a 1.6 GHz antenna, with forward simulations across 15 stratified road models showing mean relative errors of 4.23–5.53 percent (Wang et al., 2022).
- Shallow HMA layers typically 3–10 cm fall below the nominal vertical resolution for 1,000–2,000 MHz systems, requiring deconvolution that introduces artifact risk without expert parameterization (Bianchini Ciampoli et al., 2019).
- Operational constraints include the inability to perform GPR on wet pavements, the presence of slag or other additives that may affect dielectric values, the influence of underlying old asphalt in remix pavements, and reduced reliability for very thin asphalt layers (<30 mm) (Sebesta et al., 2012).
- A study integrating GPR and surface 3D imaging for concrete patch detection found that "inverted-T" patches were not discriminable in GPR alone at tested configurations due to low signal-to-noise ratio and detection geometry; deep-learning imaging-only trials were reported as inconclusive due to limited training data, and GPR patch tables exhibited high false-alarm rates requiring IRI-based filtering before usable results could be obtained (Cheng et al., 2021).
- A vehicle-mounted GPR with GPS georeferencing scanned 570 miles of critical state routes at 45–65 mph without traffic controls using a 2 GHz horn antenna and 400 MHz ground-coupled antenna; a semi-empirical dielectric-to-density model showed overall error less than 11 percent at most surveyed stations, with accuracy greater for low-moisture soils, and GPR-derived density trends along a one-mile I-75 section agreed with FWD-backcalculated subgrade modulus trends after accounting for boundary conditions (Kim et al., 2021).

Stakeholder Perspectives: One panelist described GPR as common practice applicable to airports but cautioned that "the challenge on the GPR is the interpretation of the data that you're collecting. Not many people have that knowledge." Another noted these technologies have been pushed "for quite some time" and rated them high-impact, adding that adoption "relates back to the specifiers, allowing them and acceptance of them." Panelists highlighted that paving-integrated technologies "could cut the need for doing cores." One participant distinguished GPR from dielectric profiling, noting that GPR targets "the underground structures, fixtures, conduits, electrical," while dielectric profiling addresses surface layers. The evolution to 3D GPR was noted as expanding coverage from a single scan line to a wider area. Panelists also observed that AI may address the interpretation bottleneck.

Machine Learning/AI Methods for NDT Data Interpretation

Machine learning (ML) and deep learning (DL) methods are applied to NDT data, primarily GPR, to automate identification, localization, and quantification of pavement distresses (Zhang et al., 2020). GPR transmits high-frequency electromagnetic waves into pavement and analyzes reflections from interfaces with differing dielectric properties, producing A-scan (single trace), B-scan (stacked traces), and C-scan (time/depth slices) (Wang et al. 2022, Küçükdemirci & Sarris, 2022). DL architectures applied to GPR B-scans include Faster R-CNN, YOLO variants, and Mask R-CNN for subsurface anomaly detection, while signal-domain networks classify waveforms and regress defect location/size (Gao et al., 2020; Tong et al., 2020).

Regulatory Context: AC 150/5320-6G Appendix C (§C.4.1.3) directly references GPR as supplementary nondeflection NDT equipment for pavement evaluation (measuring layer thicknesses, detecting voids and excess water, locating utilities, and investigating delamination). AC 150/5370-11B also references GPR in its main body (§9b(1), §9, §37, Table 20, §42d) for the same purposes and identifies GPR as a common input source for existing layer thicknesses in FAARFIELD analysis. GPR equipment availability in the United States is governed by 47 CFR §15.509 (Subpart F, Ultra-Wideband Operation), which requires that "radiated emissions at or below 960 MHz…shall not exceed the emission levels in §15.209." AC 150/5370-11B Tables 15–16 list conventional iterative backcalculation programs for deflection analysis: BAKFAA, MODULUS, BISDEF, CHEVDEF, ELSDEF, and others (AC 150/5370-11B). There is no reference to AI, ML, or automated interpretation methods in AC 150/5370-11B or any other FAA NDT guidance document.

Key Evidence from Literature:

- MV-GPRNet, a two-stage multi-view network fusing C-scan and top-scan GPR features, reported F1 scores of 91 percent for voids, 69 percent for cracks, 90 percent for subsidences, and 100 percent for pipes on 6,199 runway samples; GPR-RCNN, a one-stage B-scan detector on the same runway context, returned F1 scores of 62 percent for voids, 33 percent for cracks, 81 percent for subsidences, and 87 percent for pipes on 5,300 B-scans, with the crack F1 gap between the two models (69 percent versus 33 percent) indicating that multi-view fusion is critical for crack discrimination on runway GPR data (Liu et al., 2024).
- Laboratory slab experiments at 2 GHz established a ~5 mm resolution limit for confident crack detection, with cracks of 1.1–1.3 mm width remaining undetectable after SVD plus median filtering in a 3.5 m experimental section; water-filled cracks produced more accentuated responses than air-filled cracks; separately, finite-difference time-domain simulations and field testing identified a 1.2–2.0 GHz window as suitable for vertical crack imaging (maximum clarity near 1.6 GHz) with scanning direction required to be perpendicular to crack orientation for pronounced

reflections — and across a four-highway Faster R-ConvNet study, detection IoU dropped from 88.10 percent at 900 MHz to 84.35 percent at 300 MHz (Automated Detection of Cracks in Roads using GPR—Univ. of Birmingham; Liu et al., 2023; Gao et al., 2020).

- Multiple DL models applied to GPR images have demonstrated consistently strong automated distress detection across architectures, including Faster R-ConvNet (89.13-percent precision, 86.24-percent IoU across four highways at 300–900 MHz; ~0.03 s per image at 20–25 m/s) (Gao et al., 2020), CNN+YOLO v2 (F1 = 91.97 percent for moisture damage on 16 bridge-deck asphalt sections at 2.3 GHz) (Zhang et al., 2020), YOLOv5 variants (mAP up to 94.45 percent) (Liu et al., 2021), YOLOv3-ResNet50vd-DCN (96.2-percent F1 after Bayesian optimization) (Liu et al., 2022), and a Network-in-Network model (85.17-percent accuracy across 27,820 m of highway without specialist EM interpretation) (Tong et al., 2020), with real-time inference demonstrated at 12–16 fps.
- An improved Mask R-CNN achieved pixel-level vertical crack segmentation with 0.833 precision, 0.822 F1, 0.701 mIoU, and 4.2 FPS on 1024×1024 GPR images, with a mean crack width estimation error of 2.33 percent on a 3.5 km road section at 1.6 GHz, extending capability from binary detection to a more quantitative crack characterization (Liu et al., 2023).

Stakeholder Perspectives: Participants recognized the high-impact potential of AI/ML for crack identification and moisture detection in NDT data. However, skepticism was also prominent: one experienced participant described ML methods as “pie in the sky stuff” and noted he was “very leery” given early-stage development. Another panelist countered that explainable AI tools (e.g., SHAP, counterfactual analysis) and confidence scoring are reducing the black-box concern: “now, there is something called explainable AI, which is actually coming up where you can try to make sense out of what these black boxes are spitting out.” That panelist concluded: “It’s definitely in the near future we’ll be using them widespread.” A third panelist observed that AI development “areas are moving quite faster than we may want to acknowledge.”

Cold In-Place Recycling (CIR)

CIR is an in-situ asphalt pavement rehabilitation process that mills a portion of the existing asphalt layers, blends RAP with a stabilizing agent, asphalt emulsion (CIR-E) or foamed asphalt (CIR-F), places and compacts the recycled mixture on grade, and protects the recycled layer with an HMA overlay (Sebaaly et al., 2018; Diefenderfer & Apeagyei, 2014). Construction uses a continuous “train” integrating milling, sizing, mixing with recycling agents and active fillers (e.g., cement, lime), laydown, and compaction in a single pass without heating the recycled mass (Diefenderfer et al., 2012). Typical treatment depths are 2–5 inches (Sebaaly et al., 2018). An HMA overlay is standard practice because cold recycled mixtures have higher AV contents and require a surface course for raveling

resistance and moisture protection (Sebaaly et al., 2018). A central-plant variant (CCPR) hauls cold-recycled mix from a mobile plant for conventional paver placement (Diefenderfer & Apeagyei, 2014).

Regulatory Context: CIR is not a defined specification item in AC 150/5370-10H. P-207 covers FDR but not CIR. AC 150/5320-6G §4.1.1 states that recycled materials other than P-219 require an MOS "due to variability of recycling materials and methods." FAA Order 5300.1G requires approval for new construction methods with no previous MOS approval, and the airport's request must certify that "the finished product will perform for its intended design life, based on historical data." In FAARFIELD, a CIR layer would need to be modeled as a User Defined layer (as FDR is per AC 150/5320-6G §4.11.2.1.3). According to Order 5100.38D §3-26, State highway specifications may be used at nonprimary airports, and some State DOTs have established CIR specifications.

Key Evidence from Literature:

- Cold recycling with an overlay can reduce project cost by 40–60 percent compared to conventional mill-and-fill; Alabama CIR and CCPR cases showed 56- to 64-percent lower energy use and 39- to 46-percent lower GHG emissions versus new asphalt pavements (Hand & Aschenbrener, 2023).
- CIR production is typically about 18–20 ft/min, enabling a little more than one lane-mile per day; newer equipment has achieved up to about 3 lane-miles per day; across CIR-foam, CIR-emulsion, CCPR-foam, and CCPR-emulsion case studies, reduced net present costs of 12–32 percent, energy reductions of 56–67 percent, and GHG reductions of 39–46 percent were documented relative to conventional practices; a 7-mile corridor documented approximately $5 million savings in material production and construction (Bowers et al., 2023).
- On I-81 in Virginia, foamed-asphalt CIR with average layer thicknesses of AC 4.0 inches, CIR 5.0 inches, existing asphalt pavement 4.3 inches, and aggregate base 6.3 inches yielded a backcalculated structural layer coefficient of approximately 0.39 using FWD and GPR data under AASHTO 1993 empirical assumptions; rut depths were under 0.1 inches (left lane) and under 0.05 inches (right lane) after 34 months and approximately 6 million ESALs; TSR values were 79.1 percent for the CIR section and 70.2 percent for the CCPR section; across 24 recycled projects, dynamic modulus master-curve envelopes for CIR and CCPR overlapped with no statistically significant difference between foamed and emulsified stabilization, while chemical additives generally increased stiffness and reduced temperature dependency (Diefenderfer & Apeagyei, 2014; Diefenderfer et al., 2015; Diefenderfer et al., 2016).
- Field-produced, field-cured cores from 27 projects (15 CIR, 3 CCPR, 6 FDR) across the United States and Canada were tested for |E*| and repeated load permanent deformation; approximately 30 percent of Pavement ME analysis cases exhibited

poor predicted rutting, concentrated in thin surface-wearing-course scenarios, while increasing HMA surface thickness to 3–4 inches reduced rutting and aligned performance toward HMA inlay references; AASHTO TP 79 acceptable COV limits do not reflect variation typical of recycled materials (Schwartz et al., 2017).

- Approximately 100 Iowa CIR sections showed reductions in transverse, longitudinal, and fatigue cracking and improved IRI after rehabilitation; sections with 4 inches CIR retained lower IRI values longer than 3 inches CIR, with the difference especially evident after 12 years (Buss et al., 2016).

Stakeholder Perspectives: Participants expressed mixed views on CIR's airport applicability. One practitioner stated: "The thing to realize about cold-in-place recycling is that it is a base product, it is not a hot mix or a cold mix or warm mix asphalt product. It is a modified base product, and when it's treated as such, it works very well." Another noted field variability: "We had some issues with moisture and the road quality, it just didn't go very well on that specific project." Participants were generally cautious about runway use; one stated: "I don't think cold in place recycling, unless you're going to do like a taxiway or something like that, I don't think the airports are going to look to do much of that out on their runways, unless you put a substantial overlay on that." Another echoed: "I'm a little more hesitant on saying, oh, CIR is great for an airport, but I mean, again, it's about finding that group that can do it and perform it well." A recurring theme was that CIR failures during construction signal underlying distresses, one panelist noted that "when a section of the pavement fails during the cold in place recycling, that's a signal that there is other distresses on the project that need to be repaired."

Autonomous Truck-Mounted Attenuators (ATMA)

Autonomous truck-mounted attenuators (ATMA), also called autonomous impact protection vehicles (AIPV), use a leader–follower architecture in which a human-operated leader vehicle performs the maintenance task while an unmanned follower vehicle equipped with a truck-mounted attenuator replicates the leader's path at a commanded gap (Kohls, 2020). The leader transmits sequential "e-crumbs" encoding position, speed, and heading over a Vehicle-to-Vehicle (V2V) link; the follower uses these data plus by-wire actuation of steering, throttle, and braking to maintain the prescribed spacing (Kohls, 2020). Primary navigation relies on GPS with an Inertial Navigation System (INS) as short-duration backup; if GPS is not re-acquired within a specified duration, the system executes an Automatic Stop (A-Stop) (Kohls, 2020). Separate Emergency Stop (E-Stop) controls halt the follower and shut down its engine (Kohls, 2020). Obstacle detection uses LiDAR and radar within a "safety zone" between the vehicles (White et al., 2021).

Regulatory Context: Work zone safety is governed by AC 150/5370-10H Section 70-08 (CSPP) and AC 150/5370-2G (Operational Safety During Construction). 14 CFR §139.329 requires driver training and two-way radio communication (or escort) for all vehicles

operating on the AOA—an autonomous vehicle has no "driver" to train under §139.329 and may need to demonstrate equivalent communication capability. ATMA/AIPV may trigger operational safety requirements under 14 CFR §139.329, AC 150/5370-2G (including vehicle identification, OFZ/safety area restrictions, and the "least danger to aircraft" equipment standard), and §139.341(a) (marking/lighting of construction equipment that may affect safe aircraft movement).

Key Evidence from Literature:

- A survey of 13 DOT workers from Colorado and California with direct ATMA exposure reported overall positive acceptance; workers regarded ATMA as an improvement over human-driven TMA for safety and reliability; reported confidence that ATMA can reliably stop if a person walks in front averaged 7.1/10. Higher-experience workers reported a higher perceived safe maximum operating speed (mean 19.1 mph) than lower-experience workers (mean 9.2 mph). (Pourfalatoun & Miller, 2021)
- In multi-State DOT worker surveys (n = 13, CDOT/Caltrans), overall acceptance was positive and respondents regarded ATMA as an improvement over manned TMA for safety and reliability, with confidence that the system can reliably stop if a person walks in front averaging 7.1/10, though confidence decreased markedly under poor visibility, heavy rain, snow, and dense traffic (Hu & Tang, 2020; Pourfalatoun & Miller, 2021).
- Indiana open-road deployments (sweeping, raised pavement marker inspection, underdrain inspection) recorded normal operating states on average 96.62 percent of deployment time (std: 3.34 percent), but GPS loss under an overpass caused an error despite an expected 30-second tolerance, and operation below approximately 4 mph (relevant to slow pavement maintenance tasks such as crack sealing) was documented as unsuitable, with the follower entering a stop state even with large actual gaps (Tian et al., 2024).
- Object detection tests showed 100-percent stopping success for lane-center obstacles at 5 and 15 mph, dropping to 33 percent at 25 mph as the follower "overdrove" the available LiDAR range; the recommendation was to limit operations to approximately 15 mph unless the LiDAR is upgraded (Talledo Vilela et al., 2023).
- Florida's BCA using vendor-suggested inputs (technology procurement $250,000, deployment $40,000, yearly maintenance $1,000) over a 5-year life with N = 50 TMA vehicles, returned a BCR of 0.9257; Indiana independently concluded BCR < 1.0 under current technology costs and local crash statistics, and recommended exploring rentals or awaiting future cost reductions; Missouri's autonomous mobile robot pilot returned a BCR of 0.83, noting potential improvement as costs decrease through economies of scale (Agarwal et al., 2021; Tian et al., 2024; Brown et al., 2023).

Stakeholder Perspectives: One participant stated: "I've been around a few of the autonomous trucks. North Dakota actually tested out one of these, the DOT, and they do work fairly well. There's some trust building with having something follow you around in a live construction site." The same panelist emphasized the core safety rationale: "That person in that truck is obviously going to take the brunt of any accident, and if we can eliminate that person from being in it, I think that's a huge safety goal." Another participant noted: "I have not seen the autonomous attenuators, but that sounds like it would be worth it as far as a try… I'm all for anything that increases the safety around the work zones." A third panelist remarked: "Truck-mounted attenuators, autonomous, sounds amazing. But I haven't seen that one."

AI Vision Alerts for Work Zones

AI Vision Alerts for pavement work zones are camera- and software-based systems that use AI to detect safety-relevant objects and events in live video and trigger graded notifications to improve situational awareness for crews and operators (Christopher et al., 2024; Utah Department of Transportation, 2025; Yang et al., 2018; Raddaoui et al., 2020). One framework integrates real-time computer vision with an augmented reality (AR) interface delivered to smart glasses that delivers visual, auditory, and vibratory cues (Sabeti et al., 2021). Other frameworks include edge-AI object detection (YOLOv4 on embedded hardware), camera-stream anomaly detection using variational autoencoders, vision–language model evaluations for contextual defect assessment, and multi-camera conflict analytics using surrogate measures of safety (Sabeti et al., 2021; Christopher et al., 2024; Mashhadi, et al., 2025; Ahmed et al., 2023; Yang et al., 2018).

Regulatory Context: Work zone safety monitoring is currently visual and manual per AC 150/5370-2G, which states: "The airport operator and contractor should conduct onsite safety inspections throughout the project and immediately remedy any deficiencies, whether caused by negligence, oversight, or project scope change." 14 CFR §139.327 requires daily airport self-inspections, including when unusual conditions such as construction activities may affect safe operations. AC 150/5370-10H Section 70-06 requires contractor compliance with applicable federal, state, and local health and safety regulations, placing primary worker safety jurisdiction under OSHA (29 CFR 1926). Cameras placed on the AOA must not interfere with aircraft operations, lighting, or visual aids; siting may require coordination with airport security and operations.

Key Evidence from Literature:

- A pilot (AdViSE system) installed four cameras with night vision and two rear radar sensors on a State DOT dump truck and mapped 360-degree zones of visibility and detection on a 20- by 20-ft test grid under daylight and low-light conditions, with color-coded escalating proximity alerts and an automatic reverse-triggered display; a residual 2-ft blind spot remained immediately behind the truck despite full

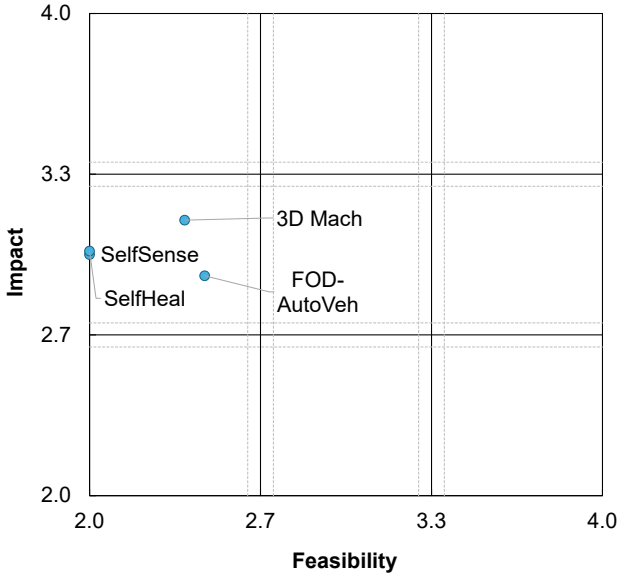
instrumentation, and low-light testing required supplemental lighting; per-truck system costs approximately $3,224 (2 cameras only), $6,148 (2 cameras plus 2 radars), and $7,432 (4 cameras plus 2 radars), and estimated benefit–cost payback periods of 2.79, 5.31, and 6.43 years respectively under assumptions of 50-percent accident reduction and 50-percent fleet penetration (Wei et al., 2021).

- A real-time smart video surveillance system deployed across more than 240 cameras on the Wuhan Rail Transit mega-project used a YOLOv2 CNN pipeline downsampled to 1 frame per second for real-time operation; people detection achieved 94-percent precision and 86-percent recall and excavator detection achieved 90-percent precision and 89-percent recall on a test dataset, with generated alerts and recorded clips used for immediate intervention and safety education; however, monocular distance estimation via reverse perspective transformation was not independently validated against ground truth, and the authors recommended stereo cameras and GPS integration to improve proximity accuracy (Luo et al., 2020).
- An AI-enabled AR alert framework for highway work zones ran YoloV4 on a Xavier AGX Jetson embedded platform at 24.83 FPS with 40.3 ms end-to-end latency, achieving 48.7-percent mAP overall (car 74.9 percent, person 58.4 percent) on a customized BDD100K dataset; wireless round-trip time to AR smart glasses measured 5.1 ms at the farthest test distance within a 120-m coverage setup, with a four-level Risk Score alert interface (Low/Medium/High/Lethal) delivered via visual, auditory, and vibratory cues. Early user research found maintenance crews responded “Neutral” on average, with top concerns being repetitive false alarms and device unreliability, and the model does not estimate velocity/acceleration, limiting Risk Score quality (Sabeti et al., 2021).

Stakeholder Perspectives: Participants expressed a spectrum of views on AI vision maturity and value. One participant with software and airport construction experience noted active field testing: “We tested an AI vision camera on a paver to make sure that people were being safe… signaling bad behaviors and training,” and referenced a roller manufacturer deploying computer-vision-based automatic stop systems. However, another participant cautioned: “What concerns me about AI is, from what I’ve seen, some things that AI do… they don’t often get things right. I think I’d rather have something like a geofence that’s been used and proven… I think we’re not there yet with AI.”

Cell 6: Medium Impact/ Low Feasibility Technologies

Figure 16 presents the Impact–Feasibility scatter plot for the four technologies classified in Cell 6. These technologies offer meaningful performance or operational benefits but face substantial barriers that limit near-term airfield deployment. Technologies in this cell are constrained by a combination of early-stage development, limited airfield-scale validation, regulatory approval pathways requiring MOS, high implementation costs, and institutional unfamiliarity. Dimension scores for each technology are presented in Table 22 and Table 23.



Source: AAPTP

Figure 16. Impact vs. Feasibility Matrix for Technologies Classified as Medium Impact/Low Feasibility

Table 22. Impact Dimension Scores for Medium Impact/Low Feasibility Technologies

Technology Name	Performance	ROI	Safety	Efficiency	Sustainability	Impact Score
Self-Sensing Asphalt Materials	3	3	3	3	3	3.00
Self/Assisted Healing Asphalt Technologies	3	2	3	4	4	3.02
Autonomous Ground Vehicles for FOD Detection	2	3	4	4	2	2.91
3D Machine Control for Asphalt Paving	4	2	3	3	3	3.14

Table 23. Feasibility Dimension Scores for Medium Impact/Low Feasibility Technologies

Technology Name	Readiness Level	Technical Issues	Upfront Cost	Regulatory Hurdles	Stakeholder Acceptance	Feasibility Score
Self-Sensing Asphalt Materials	2	2	2	2	2	2.00
Self/Assisted Healing Asphalt Technologies	2	2	2	2	2	2.00
Autonomous Ground Vehicles for FOD Detection	3	2	3	2	2	2.45

Technology Name	Readiness Level	Technical Issues	Upfront Cost	Regulatory Hurdles	Stakeholder Acceptance	Feasibility Score
3D Machine Control for Asphalt Paving	3	2	2	2	3	2.37

Self-Sensing Asphalt Materials

Self-sensing asphalt materials are asphalt-based systems that convert mechanical or environmental actions (e.g., stress, strain, temperature) into measurable electrical or optical signals, enabling the pavement itself to function as a sensor (Birgin et al., 2022a). Two implementation pathways exist. Intrinsic conductive mixtures disperse conductive phases (carbon microfibers, graphene nanoplatelets (GNPs), or carbon fiber–graphite blends) into the asphalt matrix to create a piezoresistive network whose resistance changes with deformation (Gulisano et al., 2023). The second uses coplanar electrodes on unmodified asphalt for capacitance-based sensing without conductive fillers (Ozturk & Chung, 2022).

Regulatory Context: P-401 in AC 150/5370-10H mandates Marshall or Gyratory (Superpave) mix design with specific stability, flow, VMA, and AV targets (3.5 percent). Intrinsic conductive mixtures may require additives added to a P-401 base mix, triggering MOS as a material additive but potentially preserving compliance with existing volumetric and acceptance criteria at low dosage rates. Capacitance-based electrode approaches may use unmodified P-401 mixes, potentially avoiding mix-design MOS entirely, though electrode installation may constitute a construction method modification under Order 5300.1G §8.c.

Key Evidence from Literature:

- A full-scale roadway section (3.0 m x 1.5 m x 0.08 m) embedded with 12 line electrodes in a carbon microfiber (CMF) self-sensing composite was operated autonomously for two months under 3–5 V DC. Axle-induced resistance peaks scaled linearly with vehicle gross weights, and an ANN-based workflow estimated gross vehicle weight within a 20-percent error (within the operating limits of COST323, ASTM E1318-09, and NMi accuracy standards) (Birgin et al., 2022b).
- A stone mastic asphalt (SMA 11) with 5.7 wt percent polymer-modified bitumen and 5 wt percent GNPs by bitumen mass, instrumented with four embedded copper-wire electrodes for four-probe measurement, exhibited a linear stress-electrical resistance relationship under uniaxial cyclic compression with $R^2 = 0.95$ and a stress sensitivity of 5.37 percent change in resistance per 1 MPa increase in compression (Gulisano et al., 2023).

- An optimized blend of 40 percent graphite plus 0.3 percent carbon fiber by asphalt weight reduced resistance to 433 Ohms and increased Marshall stability by 4 percent, split strength by 18 percent, and dynamic stability by 122 percent compared to plain asphalt pavement. Excessive carbon fiber at 0.6 percent by asphalt weight reduced all mechanical properties (Liu et al., 2014).
- Electrically conductive asphalt concrete has been explicitly proposed for anti-icing and de-icing in "critical paved areas such as airports." Asphalt mastic modified with 1 percent carbon fiber by mastic volume (electrically conductive asphalt mastic) was energized at 60 V AC for 10 min in an environmental chamber at −18 °C; average surface temperature increased by approximately 46 °C over that period (Arabzadeh et al., 2018).

Stakeholder Perspectives: Participants described self-sensing asphalt as a research-stage concept with uncertain feasibility. One panelist stated: "so new that I'm not sure that we have the technical information necessary to implement that at this point in time," rating the technology as "low feasibility." Another noted laboratory graphene work as "early work" and expressed uncertainty about feasibility beyond general literature. A third panelist saw potential if self-sensing "replace a lot more finicky sensors" for pavement monitoring but acknowledged going "out on a limb." Panelists broadly agreed that incorporating novel technologies into airport construction "could be very slow process" given the difficulty of obtaining material approvals even with existing materials at local airports.

Self/Assisted Healing Asphalt Technologies

Self-healing asphalt technologies are engineered materials and activation methods that promote crack closure and partial recovery of mechanical properties by enabling binder to re-establish contact, flow into voids, or deliver healing agents at crack faces under controlled rest and/or external stimulation (Bhasin et al., 2009). Two principal families exist: energy-assisted healing and materials-based healing (Norambuena-Contreras & Garcia, 2016). Energy-assisted healing embeds conductive inclusions (e.g., steel fibers/wool) so that an alternating magnetic field (induction) or microwave energy produces internal joule heating, softening bitumen to enhance wetting, diffusion, and strength recovery (Liu et al., 2012; Norambuena-Contreras & Garcia, 2016). Materials-based healing disperses capsules (e.g., calcium-alginate or urea-formaldehyde shells) or compartmented fibers containing rejuvenators in asphalt so that cracking ruptures the shell and releases oil to locally soften aged binder (Al-Mansoori et al., 2018).

Regulatory Context: P-401 in AC 150/5370-10H mandates Marshall or Gyratory (Superpave) mix design with specific stability, flow, VMA, and AV targets (3.5 percent). Both approaches may require additives added to a P-401 base mix, triggering MOS as a material additive but potentially preserving compliance with existing volumetric and acceptance criteria at low dosage rates. The closest spec item is P-632 (asphalt rejuvenation), which

covers spray-applied surface treatment only. AC 150/5380-6C prescribes conventional crack sealing, patching, and overlay.

Key Evidence from Literature:

- At the Dutch A58 motorway, a porous asphalt test section with 1.27 percent steel wool was heated to 85 °C at approximately 3 °C/s, with an estimated heating time from 5 °C to 85 °C of approximately 0.44 min; 85 °C corresponds to near-Newtonian binder behavior and was identified as the optimal healing temperature for porous asphalt in controlled testing (Liu et al., 2012).
- Full-scale induction trials at duraBAST showed top-half mean temperatures of 72.1 °C versus lower-portion mean temperatures of 39.4 °C after 60 s, with the differential increasing over heating time, a critical limitation for deep layer healing (Xu et al., 2018).
- The HEALROAD program reported that induction heating can repair individual cracks in dense and porous asphalt beams and recover up to approximately 80 percent of original strength in −20 °C three-point bending tests; lifetime increases were greater for porous surfaces due to microcrack repair in the mastic, while dense mixtures were prone to damage and bitumen segregation under overheating (Xu et al., 2018).
- Steel wool at approximately 0.3 percent by total mixture weight increased mixture price approximately 30 percent (Xu et al., 2018).
- A modeled LCCA comparing microwave (MW) heating self-healing to a traditional maintenance (TRM) program reported costs 50 percent lower (MW1) and 27 percent lower (MW2) than the traditional program at AADT1200; at AADT5000, costs were 1,576 cost per-lane foot (MW1) versus 3,864 cost per-lane foot (TRM); the modeled field process assumed a 40 kW device, 90 s of static heating, 60 s to reposition, and a three-worker crew (Nalbandian et al., 2022).
- Adding 3 wt percent microcapsules doubled the fatigue life of an AC-10 asphalt mixture in controlled fatigue-healing-refatigue testing; Ca-alginate capsules increased strength recovery ratios from 63.8 percent to 92.7 percent across 6,000 loading cycles, with fracture energy recovery reaching 180.2 percent; mixture stiffness decreased due to oil softening, indicating a healing-versus-rutting trade-off relevant to high tire-pressure airfield loading (roadway-only) (Sun et al., 2018; Zhang et al., 2019).

Stakeholder Perspectives: One participant noted: “I’m also interested in…self-healing there because there’s a lot of work in the concrete. I haven’t seen a whole lot …on the asphalt side. So, I’m not sure what the feasibility would be on that.” Another stated: “both of them are so new that I’m not sure that we have the technical information necessary to implement that at this point in time.” A third participant echoed this: “it sounds very exciting, the self-healing, self-sensing. I’m not sure where we’re at with that as far as actually making it come together.” One panelist offered a contrasting view, noting

familiarity with the technology but questioning its cost-effectiveness relative to simpler approaches: “I think it’s technically possible. I don’t get the sense that it’s the easiest way to solve a problem. I think it’s a little bit of a fancier way to solve a problem.”

Autonomous Ground Vehicles for FOD Detection

Autonomous Ground Vehicles (AGVs) are driverless platforms that integrate perception, navigation, and control to detect and localize FOD on airport runways, taxiways, and aprons (Yuan et al., 2020). FOD is any object in an inappropriate airport location with potential to injure personnel or damage aircraft (Noroozi & Shah, 2023). On-vehicle sensing includes optical imaging, LiDAR, and millimeter-wave radar, often fused with GNSS/INS positioning for georeferenced alerting (Ravi et al., 2021; Yuan et al., 2020). Optical systems capture forward imagery in real time, assign hazard levels, and issue alarms at patrol speeds reaching 60 km/h or more (Yuan et al., 2020). Mobile Mapping Systems (MMS) use vehicle-mounted LiDAR to produce georeferenced point clouds for debris identification (Ravi et al., 2021). Radar is described as less weather-affected but higher-cost with higher false-positive rates for small debris, supporting hybrid radar/visible/infrared configurations (Yuan et al., 2020; Farooq et al., 2024).

Regulatory Context: 14 CFR §139.305(a)(4) requires that “mud, dirt, sand, loose aggregate, debris, foreign objects, rubber deposits, and other contaminants must be removed promptly and as completely as practicable.” §139.327(a) requires airports to inspect daily, when required by unusual conditions, and immediately after an accident or incident. AC 150/5220-24 §3.1.c(1)(d) mentions Mobile Radar as “a radar detection system mounted on top of a vehicle” scanning “an area 600 ft by 600 ft (183 m by 183 m)” to detect FOD measuring “1.2 inch (3.0 cm) high and 1.5 inch (3.8 cm) in diameter” at “speeds of up to 30 mph (50 km/h).” §3.2.b(1) requires mobile systems to meet detection performance “at a minimum speed of 20 mph (30 km/h).”

Key Evidence from Literature:

- A FOD detecting car integrating differential GPS (DGPS), four GT2050C cameras (2048 × 2048 px each) providing a combined 5 m scan width, an alarm/notification module, and a FOD management database was tested on images collected at Tianjin Binhai International Airport. The system targeted real-time operation at 25 fp on a GTX 1080 Ti, achieving mAP = 98.41 percent, and FAR = 0.66 percent and was tested on 12,231 airfield pavement images including screw and stone FOD (Cao et al., 2018).
- An MMS platform equipped with dual 2D profiler LiDAR and GNSS/INS georeferencing processed runway FOD using a scan-line plus local-neighborhood algorithm. In a controlled validation using a debris field of 50 airport-collected FOD pieces: 100 percent of items larger than 2 cm were detected at approximately 15–20 mph (24–32 km/h) with no false detections across eight individual traverses. Items

smaller than 2 cm were not detected due to a 2 cm normal-distance threshold (ndTh = 2 cm) set based on MMS point cloud relative accuracy (Ravi et al., 2021).
- A deep convolutional neural network was trained for FOD material recognition using an outdoor dataset that included images from the backup runway of Shanghai Hongqiao International Airport. Metallic FOD was frequently misclassified as concrete or plastic without targeted FOD-specific training (Xu et al., 2018).
- Metallic FOD was the easiest material to detect in radar contexts; glass posed the greatest challenge in monostatic configurations (Nsengiyumva et al., 2019).

Stakeholder Perspectives: Participants viewed AGVs for FOD detection favorably as a concept but raised operational concerns. One panelist noted AGVs are "probably up there in my opinion" alongside fixed systems for geotagged alert operations. Another stated, "like a vehicle, you can drive in any weather conditions…if those sensors on board are operating, then they can do just about everything." However, concerns centered on active-runway integration. One participant observed, "I don't think they can hop off and hop on as easily as a drone," noting that if inspections occur only during clear-runway windows, the purpose is undermined. Another expressed caution: "I'm a little concerned with autonomous vehicles because … there's a lot of science back here and a lot of things can kind of go astray."

3D Machine Control for Asphalt Paving

3D machine control, also termed automated machine guidance (AMG), uses three-dimensional engineered models with high-precision positioning instruments to guide construction equipment for elevation, cross-slope, and alignment in real time (Mitchell et al., 2021). Positioning is typically provided by robotic total stations or GNSS laser-augmented setups (commercially termed mmGPS), both relying on line-of-sight communications to machine-mounted sensors while a controller interfaces with machine hydraulics to maintain grade from a digital 3D design file (Mitchell et al., 2021). High-quality 3D design data and survey control are prerequisites, because model uncertainty can cause construction delays if not verified before use (Maier et al., 2017).

Regulatory Context: P-401 §401-4.5 requires "a control system capable of automatically maintaining the specified screed grade and elevation" (AC 150/5370-10H). The language is method-neutral; 3D machine control is neither listed nor excluded. P-401 §401-4.14 specifies surface tolerance by straightedge. Because the spec defines an outcome (grade tolerance) rather than a specific tool, 3D machine control may not require MOS under FAA Order 5300.1G (§8.c).

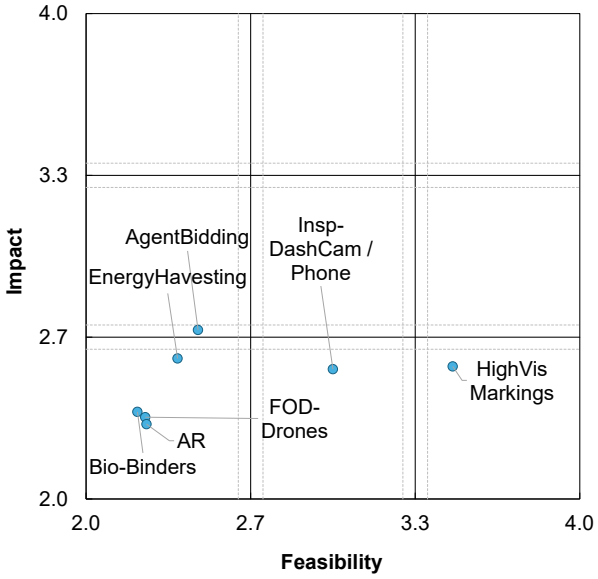
Key Evidence from Literature:

- An analysis across five case studies found a lack of statistically conclusive evidence that AMG improves overall initial pavement smoothness compared with non-AMG methods, with high heterogeneity and mixed site-level results (Mitchell et al., 2021).
- Asphalt pavers are described as less sensitive to grade-control systems than concrete pavers, leading many contractors to use AMG for base grading and rely on sonic averaging skis for asphalt paving (Mitchell et al., 2021).
- Manufacturers require a minimum of three robotic total stations for mainline paving control, and signal losses causing paver stops, which introduce localized roughness, were documented on AMG sites (Mitchell et al., 2021).
- In a Utah corridor, reducing the AMG template drop interval from 30 ft (stringline) to 12.5 ft (stringless) was associated with a 1-percent paving yield improvement, though asphalt paving smoothness and depth-control benefits remained uncertain across cases due to slower paver response and compaction effects. A separate 13.4-mile resurfacing case concluded that 3D methods would add survey, design, and staff costs without offsetting gains in quality or speed compared to sonic averaging under that project's payment structure (Maier et al., 2017).
- A national survey found 82 percent of DOTs reported using AMG, but 93 percent of those did so on less than 20 percent of their projects. The most prevalent applications were subgrade construction and base course placement (Vonderohe & Hintz, 2010).

Stakeholder Perspectives: One participant stated: "We use 3D machine control, just because of the tolerance on elevation. On the paving and concrete side. That's pretty much the only way we can… we just did our first project this year, where we had no grinds on like 56,000 tons on a runway." The same participant noted that "3D machine control and intelligent compaction are around every single time we pave," but cautioned: "It's very expensive… Out of all four of these [IC, IRTP, DPS, 3D Machine Control], 3D machine control is probably 5 times more expensive than any other one." Another participant reported limited use: "We only used it twice from an asphalt side in the state of Florida… the margin of error was very, very small, that we were allowed, so then that came up as an option. But as far as an everyday type of thing, I'm not sure we're quite there yet." Another participant noted that in the concrete world, 3D machine control "has pretty well taken over," but had less familiarity with hot-mix applications.

Cells 7-8-9: Low Impact Technologies

Figure 17 presents the Impact–Feasibility scatter plot for the seven technologies classified in Cells 7, 8, and 9. These technologies share relatively modest impact scores across performance, ROI, safety, efficiency, and sustainability dimensions, limiting their prioritization regardless of feasibility classification. While some, such as High-Visibility Colored Pavement Markings and Dash-Cam/Smartphone inspection, face few deployment barriers, their limited impact within airfield contexts constrains their overall value proposition. As their impact limitations preclude meaningful prioritization, these technologies are not subject to the detailed analysis afforded to higher-ranked counterparts. Dimension scores for each technology are presented in Table 24 and Table 25.



Source: AAPTP

Figure 17. Impact vs. Feasibility Matrix for Technologies Classified as Low Impact

Table 24. Impact Dimension Scores for Low Impact Technologies

Technology Name	Performance	ROI	Safety	Efficiency	Sustainability	Impact Score
Bio-Oil or Bio-Binder	2	2	3	3	2	2.36
High-Visibility Colored Pavement Markings	3	2	2	3	3	2.55
Agent-Based Models of Construction Bidding	3	2	3	3	2	2.70
Drone Swarms for FOD Detection	3	2	2	2	2	2.34
Dash-Cam/ Smartphone for Pavement Inspection	3	2	2	4	2	2.54
Energy-Harvesting Pavements	2	2	3	3	4	2.58
Augmented Reality (AR) for Construction	2	2	2	4	3	2.31

Table 25. Feasibility Dimension Scores for Low Impact Technologies

Technology Name	Readiness Level	Technical Issues	Upfront Cost	Regulatory Hurdles	Stakeholder Acceptance	Feasibility Score
Bio-Oil or Bio-Binder	2	2	3	2	2	2.21
High-Visibility Colored Pavement Markings	4	3	3	4	3	3.49
Agent-Based Models of Construction Bidding	2	2	3	3	2	2.45
Drone Swarms for FOD Detection	3	2	2	2	2	2.24
Dash-Cam/ Smartphone for Pavement Inspection	3	3	3	3	3	3.00
Energy-Harvesting Pavements	3	2	2	2	3	2.37
Augmented Reality (AR) for Construction	2	2	2	3	2	2.25

GAP Analysis Findings

The three indicators (Impact, Feasibility, and Gap Alignment scores) are combined into a Total Score (0–100) using a weighting scheme shown in Table 10. The resulting rankings for all 51 technologies are shown in Figure 18. The gap analysis framework rewards strategic relevance alongside technical excellence and feasibility. The contrast between HiMA and BMD illustrates this most clearly. HiMA has higher Feasibility than BMD (3.6 versus 3.0) and comparable Impact scores to BMD (3.7) yet ranks 24th (54.0) while BMD ranks 2nd (75.7). The point gap is attributable entirely to Gap Alignment. BMD provides the framework to modernize specifications for all mixtures, whereas HiMA is a beneficiary of that modernization.

Technologies Addressing High-Priority Gaps

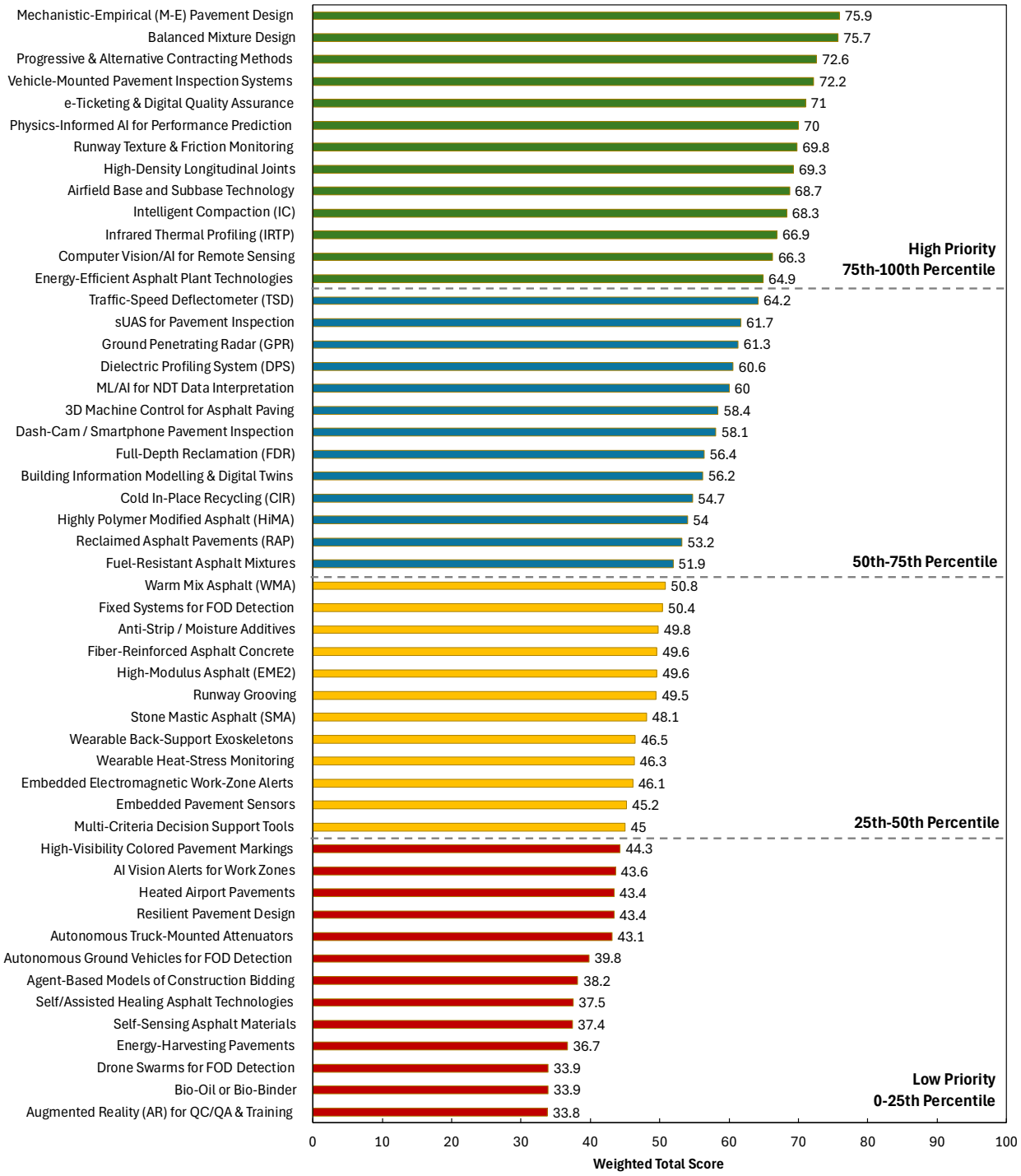
Four technologies score 3 on Gap Alignment by addressing one or more High-priority gaps. Two technologies address the Modernize Specifications gap by providing the mechanism through which specifications can change:

- BMD: BMD provides a technical framework for performance-based design. The testing methods (e.g., IDT-CT, HWTT, AMPT) would supplement or replace P-401's prescriptive volumetric criteria with performance indices. BMD simultaneously addresses Innovation and Change Management by giving agencies quantitative, performance-based data to evaluate and approve innovative materials before field deployment, thus enabling quicker technology adoption by decreasing the perceived risk of new technologies.
- Progressive and Alternative Contracting Methods: The methods provide the contractual mechanism for specification modernization. Delivery methods including performance-based DB, PBC, and CM/GC arrangements structurally require outcome-based specifications (e.g., performance-based or performance-related specifications) rather than prescriptive ones. They also address Innovation and Change Management directly by sharing risk between owner and contractor and rewarding innovation through BV selection.

Two technologies address the Innovation and Change Management gap by providing simulation-based mechanisms to de-risk novel technology adoption:

- M-E Pavement Design Tools: These tools enable site-specific mechanistic simulation of new materials, including HiMA, EME2, SMA, fiber-reinforced mixes, and higher RAP, within realistic pavement structures under project-specific climate and traffic loading. By generating service life predictions before field deployment, M-E analysis reduces the uncertainty and risk aversion that blocks adoption of novel materials. It additionally addresses the Design Tools and Analysis gap, earning the highest Total Score in the dataset.

- Physics-Informed AI for Performance Prediction: extends the de-risking mechanism through physics-constrained ML that predicts material and structural performance while maintaining mechanistic consistency. It enables faster screening and performance prediction of novel materials, reducing adoption uncertainty through a complementary pathway to M-E design and toward the same Innovation and Change Management gap.



Source: AAPTP

Figure 18. Weighted Total Score Rankings for All 51 Technologies, Grouped by Quartile Priority Tier

Technologies Addressing Medium-Priority Gaps

Fifteen technologies address Construction Quality, a Medium-priority gap, earning Gap Score 2. These represent the near-term, actionable investment layer since these are technologies that can be deployed to improve construction processes or post-construction condition assessment.

- Vehicle-Mounted Pavement Inspection Systems
- e-Ticketing & Digital Quality Assurance
- Runway Texture and Friction Monitoring
- High-Density Longitudinal Joints
- Airfield Base and Subbase Technology
- Intelligent Compaction (IC)
- Infrared Thermal Profiling (IRTP)
- Computer Vision/AI for Remote Sensing
- Traffic-Speed Deflectometer (TSD)
- Small Unmanned Aircraft Systems (sUAS) for Pavement Inspection
- Ground-Penetrating Radar (GPR)
- Dielectric Profiling System (DPS)
- ML/AI for NDT Data Interpretation
- 3D Machine Control for Asphalt Paving
- Dash-Cam/Smartphone Pavement Inspection

Several of these technologies (e.g., IC, IRTP, and 3D Machine Control) are already in active use on highway projects and face low regulatory barriers for airfield adoption. Their primary challenge is the absence of FAA-specific guidance and acceptance criteria.

None of the evaluated technologies earn Gap Alignment credit for the Workforce and Training gap. Several technologies were considered for this gap during scoring (including Augmented Reality for QC/QA & Training and the use of AI) but were ultimately excluded because the gap definition targets inspector and engineer skill shortages and inconsistent enforcement of standards, not the introduction of new tools that themselves require training. That said, the AI and ML technologies evaluated in this project have meaningful long-term relevance to the workforce challenge. These include:

- ML/AI for NDT Data Interpretation
- Computer Vision/AI for Remote Sensing
- Physics-Informed AI for Performance Prediction
- AI Vision Alerts for Work Zones
- Augmented Reality (AR) for Construction

These technologies can contribute to workforce development in two ways. First, they lower the expertise threshold for complex tasks (e.g., automating pattern recognition in NDT data, standardizing condition assessment, and providing training simulations), potentially democratizing knowledge that currently resides with experienced practitioners. Second, and more structurally, AI tools may shift workforce needs over time: fewer specialists performing manual inspections, replaced by personnel skilled in deploying, calibrating, and interpreting AI-assisted systems. Whether this shift represents workforce augmentation or displacement remains an open question. The effects of AI on the technical workforce are still unfolding. Ongoing research through NCHRP 23-46 (AI Integration and Workforce Transformation for State DOTs) is expected to yield structured insights on this topic that may be directly relevant to airfield pavement practitioners. As these findings emerge, the workforce implications of the AI technologies identified in this assessment should be revisited.

Technologies Addressing Low-Priority Gaps

Five technologies earn Gap Score 1, addressing one or more Low-priority gaps (Budget Constraints or Design Tools and Analysis). These technologies receive fewer points from the gap analysis but enough to differentiate them from the 27 technologies scoring 0. Their rankings are therefore determined primarily by Impact and Feasibility scores.

Four technologies address the Budget gap through documented cost savings from material reuse or energy efficiency:

- Full-Depth Reclamation (FDR)
- Cold In-Place Recycling (CIR)
- Reclaimed Asphalt Pavements (RAP)
- Energy-Efficient Asphalt Plant Technologies

One technology addresses the Design Tools and Analysis gap:

- Building Information Modelling and Pavement Digital Twins

It is worth noting that M-E Pavement Design and Physics-Informed AI also address the Design Tools gap, but both earn Gap Score 3 through their primary contribution to the higher-priority Innovation and Change Management gap.

Technologies Addressing No Gaps

Of the 51 technologies evaluated, 27 score 0 on Gap Alignment. Many of these technologies are high-performing materials and methods that are structurally blocked by current prescriptive specifications and score 0 precisely because they cannot drive specification change themselves. Other technologies address airport operations/safety or

worker health with no gap relevance, while a few are already specified and in practice. Examples of these technologies include:

- HiMA: P-401 PG grade tables extend only to PG 82, and HiMA-relevant grades above PG 82 require engineering justification or MOS per FAA Order 5300.1G. HiMA is not fully accommodated by current specs and benefits from their modernization but does not cause it. FAARFIELD assigns fixed modulus values to P-401 HMA layers (200,000 psi surface, 400,000 psi stabilized base) regardless of material modification, providing no structural design credit for enhanced properties from HiMA.
- EME2, SMA, and FRAC: These technologies are entirely absent from AC 150/5370-10H. FAARFIELD assigns fixed modulus values (200,000 psi surface, 400,000 psi stabilized base, and the variable stabilized flexible base option caps at 400,000 psi) that provide no structural design credit for these technologies.
- WMA is also absent from AC 150/5370-10H and may directly conflict with P-401 delivery temperature requirements (275–325 °F). WMA is a production technology controlled by those requirements, not a driver of change to them.
- Fuel-Resistant Asphalt Mixtures score 0 on Gap Alignment despite strong Impact and Feasibility scores because the regulatory framework is in place through P-404. Fuel-resistant mixes do not drive spec modernization, do not de-risk the adoption of other technologies, and do not address any of the remaining four gaps.

This pattern directly validates the stakeholders' identification of Modernize Specifications as the top-ranked gap (91-percent selection rate): the specifications themselves are the binding constraint preventing deployment of technologies that otherwise rated highly on technical merit. BMD and Progressive and Alternative Contracting are the two technologies that unlock this bottleneck.

Strategic Insights

Figure 19 presents the 26 technologies that scored in the 50th percentile or above on the Total Score, organized into two groups (75th–100th percentile and 50th–75th percentile). Each technology is labeled with its Impact–Feasibility cell classification (C1 through C9) and its Gap Alignment priority (H: addresses high-priority gaps; M: addresses medium-priority gaps; L: addresses low-priority gaps or none). Technologies with no gap-alignment label fulfill none of the gaps. Notably, technologies classified in Cells 7 through 9 are largely absent from this ranking, aside from one exception, which is a natural consequence of their low impact scores suppressing their Total Score.

Technologies in the 75th-100th Percentile		Technologies in the 50th-75th Percentile	
Mechanistic-Empirical (M-E) Pavement Design	C2 H	Traffic-Speed Deflectometer (TSD)	C2 M
Balanced Mixture Design	C2 H	sUAS for Pavement Inspection	C5 M
Progressive & Alternative Contracting Methods	C3 H	Ground Penetrating Radar (GPR)	C5 M
Vehicle-Mounted Pavement Inspection Systems	C1 M	Dielectric Profiling System (DPS)	C3 M
e-Ticketing & Digital Quality Assurance	C1 M	ML/AI for NDT Data Interpretation	C5 M
Physics-Informed AI for Performance Prediction	C5 H	3D Machine Control for Asphalt Paving	C6 M
Runway Texture & Friction Monitoring	C4 M	Dash-Cam / Smartphone Pavement Inspection	C8 M
High-Density Longitudinal Joints	C1 M	Full-Depth Reclamation (FDR)	C2 L
Airfield Base and Subbase Technology	C1 M	Building Information Modelling & Digital Twins	C2 L
Intelligent Compaction (IC)	C1 M	Cold In-Place Recycling (CIR)	C5 L
Infrared Thermal Profiling (IRTP)	C1 M	Highly Polymer Modified Asphalt (HiMA)	C1
Computer Vision/AI for Remote Sensing	C2 M	Reclaimed Asphalt Pavements (RAP)	C5 L
Energy-Efficient Asphalt Plant Technologies	C1 L	Fuel-Resistant Asphalt Mixtures	C1

C1 Cell 1: High Impact, High Feasibility
C2 Cell 2: High Impact, Medium Feasibility
C3 Cell 3: High Impact, Low Feasibility
C4 Cell 4: Medium Impact, High Feasibility
C5 Cell 5: Medium Impact, Medium Feasibility
C6 Cell 6: Medium Impact, Low Feasibility
C7 Cell 7: Low Impact, High Feasibility
C8 Cell 8: Low Impact, Medium Feasibility
C9 Cell 9: Low Impact, Low Feasibility
H Addresses High Priority Gaps
M Addresses Medium Priority Gaps
L Addresses Low Priority Gaps

Source: AAPTP

Figure 19. Technology Prioritization Summary by Total Score Percentile with Flags Indicating Impact/Feasibility Cell and Gap Alignment

The main insights can be derived by looking at the following seven technology bundles:

Technology Bundle 1: BMD, M-E Pavement Design, Alternative Contracting, and Physics-Informed AI

These four technologies address the two high-priority gaps identified by the focus group respondents. Of the 51 technologies evaluated, 27 score 0 on Gap Alignment, and the majority of these are materials or methods with competitive Impact and Feasibility scores that are constrained by the absence of supporting specifications, performance-based acceptance criteria, or design framework updates. These four technologies address the structural conditions that block this broader group. BMD supplies the performance testing framework through which innovative mixtures can be evaluated against performance criteria rather than just volumetric criteria. Progressive and Alternative Contracting Methods restructure procurement to require performance-based outcomes rather than prescriptive methods, thus incentivizing adoption of those validated materials through risk-sharing and BV selection. M-E Pavement Design provides analytical tools to generate service life predictions for novel materials under site-specific loading and climate conditions prior to field deployment, reducing the technical uncertainty that limits adoption. Surrogate Physics-Informed AI models represent the next evolutionary step beyond conventional M-E tools. These models have the potential to reduce computational cost associated with full finite-element analysis, which enables rapid evaluation of

mixtures and structures under a variety of loading configurations and climate scenarios that would otherwise require extensive simulation time.

Technology Bundle 2: HiMA and Fuel-Resistant Asphalt Mixtures

HiMA and fuel-resistant mixtures are ranked on the lower end of the 50th–75th percentile group although they both belong to Cell 1 with very high feasibility and impact scores. Neither of these technologies address any identified gaps, but they benefit from specifications being modernized. For example, HiMA laboratory and field data show rut depth reductions of 35–40 percent, approximately 3.5 times greater predicted fatigue life, and potential asphalt pavement thickness reductions of 46–54 percent at equivalent fatigue performance (Kwon et al., 2020; Habbouche et al., 2018). These benefits are not captured by volumetric acceptance criteria, which may classify HiMA and conventional PMA mixes as equivalent under current P-401 requirements. In addition, FAARFIELD presents two structural design limitations: (1) fixed modulus inputs (200,000 psi surface, 400,000 psi stabilized base) provide no design credit for HiMA's enhanced stiffness regardless of binder modification (AC 150/5320-6G) and (2) the layered elastic framework lacks constitutive damage models to capture fatigue life extension and damage tolerance, which are HiMA's primary performance benefits. BMD provides the performance testing framework through which HiMA's rutting and cracking resistance can be measured and differentiated from a conventional PMA control. In addition, M-E design tools, such as FlexPAVE, are capable of accepting measured dynamic modulus, fatigue cracking, and rutting model coefficients as inputs and therefore are able to translate HiMA's measured material property differences into structural thickness and lifecycle predictions.

Technology Bundle 3: Runway Texture & Friction Monitoring and BMD

Runway texture and friction monitoring is technically mature and operationally embedded in current airfield practice under AC 150/5320-12C. The gap identified in the focus group data is at the mix design stage. No laboratory macrotexture or friction requirements are currently specified in P-401 as part of the mix design process. As surface mixes incorporate non-conventional materials (RAP, fiber reinforcement, polymer-modified binders at grades approaching or exceeding PG 82), integration of laboratory macrotexture and friction testing into the BMD acceptance framework, alongside rutting and cracking criteria, becomes important. This integration may be more important for runways where friction-critical surface performance must be managed and monitored. One focus group participant referenced a case where the British Pendulum test had to be specifically requested to evaluate the friction impact of fiber addition at a Vancouver airport project.

Technology Bundle 4: Vehicle-Mounted Pavement Inspection Systems, e-Ticketing and Digital QA, High-Density Longitudinal Joints, Airfield Base and Subbase Technology, Intelligent Compaction (IC), Infrared Thermal Profiling (IRTP), and Computer Vision/AI for Remote Sensing

The seven technologies share a commonality. They are already heavily deployed in highway practice, face low or no regulatory barriers to airfield use, and/or are constrained not by technology readiness but by the absence of documented airfield-specific correlations that are needed to advance from supplementary process control to acceptance-level instruments. Six of the seven are classified in Cell 1 (High Impact/High Feasibility), and the remaining one, Computer Vision/AI for Remote Sensing, is classified in Cell 2 (High Impact /Medium Feasibility), which is attributable to the need for locally trained models rather than any fundamental technology barrier. Collectively these technologies address the Construction Quality gap.

Vehicle-mounted pavement inspection systems are the most immediately deployable of the group. Vehicle access under 14 CFR §139.329 is well-established, no airspace authorization is required, and field validation at an international airport demonstrated full runway coverage in 3 days versus 3 weeks for 43 manual sampling units on foot, with PCI agreement at $R^2 = 0.90$ and section-level differences ≤2 points (Santos et al., 2020). Current FAA condition assessment relies on visual PCI surveys per ASTM D5340 as recommended by AC 150/5320-17A; automated systems must produce data compatible with the ASTM D5340 methodology to be accepted for APMS, which constitutes the primary remaining step toward full adoption.

e-Ticketing and Digital QA function as the data infrastructure layer for this entire bundle. Electronic ticketing digitizes material delivery records and links each asphalt load to time and location via GPS-equipped trucks crossing virtual geofences at the plant, scale, jobsite, and paver (Sturgill et al., 2019). Integration with IC, IRTP, and DPS data through platforms such as the MDMS and Veta overlays dump locations with IC and thermal profiling data to link QA tests and acceptance decisions to specific loads, stationing, thermal patterns, and pass counts (Embacher, 2021). No FAA AC or Engineering Brief currently establishes e-Ticketing requirements for airport construction. However, because e-Ticketing does not modify physical design, materials, or construction methods, it may not be subject to the MOS process under FAA Order 5300.1G. This regulatory distinction positions e-Ticketing as one of the most immediately deployable technologies in the entire dataset.

IC and IRTP are both deployed in routine highway construction under FHWA and AASHTO specifications, with Veta required in more than 25 State DOT IC and PMTP specifications. In a Vermont IC demonstration, target ICMV re-rolling increased average nuclear gauge density from 125.5 to 128.4 lb/ft^3 (Foroutan & Ghazanfari, 2019). An integrated IC+IRTP field

study demonstrated that introducing a material transfer vehicle reduced severe thermal segregation events when both data streams were used to guide corrective action (Chang et al., 2018). The shared constraint on both technologies is that IC ICMV indexes correlate well with FWD stiffness but poorly and inconsistently with core density (Sivagnanasuntharam et al., 2021), which is the P-401 acceptance metric under the C-110 PWL method (§401-5.5). FHWA characterizes IC for asphalt mats as at the "field demonstration" stage with evolving verification requirements for acceptance (Von Quintus et al., 2023).

High-Density Longitudinal Joints and Airfield Base and Subbase Technology both address construction quality through methods that are either already partially specified in P-401 or fall under existing FAA specification items. Engineering Brief 56 explicitly recognizes joints as "historically the poorest performing portion of pavements," and joint density acceptance is evaluated via cores under the PWL method. At Yakutat Airport, echelon paving and IR joint heaters eliminated approximately 600 m^3 of wasted asphalt and helped meet FAA density requirements (Chitnis et al., 2024). The IR joint heater cost was approximately $0.12 per linear foot and joint stabilizer application $0.36–$0.57 per linear foot (Williams, 2011; Chitnis et al., 2024). For base and subbase technology, AC 150/5370-10H defines seven specification items and AC 150/5320-6G §3.13.3.2 mandates stabilized base for aircraft with gross loads of 100,000 lb or more. The technology gap identified by focus group participants is material characterization inputs for M-E design software, where recycled concrete aggregate and several stabilized variants do not yet have modeled material options.

Lastly, Computer Vision/AI Methods for Remote Sensing is one of the primary applications of AI in the field of pavement engineering. It is positioned in Cell 2 rather than Cell 1 because model performance requires local training, as focus group participants noted, "AI models must be trained locally" because "a general system doesn't work everywhere." Literature results are nevertheless strong: YOLO v3 and Faster R-CNN matched Iowa DOT manual QC/QA labels at 97.56 percent and 96.9 percent accuracy on 3D pavement images (Ghosh & Smadi, 2021), and DMA-Net trained on Fitchburg Municipal Airport runway imagery achieved Dice/mIoU of 69.9/55.9 percent on airport-specific distress data (Sun et al., 2022). The technology is most directly linked to vehicle-mounted inspection systems, where it automates the image analysis step that currently limits throughput, and to sUAS inspection, where it is a prerequisite for converting high-resolution orthomosaics into ASTM D5340-compatible PCI data. These technologies are most effectively advanced together.

Technology Bundle 5: Traffic-Speed Deflectometer, sUAS for Pavement Inspection, Ground-Penetrating Radar, Dielectric Profiling System, ML/AI for NDT Data Interpretation, 3D Machine Control for Asphalt Paving, and Dash-Cam/Smartphone Pavement Inspection

The technologies in this bundle face a more substantive barrier to airfield adoption than those in Bundle 4. The barriers range from cost and mobilization constraints (TSD, 3D machine control) to an extensive airfield-specific regulatory framework (sUAS), to fundamental data interpretation limitations that require research investment rather than pilot projects (GPR, DPS, ML/AI for NDT when applied to deflection data).

TSD costs approximately $25–$40 per mile for collection and $75–$90 per mile with processing (Flintsch et al., 2013) aside from mobilization. Focus group participants noted that "for very short distances… it will be a little expensive." More fundamentally, TSD is not listed in AC 150/5370-11B Table 1 among recognized NDT device categories, and FAA backcalculation programs assume impulse-load deflection basins under multilayer elastic theory. One of the few documented airfield TSD deployments is in Copenhagen Airport, where 189 km of two runways were surveyed in 4 hr at approximately 80 km/h (Nielsen & Jensen, 2022). A test-track study showed TSD deflections are more sensitive to temperature than to survey speed, making temperature normalization the critical step for multi-trip data comparability (Zhang et al., 2023). The two gaps, temperature normalization and HWD load-equivalency correlation, are areas that require further research ahead of structured TSD pilot projects.

The regulatory framework for sUAS for pavement is among the most extensive of any technology reviewed in this project. The FAA Letter to Airport Sponsors explicitly designates pavement inspection as a UAS research application and states that sUAS "cannot be used as a sole means of compliance with federal regulations and requirements and must be supplemented by traditional methods" until guidance is formalized. Operational requirements include Part 107 certification, VLOS under §107.31, air traffic control authorization under §107.41, DroneZone submission per FAA Order JO 7200.23D §2-6, Air Traffic Manager coordination, airport authority approval, and a mandatory HIRF compatibility demonstration under the same order. For a 5,000- by 150-ft runway at 2 mm GSD, estimated capture time is 2.25 hr, followed by a minimum two-day processing cycle on a single computer (Valecha et al., 2023). In addition, low-severity joint seal damage, alkali-silica reaction, and weathering/raveling showed no consistent detectable traits even at the highest tested resolutions (Sourav et al., 2023). These regulatory, operational, and technical constraints reduce the incremental value over vehicle-mounted systems for most commercial service airport contexts.

GPR is referenced directly in AC 150/5320-6G Appendix C (§C.4.1.3) and AC 150/5370-11B as supplementary NDT equipment for layer thickness measurement, void detection, and

delamination investigation, making it one of the few technologies in this bundle with an existing FAA regulatory reference. However, the gap identified in focus group discussions is interpretive rather than technical: “the challenge on the GPR is the interpretation of the data that you’re collecting. Not many people have that knowledge.” Thin HMA layers of 3–10 cm fall below the nominal vertical resolution of 1,000–2,000 MHz systems and require deconvolution that introduces artifact risk without expert parameterization (Bianchini Ciampoli et al., 2019). Wet pavements prevent data collection. Slag and certain aggregates affect dielectric values. Thus, GPR’s medium Impact and medium Feasibility scores reflect a technology that is widely available and operationally mature but constrained by interpretation skill gaps that ML/AI methods are beginning to address.

ML/AI Methods for NDT Data Interpretation are most directly applicable to GPR data, where F1 scores of 91 percent for voids, 69 percent for cracks, 90 percent for subsidences, and 100 percent for pipes on 6,199 runway samples have been reported using the MV-GPRNet multi-view fusion architecture (Liu et al., 2024). For deflection-based NDT (FWD, HWD, and TSD) the relevant limitation is not in the system identification algorithm but in the forward model of distressed pavement response, which assumes a continuous intact structure and cannot generate physically meaningful training data for pavements with cracks, faulting, or delamination. Consequently, ML/AI for NDT data interpretation is best understood as a near-term solution for GPR interpretation bottlenecks and a longer-term research subject for deflection data from distressed pavements.

DPS has a high impact potential for continuous density mapping but currently faces technical limitations. At Helsinki-Vantaa Airport, a 900 m × 60 m area was surveyed in approximately 3 hr at 50–70 km/h and GPR-predicted density error was 0.5–1.1 percent versus nuclear gauge errors of 1.2–3.1 percent for non-slag mixtures (Leng, 2011). However, a project-specific correlation between measured dielectric and mat density must be established using field cores or lab-compacted pucks for every project, because lift thickness, moisture, aggregate type, and underlying layers all influence the relationship; correlations (R^2) ranged from 0.52 to 0.98 across nine roadway projects (Diefenderfer & Nair, 2025). A practitioner with direct DPS ownership stated that “it’s not really feasible right now as a technology” and that “it is starting to get mounted in smaller applications to rollers for real-time density, so I think its feasibility’s starting to prove itself.” A third panelist concluded: “The DPS systems just… I think they need more time. There’s more development that is necessary.”

Regarding 3D Machine Control for Asphalt Paving, a contractor participant stated that it was “probably 5 times more expensive than any other one” in the IC, IRTP, DPS, 3D machine control group. Evidence on smoothness improvement is mixed. An analysis across five case studies found no statistically conclusive evidence that AMG improves overall initial pavement smoothness compared with non-AMG methods (Mitchell et al., 2021), and asphalt pavers are described as less sensitive to grade-control systems than

concrete pavers, with many contractors defaulting to sonic averaging skis for asphalt paving rather than 3D control. A national survey found 82 percent of State DOTs reported using AMG, but 93 percent of those did so on less than 20 percent of their projects, with the most prevalent applications being subgrade and base course placement rather than asphalt paving (Vonderohe & Hintz, 2010). One airport-specific demonstration in which a track paver with Trimble 3D control placed approximately 6,600 yd^3 of P-209 base to FAA grade tolerance of ±0.5 inches in 17 days versus an estimated ≥25 days without 3D technology is documented in the literature (For Construction Pros, 2013), suggesting stronger applicability to base course operations than to asphalt surface placement.

Dash-Cam/Smartphone Pavement Inspection occupies the lowest-scoring position within this bundle. The underlying rationale is that the technology's primary value case depends on crowdsourced data from a large fleet of vehicles traveling the same road repeatedly, a condition that characterizes highway networks rather than airport pavements, where vehicle traffic is sparse, controlled, and restricted to authorized users. Without the volume and repetition that makes crowdsourcing effective, the technology reduces to a single-observer dashcam system, which offers lower data quality and lower positional accuracy than vehicle-mounted inspection systems with dedicated sensors, PPK-corrected GNSS, and LiDAR. Its inclusion in the 50th–75th percentile of the overall ranking reflects its medium Feasibility and medium Gap Alignment against the Construction Quality gap.

Technology Bundle 6: Full-Depth Reclamation (FDR), Cold In-Place Recycling (CIR), and Reclaimed Asphalt Pavements (RAP)

FDR, CIR, and RAP are grouped together because all three involve the reuse of existing pavement material and share a common position in the Gap Alignment by addressing the Budget gap through documented, quantified cost savings from material reuse. The three technologies, however, are not equivalent in what they do, in their regulatory status, or in the complexity of what FAA adoption would require.

FDR is the most straightforwardly deployable of the three. Item P-207 in AC 150/5370-10H provides a complete specification covering materials, equipment, construction methods, and compaction. In FAARFIELD, AC 150/5320-6G §4.11.2.1.3 directs that the FDR layer be modeled as a User Defined layer with a recommended modulus of 25,000–50,000 psi. A Colorado statewide probabilistic LCCA reported average 10-year agency costs of $576,312 per lane-mile for FDR versus $754,555 for overlays, with initial construction cost higher for FDR ($617K versus $338K per lane-mile) but lower maintenance driving the lifecycle advantage (Torres-Machi et al., 2024). An LCA found FDR produced 51-percent lower GHG emissions and 64-percent lower energy consumption than mill-and-fill at the base-rehabilitation stage (Souza et al., 2024). However, a multi-State practitioner survey found airports are the least utilized pavement type for FDR among all surveyed categories (Owino et al., 2022), and the focus group participants emphasized execution sensitivity: "Done

improperly or by people that don't completely understand the technology… it ends up in disaster." FDR's suitability is therefore well-established in principle, with the primary implementation gap being practitioner familiarity.

CIR is not a defined specification item in AC 150/5370-10H. Highway applications show that CIR with an overlay can reduce project cost by 40–60 percent compared to conventional mill-and-fill; Alabama CIR and CCPR cases documented 56- to 64-percent lower energy use and 39- to 46-percent lower GHG emissions versus new asphalt pavements (Hand & Aschenbrener, 2023); and a 7-mile corridor documented approximately $5 million savings in material production and construction (Bowers et al., 2023). However, focus group participants were consistently cautious about runway applications, with one stating: "I don't think cold in place recycling, unless you're going to do like a taxiway or something like that, I don't think the airports are going to look to do much of that out on their runways, unless you put a substantial overlay on that." A recurring observation was that CIR failures during construction signal underlying distresses that were not previously diagnosed. This risk is more consequential on airfield pavements, where unplanned closure events carry high operational cost. CIR's most defensible near-term position for airports is as a base-rehabilitation treatment on taxiways, aprons, and low-activity pavements at nonprimary airports, where Order 5100.38D §3-26 permits state highway specifications that may include CIR.

Under P-401 §401-3.4, RAP is currently prohibited on airfield surface courses and capped at 30 percent in intermediate courses, with a one-grade softer binder required when RAP exceeds 20 percent. On federally funded projects, use of recycled materials other than those meeting P-219 may require an MOS under FAA Order 5100.1. The consequences of premature distress, FOD risk, unplanned closure, or emergency repair on airfield surfaces are substantially higher than on highway surfaces, and the implementation complexity of RAP increases non-linearly with RAP content. The core technical challenge is that RAP introduces multiple coupled uncertainties that standard volumetric mix design does not adequately capture. Source variability (in aggregate gradation, binder content, aging state, contaminants, and fractionation practices) directly affects blended mixture performance in ways that are difficult to predict without explicit material characterization. More fundamentally, the assumption that recycled binder is fully available to the new mixture can be flawed. NCHRP IDEA 236 established that RAP agglomerations ("black rocks") are the principal driver of partial binder contribution. Under the resulting AAMD framework, a washed sieve analysis method produces RBA values that correlated with measured RBC. The AAMD procedure accounts for unavailable binder volume in the aggregate structure explicitly (Castorena et al., 2024; Castorena et al., 2023). At 50-percent RAP, AAMD-designed mixtures met North Carolina DOT APA acceptance criteria while improving cracking tolerance index compared to current-practice designs in laboratory evaluations. Without this kind of explicit binder availability accounting, high RAP contents can produce mixtures that are volumetrically compliant but more brittle. An NCAT Phase VI test track

case illustrates that a 20-percent RAP plus 5-percent RAS mixture paved without silo storage developed slippage cracking at approximately 4 months and 1.8 million ESALs. Forensic analysis attributed distress to incomplete rejuvenator–binder interaction leaving the virgin binder over-softened. Redesigning to 35-percent RAP-only with a 2-hr silo hold eliminated the prior failure, with the redesigned section performing satisfactorily through approximately 7.5 million ESALs (West et al., 2019). The sensitivity to production details in that case (silo storage time, rejuvenator dosage, RAP content) illustrates the QC demands that accompany higher RAP contents, which are demands that may be challenging to maintain consistently across the range of contractors and project types that characterize FAA-funded airport construction.

An implementation pathway for RAP may be done in stages. Low RAP contents (less than 20 percent) may be manageable within an enhanced QC framework and performance verification using BMD test methods, without requiring the full AAMD approach. This stage represents a logical first step toward surface course acceptance. Higher RAP contents may require the implementation of AAMD or equivalent approaches to correctly represent recycled binder contribution and RAP agglomeration effects. Additives or rejuvenators may be added as appropriate with clear mix design controls to restore cracking resistance to virgin-equivalent behavior. This implementation pathway amounts to an upgrade of the entire design and acceptance system for RAP-containing mixes, which is a substantial undertaking relative to technologies such as HiMA, where the primary intervention is binder substitution within the existing mix design framework. In essence, significant effort is required just to bring RAP mixtures to parity with virgin performance, while technologies like HiMA offer enhanced performance with far less implementation complexity.

Technology Bundle 7: e-Ticketing & Digital Quality Assurance, Building Information Modelling and Pavement Digital Twins

e-Ticketing & Digital Quality Assurance and Building Information Modelling and Pavement Digital Twins represent successive stages of a data integration trajectory that begins during material production and, if fully realized, extends across the entire pavement lifecycle. e-Ticketing and Digital QA operate at the construction event level, capturing what material was placed, where, when, at what temperature, and under what compaction conditions, in a geospatially referenced and time-stamped record. BIM/digital twins operate at the asset level, connecting design files, construction records, structural evaluation histories, condition monitoring outputs, and rehabilitation decisions into a single connected platform capable of supporting predictive analytics and maintenance optimization across the pavement's service life. In one example, an airport-focused BIM Execution Plan aligned with the APMS used Coordination 3D to reduce construction interference and Planification 4D to link schedules bidirectionally with planning systems during airfield works, with federated storage of encrypted BIM models, FEA models, and sensor data in an HDF5-compatible Exdir structure (Pacios Alvarez et al., 2021). Another example documented in

the literature also includes BIM combined with WebGL visualization of airport pavement quality and a SysML-based airport digital twin platform (Chang et al., 2024). A comprehensive transportation digital twin survey confirms that predictive maintenance supported by digital twins significantly reduces emergency repairs and service interruptions, while identifying interoperability, data quality and accuracy requirements, and privacy and security as persistent challenges, and noting that full-scale predictive maintenance systems require substantial investments in sensors, processing infrastructure, and human resources (Wu et al., 2025).

A critical context documented directly in focus group discussions shows that airport BIM adoption has proceeded on the building and terminal side but has not extended to civil pavement infrastructure. An airport operator participant confirmed this directly: "we haven't really done anything at all on the civil side from a BIM perspective," despite characterizing BIM/digital twins as "something that would be extremely useful to us should we implement that" from an operations and maintenance perspective. This context demonstrates that BIM adoption in buildings and terminal assets is already established, positioning pavement infrastructure as the natural next frontier for implementation within the same airport environment. The transition is supported by active FHWA investment as noted by a Federal agency focus group participant describing FHWA's ongoing ADCMS grant program as a 5-year effort focused on "lifecycle data management so that all that information from planning to design, the materials information, the testing information, the certification information, all gets preserved and appended to the model." Finally, the growing adoption of AI tools further amplifies the value of BIM/digital twins-enabled data integration, as these tools depend on and derive greater benefit from unified, structured, and continuously updated data environments.

Notable Technologies Outside the Top Percentiles

WMA, ASA, FRAC, SMA, and EME2

These technologies score in the 25th–50th percentile because, like HiMA, they do not contribute to any identified gaps. They are beneficiaries of specification modernization rather than its drivers. SMA in particular carries documented airfield precedent. The DOD maintains a formal military airfield specification (UFGS-SMA 32 13 17), and a Johannesburg Airport runway trial demonstrated friction values meeting ICAO texture requirements without post-construction grooving (Jamieson & White, 2020). As BMD is adopted and P-401 is modernized, this group represents a ready pipeline of materials that can advance relatively quickly once the specification bottleneck is resolved.

Fixed Systems for FOD Detection

This technology falls just outside the top 50th percentile but is uniquely positioned within this range as the only one fully specified under an existing FAA framework (AC 150/5220-

24). It is eligible for AIP funding at large-hub airports (Order 5100.38D Appendix L) and achieves a BCR of 2.64 when indirect costs are considered, with a break-even point at Year 3 (Hilburn & Pesmen, 2023). Its ranking is primarily limited by its lack of direct alignment with the identified gaps. Fixed systems employ EO methods, utilizing video and image-processing technologies as the primary mechanism for detecting FOD on runways and AOA surfaces, thereby establishing an FAA-recognized precedent for image-based sensing on airfield infrastructure.

Embedded Pavement Sensors and Self-Sensing Asphalt Materials

These technologies represent two generations of the same underlying concept—instrumented pavements capable of providing real-time structural response and environmental data for monitoring and, ultimately, for digital twin integration). Embedded discrete sensors (strain gauges, thermocouples, TDRs, and fiber-optic cables) have been deployed at scale at Denver International Airport (460 sensors across 16 runway slabs) and at Zurich Airport (armored fiber-optic cables capturing strain fields beneath an A330-300) (Ceylan et al., 2016; Hauswirth et al., 2020). However, the NAPTF experience, where over 1,000 sensors were embedded and many were damaged with sections replaced on approximately an 18-month cycle under accelerated testing (Ceylan et al., 2016), illustrates the durability and service-life limitations that currently confine embedded sensors to research and instrumented monitoring applications rather than broad practice adoption. Sensor drift, limited service life, complications during milling and rehabilitation, and the difficulty of coordinating installation with pavement lifecycle all constrain widespread deployment. Self-sensing asphalt materials represent a potential resolution to these limitations by making the pavement matrix itself the sensor, through conductive phases such as carbon microfibers or graphene nanoplatelets that create a piezoresistive network whose resistance changes measurably with deformation (Gulisano et al., 2023; Birgin et al., 2022b). Focus group participants acknowledged the concept's potential. One participant saw value if self-sensing could "replace a lot more finicky sensors," but the consensus was that the technology is not yet at a stage where implementation could be responsibly recommended. Should self-sensing materials reach sufficient technical maturity to serve as a distributed sensing layer within the pavement structure itself, the constructability, durability, and lifecycle coordination barriers that limit discrete embedded sensors would be substantially reduced, and the resulting continuous strain and structural response data would become a direct and practical input to pavement digital twin platforms.

Heated Airport Pavements

This technology is eligible for AIP funding under Order 5100.38D §3-78 and carries documented benefit-cost ratios of up to 2.05 at Minneapolis–St. Paul, rising to 3.78 when deployment is targeted to 20 percent of apron area (Anand et al., 2017). Operational deployments exist at Oslo Gardermoen (35,700 m^2 of apron) and Chicago O'Hare (697 m^2

taxiway sustaining 200,000 aircraft passes without cracking), though operating costs of approximately $2,400 per hr for a 10,000-ft runway limit full-runway applicability (Anand et al., 2017; Ceylan et al., 2014). The technology is most appropriately positioned as a site-specific candidate for targeted deployment at high-volume northern airports, contingent on favorable benefit-cost outcomes, rather than near-term programmatic adoption.

Pilot Project and Demonstration Opportunities

The technologies evaluated in the preceding sections were cross-referenced with the six identified industry gaps to identify which technologies are positioned for near-term pilot implementation.

Vehicle-Mounted Systems for Pavement Inspection.

The condition assessment technologies, taken together, form a progression away FOG PCI inspection. Vehicle-mounted systems represent the most immediate upgrade: no airspace authorization is required, vehicle access procedures under 14 CFR §139.329 are well established, and field validation at an international airport demonstrated full runway coverage in 3 days versus 3 weeks for 43 manual sampling units on foot, with PCI agreement R^2 = 0.90 and section-level differences ≤2 points (Santos et al., 2020). sUAS inspection offers higher spatial resolution at comparable cost per square yard ($0.10–$0.25/yd^2 versus $0.08–$0.15 for FOG; Valecha et al., 2023), and at 2 mm GSD, orthomosaics were judged better quality than digital survey vehicle imagery for distress interpretation (Valecha et al., 2023). However, operational constraints at airports are substantial: Part 107 certification, VLOS requirements, DroneZone submission, HIRF compatibility, and capture times of approximately 2.25 hr for a 5,000- by 150-ft runway at the recommended resolution, followed by a minimum 2-day processing cycle (Valecha et al., 2023). FAA has explicitly designated pavement inspection as a UAS research application and stated that sUAS “cannot be used as a sole means of compliance with federal regulations and requirements and must be supplemented by traditional methods” until guidance is formalized. Additionally, low-severity joint seal damage, alkali-silica reaction, swell, and weathering/raveling showed no consistent detectable traits even at the highest tested resolutions (Sourav et al., 2023). Given these constraints, vehicle-mounted systems may represent the more immediate transition from FOG inspection, with sUAS positioned as a medium-term complement contingent on FAA guidance formalization and streamlined on-airport Part 107 authorization. The relative suitability of each platform is also dependent on airport-specific context. Large hub airports with high daily operations and limited closure windows may favor vehicle-mounted systems for their lower coordination burden; smaller general aviation airports with more flexible airspace access and longer available inspection windows may be better candidates for early sUAS adoption under the current Part 107 framework.

IC, IRTP, DPS, and 3D Machine Control

IC, IRTP, DPS, and 3D Machine Control produce real-time data during construction, but that data is not currently connected to the acceptance framework. P-401 acceptance is determined by cores under the C-110 PWL method; nuclear density gauge is permitted for contractor QC monitoring (§401-5.3f). IC ICMV indexes correlate well with FWD stiffness but poorly and inconsistently with core density (Sivagnanasuntharam et al., 2021), which is the acceptance metric. DPS correlates dielectric to density, but calibration accuracy varies with aggregate type, mixture design, and layer thickness as shown through correlations (R^2) ranging from 0.52 to 0.98 across nine roadway projects (Diefenderfer & Nair, 2025). IRTP identifies temperature differential zones that predict AV variability. The causal chain from thermal segregation to post-compaction density to long-term performance is established in the literature (Sebesta et al., 2024). The result is that each of these tools functions as a contractor process-control aid, useful for identifying problems during paving and guiding corrective action. The transition from supplementary QC tool to an acceptance-level instrument requires, for each technology, a documented correlation between the tool's output and the performance indicator specified in P-401, demonstrated across a representative range of airfield mix types, climates, and aggregate sources. FHWA characterizes IC for asphalt mats as at the "field demonstration" stage with evolving verification requirements for acceptance (Von Quintus et al., 2023), which is an accurate description of where all four technologies currently sit relative to the airfield framework. Structured pilot programs that collect IC, IRTP, DPS, and core data on the same projects across multiple airports would accelerate this transition.

HiMA, BMD, and M-E Pavement Design

From an operational standpoint, HiMA has a lower adoption barrier than most high-performance alternatives in the dataset. Binder substitution does not require aggregate source changes, supplier transitions, or the specialized production controls associated with gap-graded mix types such as SMA. Laboratory and field data document rut depth reductions of 35–40 percent, approximately 3.5 times greater predicted fatigue life, and potential asphalt pavement thickness reductions of 46–54 percent at equivalent fatigue performance (Kwon et al., 2020; Habbouche et al., 2018). These benefits are not captured by volumetric acceptance criteria, which may classify HiMA and conventional PMA mixes as equivalent under current P-401 requirements. In addition, FAARFIELD presents two structural design limitations: (1) fixed modulus inputs (200,000 psi surface, 400,000 psi stabilized base) provide no design credit for HiMA's enhanced stiffness regardless of binder modification (AC 150/5320-6G); and (2) the layered elastic framework lacks constitutive damage models to capture fatigue life extension and damage tolerance, which are HiMA's primary performance benefits. BMD provides the performance testing framework through which HiMA's rutting and cracking resistance can be measured and differentiated from a conventional PMA control. Established M-E design tools outside FAARFIELD, such as

FlexPAVE, accept measured dynamic modulus, fatigue cracking, and rutting model coefficients as inputs and are capable of translating those measured material property differences into structural thickness and lifecycle predictions. A structured pilot at two to three airports, pairing HiMA and conventional P-401 control sections with full BMD characterization and parallel M-E design analyses, would generate the airport-specific performance data and the documented comparison between tool-predicted and measured structural behavior needed to support a future FAARFIELD enhancement proposal.

Research Needs and Draft Problem Statements

Research Need 1: M-E Design Framework Enhancement for Different Mix Types

FAARFIELD is the tool mandated by AC 150/5320-6G §3.2 for structural design on federally funded projects; it implements layered elastic analysis for flexible pavements and 3D FEA for rigid pavements, with fixed modulus inputs for P-401 HMA layers set at 200,000 psi (surface) and 400,000 psi (stabilized base) regardless of the actual mix type or binder modification used. It also does not include constitutive damage models to capture the material's damage tolerance or cracking performance. Thus, no structural design credit is available within FAARFIELD for the enhanced stiffness, fatigue resistance, or damage tolerance of HiMA, EME2, SMA, or any BMD-optimized mix.

Current BMD test methods and evaluation frameworks present a parallel and compounding limitation. While BMD indexes can distinguish the performance of innovative mixes from conventional dense-graded P-401, these indexes are empirical in nature. They do not yield fundamental material properties, such as dynamic modulus master curves or fatigue properties, that can be used directly as inputs to M-E pavement design. In other words, BMD can detect that a HiMA mix outperforms a conventional mix in cracking and rutting resistance, but the data produced cannot be readily ingested by an M-E design engine to quantify that advantage as a structural or economic benefit.

Other established M-E design tools used in highway practice, e.g., FlexPAVE, accept material-specific inputs including measured dynamic modulus, fatigue cracking, and permanent deformation parameters, and are capable of differentiating the structural behavior of innovative materials and conventional dense-graded mixes at the design stage. These tools are not currently authorized for use in federally funded airfield design and have not been calibrated against airfield-specific loading spectra, aircraft gear configurations, or the pavement layer configurations typical of FAA-funded construction.

The consequence is a two-sided gap: (1) the structural design framework cannot credit the performance advantages of innovative mixes, and (2) the mix evaluation framework does not produce the fundamental properties needed to feed an M-E analysis even if such a framework were authorized. An airport engineer designing a new runway with a HiMA surface course could demonstrate via BMD that the mix outperforms conventional P-401 in both rutting and cracking resistance but could not translate that performance advantage into a thinner pavement section, a longer design life, or a lower lifecycle cost within the existing FAARFIELD framework.

The research need can thus be divided into three areas: (1) developing or adapting performance test methods that yield fundamental material properties from the same test protocol used for mix evaluation, such that a single test procedure serves both BMD and M-

E design, (2) establishing that one or more existing M-E design tools can be applied to airfield pavement structures with sufficient accuracy to support design decisions, by calibrating transfer functions, damage models, and climate inputs against airfield-specific loading spectra and NAPTF test section data, and (3) defining the pathway by which calibrated M-E design results can be accepted within the FAA regulatory framework (e.g., either through formal incorporation into FAARFIELD or through authorization of validated external tools as an alternative compliance pathway).

A framework of this kind, where a single test method supports mix design, performance screening, M-E design, and potentially QA, would represent a meaningful consolidation of the material characterization effort currently distributed across separate workflows. This framework could provide a pathway toward climate-region-independent thresholds. Unlike empirical BMD indexes, fundamental material properties can in principle be applied within constitutive models across varying temperature and loading environments. This distinction matters more for the FAA than for any individual State DOT. The FAA administers a national program in which P-401 must perform consistently across airports spanning hot and cold climates, diverse aggregate sources, and aircraft loading conditions that differ fundamentally from highway traffic. Thus, a framework grounded in fundamental material properties could, in principle, support a single set of threshold values that produce equivalent levels of pavement performance across the full range of conditions under FAA jurisdiction, which covers airports spanning diverse climatic regions, materials, and loading conditions across the United States.

Research Need 2: Temperature Correction Protocols for Traffic-Speed Deflectometer Data in Airfield Applications

The TSD has demonstrated capability for high-speed network-level structural assessment and its documented use at Copenhagen Airport, where 189 km of runway pavement was surveyed in 4 hr with viscoelastic backcalculation of layer moduli and detection of slab joint movement (Nielsen & Jensen, 2022). However, TSD surveys conducted at different times of day or across seasonal data collection campaigns produce deflection measurements that are not directly comparable without correction to a common reference temperature. A test-track study conducted at 70 km/h demonstrated that TSD deflections are more sensitive to temperature variation than to survey speed, and that the AASHTO D0 temperature correction applies to TSD data, but also that temperature normalization is “the more critical step for multi-trip comparability” (Zhang et al., 2023). In addition, the TSD operates with a rolling dual-tire axle load; FAA’s primary structural evaluation device is the HWD, which applies impulse loads representative of aircraft gear configurations. The correlation between TSD-derived deflection basin indices and HWD-measured structural capacity has not been established for airfield pavement sections. Existing studies that convert TSD basins to FWD-equivalent inputs (Zihan et al., 2020) have relied on highway data sections and have not been validated for airfield pavement structures. Therefore,

there is a need to develop and validate a temperature normalization procedure for TSD deflection data and establish the correlations between TSD-derived deflection basin indices (e.g., D0, SCI_12, D60) and HWD-measured structural indicators.

Research Need 3: Deflection Analysis of Distressed Airport Pavements for Remaining Life Prediction

Current FWD-based structural evaluation practice on distressed pavements faces a fundamental analytical limitation. When FWD is applied to a pavement section that contains transverse or longitudinal cracks, joint faulting, or partial delamination, the resulting deflection basin is discontinuous (i.e., sensor readings on opposite sides of a crack or fault may diverge in ways that cannot be interpreted using the continuum mechanics-based backcalculation software). In practice, this causes users to locate FWD test points on intact pavement sections to obtain interpretable deflection basins, which means that the structural evaluation deliberately excludes the most deteriorated areas of the pavement, precisely the areas for which remaining life prediction and layer-specific diagnosis are most critical. Multiple studies have demonstrated that neural networks trained on layered elastic outputs can predict layer moduli from deflection basins with high accuracy under controlled conditions. However, this accuracy does not transfer to distressed pavements, because the forward model used to generate training data assumes a continuous, intact pavement structure. Where that assumption fails, as it does whenever a crack, joint, or delamination is present in the sensor footprint, the modulus predictions produced by the network are not physically meaningful. The research gap is therefore not in the system identification algorithm; it is in the forward model of distressed pavement behavior, without which no analytical method, conventional or AI-assisted, can reliably diagnose layer-level structural deficiency from surface deflection data on cracked or deteriorated airport pavements. Therefore, research is needed to develop a methodology to estimate remaining structural life from deflection data on distressed sections without requiring the evaluator to locate intact zones that may not represent the sections requiring treatment decisions. In addition, the methodology should be able to identify, from deflection data collected on or near distressed pavement, which layer is the primary source of structural weakness (distinguishing surface course deterioration from base course failure from subgrade weakness). This capability would help determine whether rehabilitation should be limited to mill-and-overlay, should extend through the base course, or requires FDR.

Implementation Roadmap

The findings from the technology scoring, gap analysis, focus group discussions, and practitioner survey collectively support a structured, phased roadmap for technology research and integration into airfield pavement practice.

Key Research Questions and Gaps

Three research questions were identified. The first addresses the calibration and regulatory integration of M-E design tools, together with the development of material characterization approaches that provide inputs capable of crediting the structural benefits of advanced mix types. FAARFIELD assigns fixed modulus inputs of 200,000 psi (surface) and 400,000 psi (stabilized base) to all P-401 HMA layers regardless of binder modification, providing no design credit for the enhanced stiffness, fatigue resistance, or damage tolerance of HiMA or BMD-optimized mixes. Established M-E tools used in highway practice accept material-specific inputs but have not been calibrated against airfield loading spectra or NAPTF test section data and are not currently authorized for federally funded airfield design.

The second concerns temperature normalization and load-equivalency protocols for TSD data. TSD deflections are more sensitive to temperature variation than to survey speed, making normalization the critical step for multi-trip comparability (Zhang et al., 2023). In addition, the correlation between TSD-derived deflection basin indices and HWD-measured structural capacity has not been established for airfield pavement sections.

The third concerns deflection analysis of distressed airport pavements for remaining life prediction. Current backcalculation software assumes an intact, continuous pavement structure; when FWD is applied near cracks, joint faults, or delaminations, the resulting deflection basin cannot be interpreted by existing models, causing users to exclude the most deteriorated areas from structural assessment. A forward model of distressed pavement mechanical response, and a surrogate analytical method capable of layer-level diagnosis and remaining life estimation from deflection data collected on deteriorated sections, are needed to close this gap.

Institutional Leadership

The technology categories evaluated suggest a set of natural institutional roles that can be identified from the participants, organizations, and regulatory authorities engaged throughout this project.

The Office of Airports Safety and Standards (AAS) holds primary responsibility for all airport program matters related to standards for airport design, construction, maintenance, and operations, and serves as the focal point for oversight of the Airport Cooperative Research Program. The Airports Engineering Division, housed within AAS, is responsible for engineering standards and research for design, equipment, and airfield development at

civil airports, and is responsible for facilitating innovative methods of improving airport infrastructure. Any regulatory pathway for BMD adoption, advanced mix type acceptance under P-401, or FAARFIELD enhancement requires formal engagement with AAS through the MOS process governed by FAA Order 5300.1G.

The NAPTF provides high-quality, accelerated test data from rigid and flexible pavements subjected to simulated aircraft traffic. The facility consists of a controlled, enclosed test bed 900 ft long and 60 ft wide where full-scale airport pavement sections are constructed from the subbase up through the finished surface. The primary purpose of the NAPTF is to generate full-scale pavement response and performance data for development and verification of airport pavement design criteria. NAPTF is the main facility capable of generating full-scale airfield loading data under representative aircraft gear configurations, which is a prerequisite for calibrating M-E design tools to airfield conditions and for validating the performance of advanced mix types under aircraft loading.

FHWA has led the development and deployment of the technologies most immediately relevant to this roadmap's short-term phase. FHWA's IC deployment initiative included a 3-year transportation pooled fund study involving 16 IC demonstrations in 13 States, and IC has since been promoted through FHWA's Every Day Counts program. FHWA has published a practice for including IC, IRTP, and DPS in QA programs (FHWA-HIF-23-007), and the agency's construction QA program web page consolidates guidance and specifications for e-Ticketing and digital QA tools. As of the most recent FHWA technical brief on IC specifications, 23 States had developed asphalt IC specifications, and FHWA and AASHTO had developed national IC guide specifications. The methodology, tooling, and field data developed under FHWA programs represent the most immediately transferable knowledge base for airfield adaptation pilots.

The States and institutions whose published research on specific technologies is drawn upon directly in this assessment represent the most defensible set of pilot program partners. Virginia's VTRC produced the DPS density correlation data (Diefenderfer & Nair, 2025) and maintains an active BMD research compendium covering performance threshold development across multiple mix types. Veta is the data management platform required by FHWA IC specifications, AASHTO PP80, AASHTO PP81, and more than 25 State DOT IC and PMTP specifications. Its development and maintenance are sponsored by MnDOT through the Transportation Pooled Fund program (TPF-5(334)) in partnership with MnROAD. Texas A&M Transportation Institute has conducted TSD implementation research for TxDOT, comparing TSD and FWD deflections across multiple districts and developing structural classification procedures for network-level treatment decisions, with the TSD+GPR+FWD integrated workflow. Each of these institutions maintains laboratory and field infrastructure relevant to the pilot programs described in this roadmap.

Phased Implementation Approach

The findings support a structured, 10-year roadmap organized into three phases. Technologies are sequenced by readiness level, regulatory pathway complexity, and dependency relationships. Figure 20 shows how the technologies are organized across a 10-year horizon into short-term (1–2 years), medium-term (3–5 years), and long-term (6–10 years).

	Short-Term (1–2 years)		Medium-Term (3–5 years)			Long-Term (6–10 years)				
Technology	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
e-Ticketing & Digital QA	Expand Deployment									
Fixed FOD Detection Systems	Expand Deployment									
Energy-Efficient Asphalt Plant Technologies	Expand Deployment									
High-Density Longitudinal Joints	Expand Deployment									
Runway Texture & Friction Monitoring	Expand Deployment									
Airfield Base and Subbase Technology	Expand Deployment									
Fuel-Resistant Asphalt Mixtures	Expand Deployment									
Ground Penetrating Radar (GPR)	Expand Deployment									
Vehicle-Mounted Pavement Inspection	Pilot		Expand Deployment							
Computer Vision / AI for Remote Sensing	Pilot		Expand Deployment							
IC / IRTP / DPS / 3D Machine Control	Pilot		Expand Deployment							
Highly Polymer Modified Asphalt (HiMA)	Pilot					Expand Deployment				
Balanced Mixture Design	Research		Pilot			Expand Deployment				
Traffic-Speed Deflectometer (TSD)	Research		Pilot							
M-E Pavement Design	Research					Pilot		Expand Deployment		
ML/AI for NDT Interpretation	Research					Pilot				
Progressive & Alternative Contracting Methods			Pilot			Expand Deployment				
sUAS Pavement Inspection			Pilot							
Building Information Modelling & Digital Twins			Pilot					Expand Deployment		
Physics-Informed AI for Performance Prediction			Research			Pilot				
EME2 / SMA / WMA / RAP / FRAC						Expand Deployment				
Self-Sensing Asphalt Materials								Pilot		

Source: AAPTP

Figure 20. Phased Implementation Roadmap for Advanced Airfield Pavement Technologies

Phase 1: Short-Term (Years 1–2)

Technologies suitable for expanded deployment include:

- **e-Ticketing & Digital Quality Assurance:** Not subject to MOS under FAA Order 5300.1G; deployable immediately as the data infrastructure layer for IC, IRTP, and DPS integration.
- **Fixed FOD Detection Systems:** Fully specified under AC 150/5220-24, AIP-eligible at large-hub airports, and documented at a B/C ratio of 1.22 (break-even Year 9), rising to B/C 2.64 (break-even Year 3) when indirect costs and partial wildlife fringe benefits are included (Hilburn & Pesmen, 2023).
- **Energy-Efficient Asphalt Plant Technologies:** Documented measures include aggregate stockpile enclosures cutting drying energy by 10–14 percent (Young, 2008), burner retrofits recovering ~$8,000 investments in under six months (Young, 2008), and temperature reductions from 180 °C to 125 °C reducing plant energy and CO_2 by 35 percent (Hassan, 2010).
- **High-Density Longitudinal Joints:** Actionable under existing P-401 §401-4.14 provisions; at Yakutat Airport, echelon paving and IR joint heaters eliminated ~600 m^3 of wasted asphalt (Chitnis et al., 2024), with IR joint heater costs documented at $0.12/linear ft in separate highway evaluations (Williams, 2011).
- **Runway Texture and Friction Monitoring:** Already embedded in airfield practice under AC 150/5320-12C and AIP-eligible; near-term action is integrating laboratory macrotexture testing into the BMD acceptance framework.
- **Airfield Base and Subbase Technology:** Seven specification items exist in AC 150/5370-10H; deployment proceeds under current specs while characterization data is accumulated for FAARFIELD modulus input updates.
- **Fuel-Resistant Asphalt Mixtures:** Specified under existing P-404; total project cost increase is typically 5–7 percent, with application expanded from aprons to taxiways and runways (Corun, 2023).
- **Ground Penetrating Radar (GPR):** Continue targeted use and pilot advanced interpretation methods, as GPR is already recognized in FAA guidance and operationally mature, but its broader impact is limited by interpretation challenges.

Technologies that can be piloted:

- **Vehicle-Mounted Pavement Inspection:** Pilot concurrently with **Computer Vision/AI for Remote Sensing**. No airspace authorization required; field validation demonstrated coverage of all 270 sampling units in 3 days versus 43 sampling units in 3 weeks on foot, with PCI agreement at $R^2 = 0.90$ (Santos et al., 2020).
- **IC, IRTP, DPS, and 3D Machine Control:** Pilot to establish correlations between process control outputs (e.g., ICMV, temperature differentials, etc.) and acceptance metrics (e.g., in-place density) across varying mix types, aggregates, and climatic

conditions to help transition these technologies from QC tools to acceptance-level instruments within the FAA framework.

- **Highly Polymer Modified Asphalt (HiMA):** Pilot as part of the joint HiMA–BMD–M-E bundle as it offers significant performance gains (rutting, fatigue life, and thickness reduction) with minimal adoption barriers but requires BMD and M-E integration to properly quantify and incorporate its benefits into FAA design and acceptance practices.

Technologies that require further research:

- **Balanced Mixture Design (BMD):** Initiate training and continue research and benchmarking; advance BMD toward performance-based frameworks that generate fundamental material properties, enabling direct use of test results as inputs to mechanistic–empirical (M-E) design.
- **Mechanistic-Empirical (M-E) Pavement Design:** Because FAARFIELD uses fixed layer moduli and lacks fatigue damage modeling, which provides no credit for advanced materials, there is a need to validate and calibrate existing M-E design tools/models for airfield conditions (using appropriate transfer functions, damage models, climate inputs, and NAPTF data) and establish a clear pathway for their acceptance within the FAA framework.
- **Traffic-Speed Deflectometer (TSD):** Initiate temperature correction and HWD load-equivalency research; deflections are more sensitive to temperature than to survey speed (Zhang et al., 2023).
- **NDT Data Interpretation:** Develop forward models and analysis methodologies capable of interpreting deflection data from cracked and deteriorated pavements, enabling reliable remaining life prediction and layer-specific diagnosis.

Phase 2: Medium-Term (Years 3–5)

Technologies suitable for expanded deployment include:

- **Vehicle-Mounted Pavement Inspection:** Expand deployment following successful pilot validation and necessary specification and regulatory updates.
- **IC, IRTP, DPS, and 3D Machine Control:** Expand deployment following successful pilot validation and necessary specification and regulatory updates.

Technologies that can be piloted:

- **Progressive and Alternative Contracting Methods:** Pilot to test alternative contracting and delivery frameworks (e.g., PDB, CM/GC, PRS) as a means to overcome limitations of DBB and prescriptive specifications, while documenting their impact on the resulting cost, schedule, and performance outcomes in airfield projects; for example, CM/GC delivery was shown to produce mean durations of

662 days versus 2,106 days for DBB on comparable highway projects (Antoine et al., 2019).

- **Small Unmanned Aircraft Systems (sUAS) for Pavement Inspection:** Pilot as a complementary technology; current FAA restrictions and operational constraints limit it to a supplemental role, with vehicle-mounted systems representing the most immediate and practical transition from traditional foot-on-ground inspections.
- **Building Information Modelling & Pavement Digital Twins:** Pilot as data integration infrastructure; airport BIM has not yet extended to civil pavement infrastructure despite terminal-side adoption, and the technology is not expected to trigger MOS under FAA Order 5300.1G.
- **Balanced Mixture Design (BMD):** Move to pilot after tests, material indexes, and threshold values have been identified.
- **Traffic-Speed Deflectometer (TSD):** Move to pilot after addressing research needs in the first phase.

A technology that requires further research:

- **Physics-Informed AI for Performance Prediction:** Conduct research to develop, validate, and standardize physics-informed AI models that integrate mechanistic principles with data-driven approaches for reliable, interpretable, and computationally efficient pavement performance predictions.

Phase 3: Long-Term (Years 6–10)

Technologies suitable for expanded deployment include:

- **Balanced Mixture Design (BMD):** Expand deployment following pilot validation by integrating BMD into P-401 as an optional or mandatory performance verification protocol to unlock the full pipeline of materials technologies currently blocked by prescriptive acceptance criteria.
- **Mechanistic-Empirical (M-E) Pavement Design:** Expand deployment following calibration and pilot validation, establishing accepted pathways for incorporating M-E tools into FAA design practice to enable material-specific performance predictions and design optimization beyond current FAARFIELD limitations.
- **Highly Polymer Modified Asphalt (HiMA):** Expand deployment following pilot validation and integration with BMD and M-E frameworks, enabling its performance benefits to be formally recognized within FAA design and acceptance practices.
- **EME2/SMA/WMA/RAP/FRAC:** Deploy following specification modernization (e.g., BMD adoption and P-401 updates), as these technologies are already validated and represent a ready pipeline of high-performance materials that can be implemented once performance frameworks are in place.

- **Progressive and Alternative Contracting Methods:** Expand deployment following pilot validation and regulatory alignment, incorporating alternative delivery and performance-based contracting approaches into standard FAA practice to improve cost, schedule, risk allocation, and asset performance.

Technologies that can be piloted:

- **NDT Data Interpretation:** Move to pilot after forward models and analysis methodologies have been developed, enabling field validation of deflection-based remaining life prediction and layer-specific diagnosis on distressed pavements.
- **Physics-Informed AI for Performance Prediction:** Move to pilot by using validated models as surrogate analysis tools in design applications, comparing their predictions against conventional mechanistic methods to assess accuracy, interpretability, and practical value.
- **Self-Sensing Asphalt Material:** Move to pilot as technology advances to sufficient maturity as a scalable alternative to discrete sensors to enable structural monitoring and integration with pavement digital twin platforms.

Implementation Barriers and Recommended Actions

Four categories of barriers were identified across the survey, focus group, and literature synthesis findings.

Specification rigidity: The specification is described by practitioners as “restrictive and inconsistently interpreted,” and its prescriptive volumetric criteria and fixed FAARFIELD modulus inputs prevent performance-based differentiation among mix types. The recommended action is to pursue BMD adoption and alternative contracting through the MOS pathway in the short term, using pilot program data as the evidentiary basis, while simultaneously initiating the research programs that would support a more comprehensive P-401 revision in the long term.

Design tool limitations: FAARFIELD’s fixed-modulus architecture prevents lifecycle cost quantification for advanced mix types, which prohibits the primary economic argument for their adoption. The recommended action is to use validated M-E tools outside FAARFIELD for pilot design and analysis to generate the comparison data that would motivate and support a FAARFIELD enhancement proposal. FAARFIELD updates require NAPTF calibration data and FAA internal development cycles; the research and pilot programs in this roadmap are designed to supply both inputs.

Workforce and training gaps: Survey respondents identified lack of knowledge about mixture design among FAA personnel, airport engineers, and designers as a recurring barrier. The recommended action is to integrate structured training into each phase of the roadmap. Training delivery should be coordinated with the pilot program schedule so that practitioners receiving training have concurrent access to live demonstration data.

Budget and institutional risk aversion: Smaller airports and contractors face cost barriers that limit access to advanced technologies; larger institutions are described as risk-averse and rooted in traditional methods. The recommended actions are structured phasing so that low-cost, low-risk technologies with existing AIP eligibility are prioritized first; documentation of quantified cost and performance outcomes from pilot programs in a form accessible to airports; and engagement of trade associations to communicate field evidence to practitioners.

Generative AI as an Advanced Technology in This Project

Generative AI was proposed as part of the methodology of this project not only as a practical tool for managing large data volumes, but also because it represents the most rapidly advancing frontier of technology currently being developed. The associated literature remains too early in its development to support the kind of structured evidence synthesis applied to the other 51 technologies evaluated in this report. As reported by NCHRP Project 23-12 "Artificial Intelligence Opportunities for State and Local DOTs," natural language processing, a subfield of AI from which generative AI tools have emerged, accounts for only approximately 1.5 percent of the roughly 4,000 pavement-related abstracts identified across a corpus of 65,000 transportation publications. This small percentage reflects the speed at which these tools are evolving relative to the publication cycle. Incorporating generative AI into the project's own workflow, therefore, allowed the team to develop firsthand, applied understanding of where these tools perform reliably, where they fail, and what safeguards are necessary.

Generative AI was employed at two stages of this project, both of which involved data volumes that could not be practically managed through manual review alone. In Phase 1, a custom classification pipeline was applied to an initial corpus of 10,677 article titles and abstracts collected from over 30 public repositories to identify and categorize candidate technologies into nine thematic families, ultimately extracting 97 candidate technologies for further consideration. In Phase 2, a semi-automated synthesis pipeline processed 3,469 full-text publications, averaging 68 documents per technology for 51 technologies, using vector store capabilities and model access through APIs to retrieve, evaluate, and consolidate information for later scoring across 10 dimensions. A key QC mechanism embedded in this pipeline was the LLM-as-a-Judge approach, in which a language model was deployed as an automated evaluator rather than a generator, scoring each AI-produced summary against four criteria (factual accuracy, tone neutrality, information completeness, and technical depth), each on a 1–3 scale, with failed outputs routed through a correction loop before re-evaluation. This mechanism was introduced specifically in response to findings from iterative human QA reviews conducted on a subset of technologies prior to finalizing the pipeline, which identified recurring issues including incorrect unit conversions, misattributed citations, promotional framing, double-counted benefits across dimensions, and omission of negative findings. These problems were traced in part to the generative model's tendency toward positive framing and to the fact that source publications themselves frequently emphasize benefits over limitations.

Several cautions apply to the broader adoption of similar workflows in pavement engineering practice. AI outputs are highly sensitive to prompt design, the context window provided, model selection, and instruction structure, such that superficially similar configurations can produce materially different results; the pipeline described here required seven distinct prompts and multiple end-to-end development iterations before

outputs reached acceptable quality. The outputs generated by the pipeline should not be treated as authoritative. Even with LLM-as-a-Judge evaluation and human QA review at the final stage, manual post-processing remained necessary to remove coverage logs, internal tracking artifacts, extraneous punctuation, and abbreviation handling residuals from every report produced. The primary operational constraint encountered was the API rate limit, which imposed a ceiling on parallel processing and increased total compute time to approximately 50 min per batch of 45 documents. As agentic AI systems become more capable and less costly to deploy, the opportunity to embed AI-assisted monitoring and synthesis into routine research workflows is substantial. That opportunity is best realized, however, through engineered systems that combine structured prompting, automated evaluation, and human oversight checkpoints, staffed by practitioners who understand where these models tend to fail and what strategies exist to detect and correct those failures before results propagate into technical decision-making.

The applications demonstrated in this project represent early but concrete evidence of what AI-assisted workflows can contribute to large-scale engineering synthesis tasks. As model capabilities continue to advance, as context windows expand, and as agentic architectures mature, the class of problems that can be meaningfully addressed through AI assistance will broaden considerably beyond literature synthesis into domains that have historically required extensive manual effort and specialized expertise. The asphalt paving industry, which has historically faced a significant imbalance between the volume of available technical information and the practitioner capacity to synthesize it into actionable guidance, stands to benefit disproportionately from these developments. The workflows, QC mechanisms, and lessons documented in this project are intended to serve not only as a record of what was done here, but as a transferable methodological foundation upon which future efforts can build with greater confidence and efficiency.

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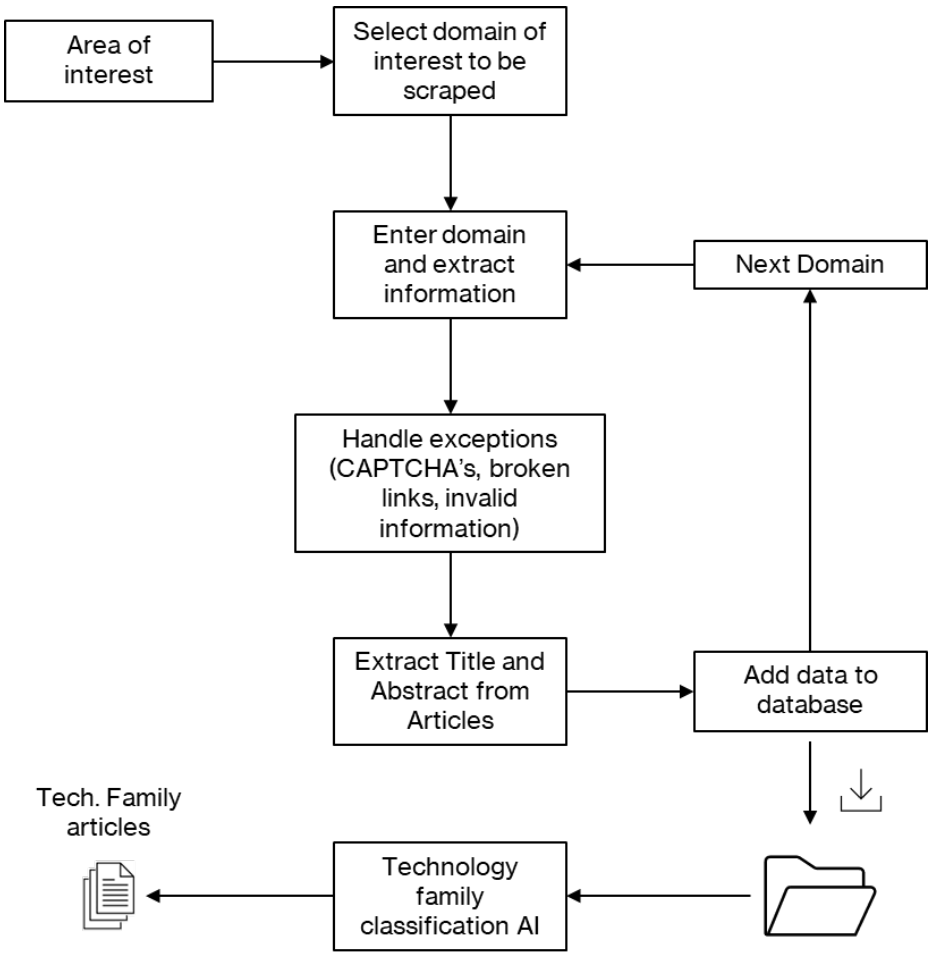
Appendix A

Domain Search and Information Extraction

The team web-scraped, collected, and parsed 10,677 abstracts from more than 30 targeted repositories and conferences. Figure A-1 presents a flowchart illustrating this activity. Sources included:

- TRB Annual Meeting Program 2025
- Transportation Research International Documentation (TRID)
  - 'Aviation': January 2024 onward
  - 'Pavement': March 2024 onward
  - 'Asphalt': October 2024 onward
- Transportation Research Board (TRB) Research Needs Statements (RNS)
  - 'Highways', 'Materials', 'Aviation', 'Pavements': 2022 onward
- International Conference on Asphalt Pavements (ISAP) 2024
- International Union of Laboratories and Experts in Construction Materials, Systems, and Structures (RILEM)
  - Spring Convention and Conference 2024
  - Transforming Construction: Advances in Fiber Reinforced Concrete 2024
  - International Workshop on the Use of Biomaterials in Pavements 2024
  - International Conference on Concrete and Digital Fabrication 2024
  - Pavement, Roadway, and Bridge Life Cycle Assessment 2024
  - Testing and Experimentation in Civil Engineering 2023
- American Society of Civil Engineers (ASCE) International Conference on Transportation and Development 2024
- ASCE International Conference on Transportation and Development 2023
- ASCE International Airfield and Highway Pavements Conference 2023
- Australian International Flexible Pavement Conference 2023
- Canadian Technical Asphalt Association (CTAA) 2023
- ASCE & COTA International Conference of Transportation Professionals
- International Conference on the Bearing Capacity of Roads, Railways and Airfields (BCRRA) 2022
- International Conference on Accelerated Pavement Testing (APT) 2020
- World of Asphalt 2025
- Digital Construction Week 2025
- Construction Research Congress (CRC) 2024
- International Conference on Unmanned Aircraft Systems (ICUAS) 2024
- AUVSI Xponential – Robotics Conference 2025
- IEEE Smart Cities 2023

- SSDM – American Society of Mechanical Engineers 2nd Annual Aerospace Structures, Structural Dynamics, and Materials Conference 2024
- AI4MAT – AI for Accelerated Materials Discovery 2025



Source: AAPTP

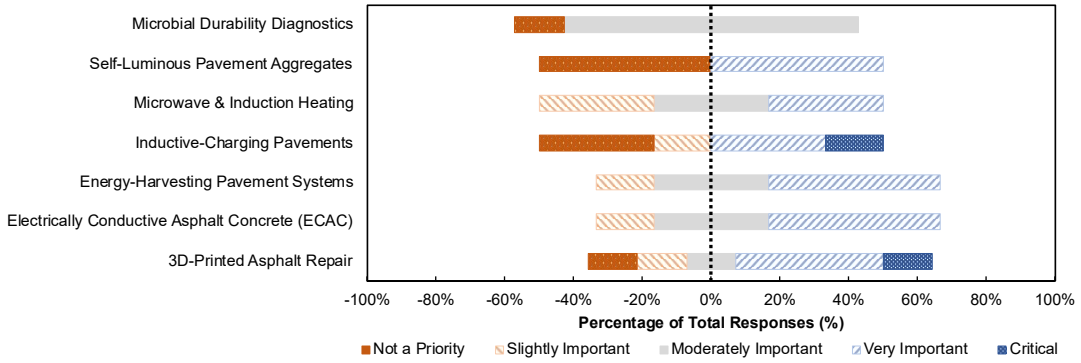
Figure A-1. Domain Search and Information Extraction Flowchart

This flowchart illustrates the process of accessing (entering) a selected domain to retrieve articles relevant to a given area of interest. As part of this process, a dedicated step is included to handle exceptions that may disrupt the automated identification and extraction of valid information assets. These exceptions may include CAPTCHA challenges, broken links, non-relevant documents (e.g., committee briefings or policy statements), and other unforeseen interruptions. Once these issues are addressed, all accessible articles containing titles and abstracts are downloaded and integrated into the project's literature database for that specific area. If additional domains are available for that topic, the process is repeated accordingly. Upon completion of the data collection phase, the

compiled articles are classified into one of the nine predefined technology families established in Phase 1.

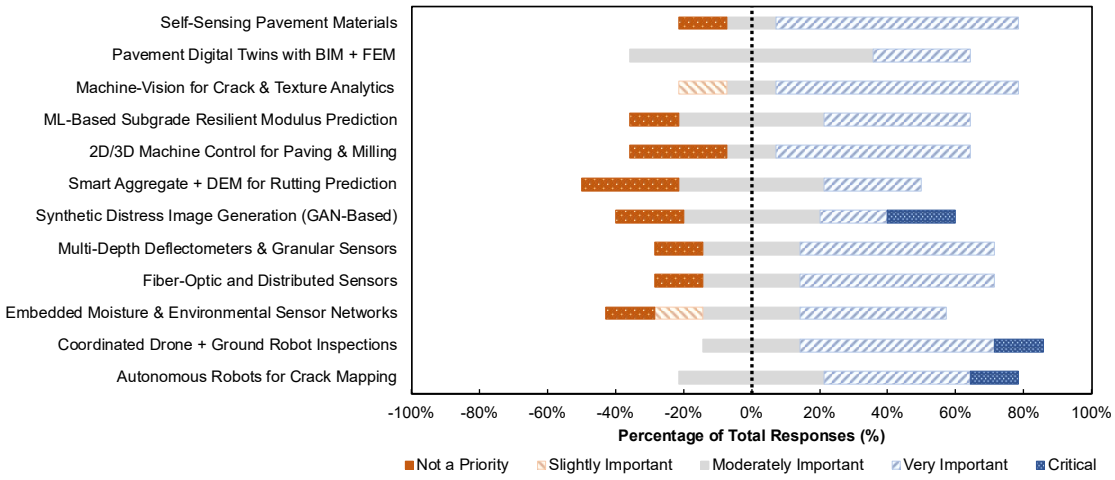
Appendix B

Figure B-1 through Figure B-9 present the detailed distribution of ratings across all nine technology families.



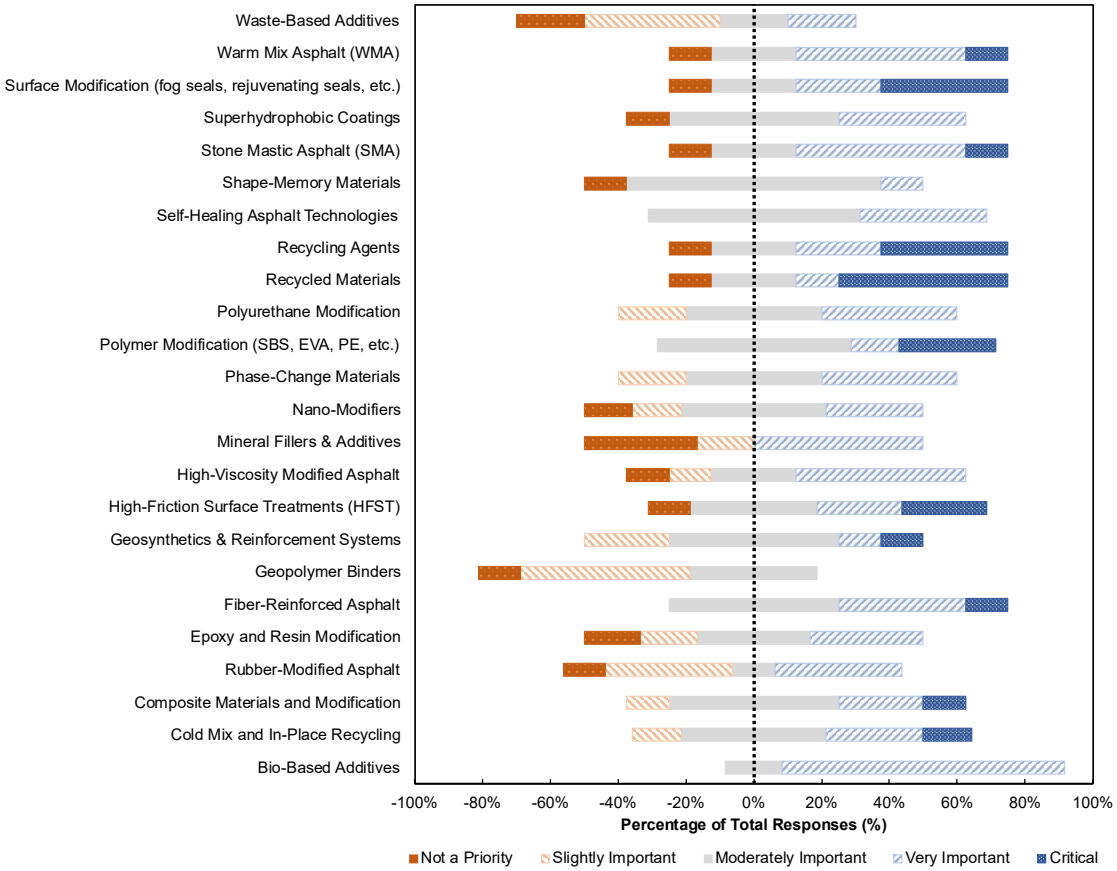
Source: AAPTP

Figure B-1. Panel Survey Results for Advanced and Emerging Concepts



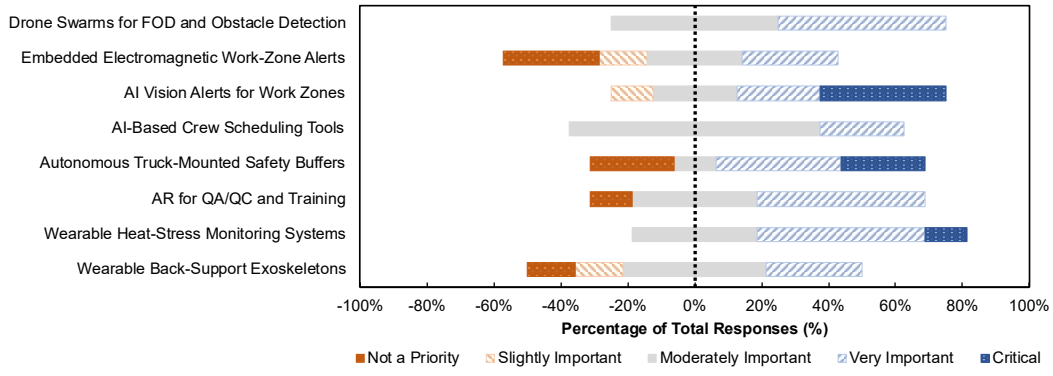
Source: AAPTP

Figure B-2. Panel Survey Results for Digital and Smart Technologies



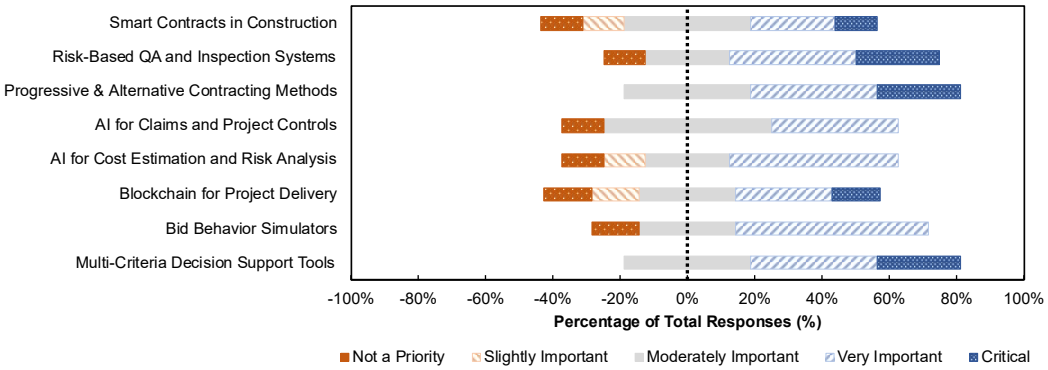
Source: AAPTP

Figure B-3. Panel Survey Results for Materials and Mixtures



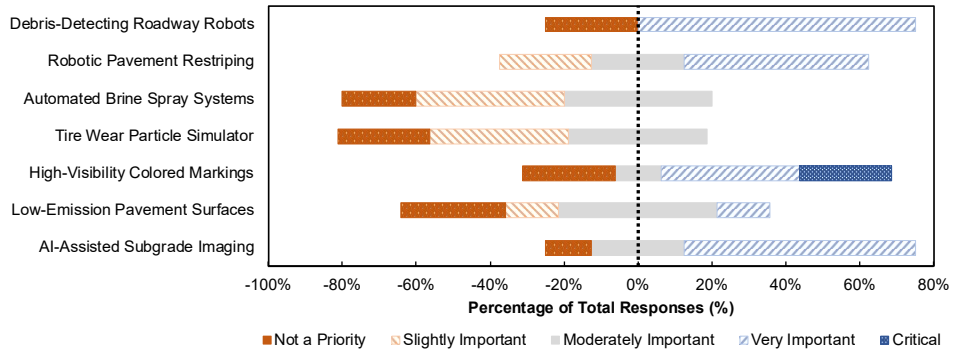
Source: AAPTP

Figure B-4. Panel Survey Results for Peripheral and Enabling Technologies



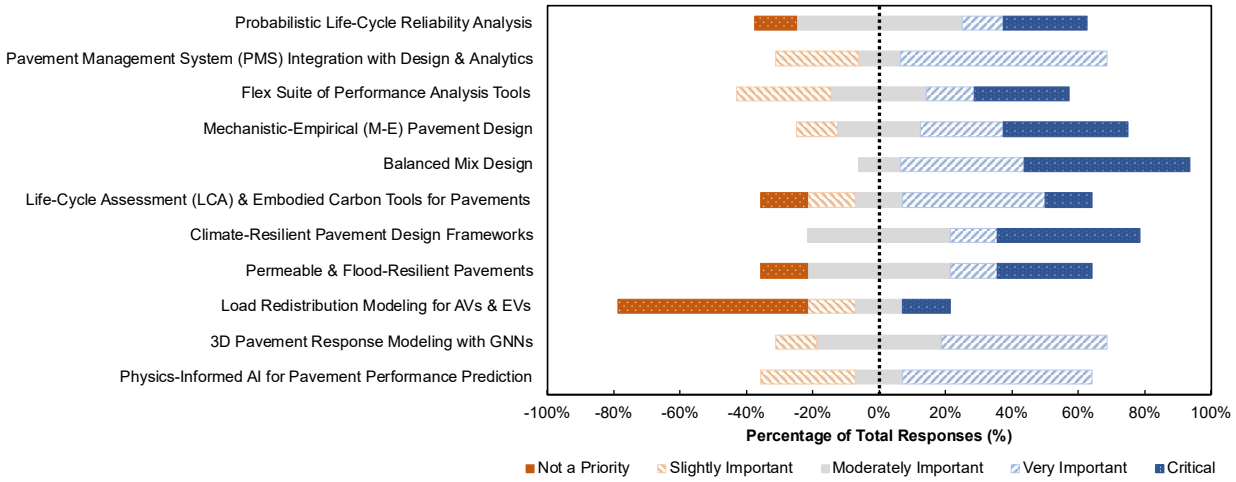
Source: AAPTP

Figure B-5. Panel Survey Results for Project Delivery and Contracting



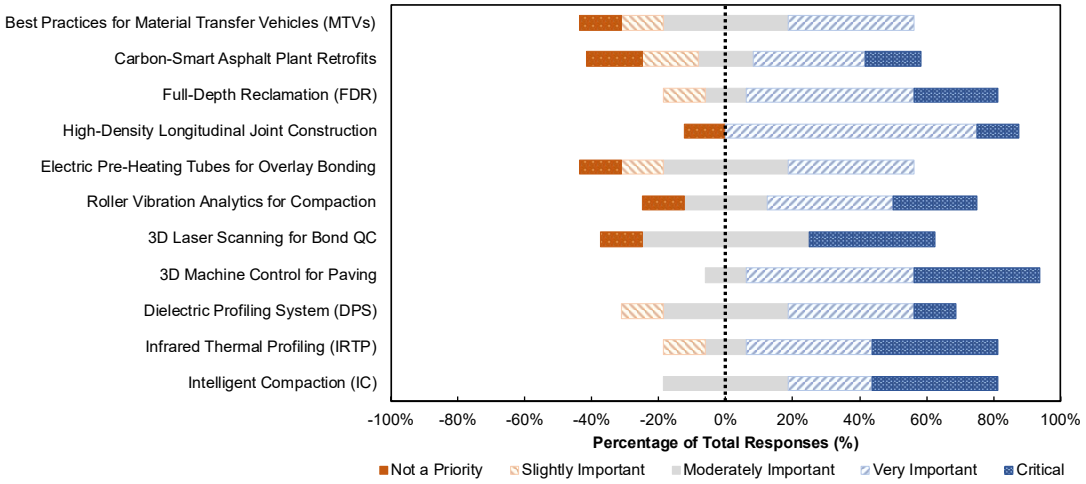
Source: AAPTP

Figure B-6. Panel Survey Results for Other/Uncategorized Cross-cutting



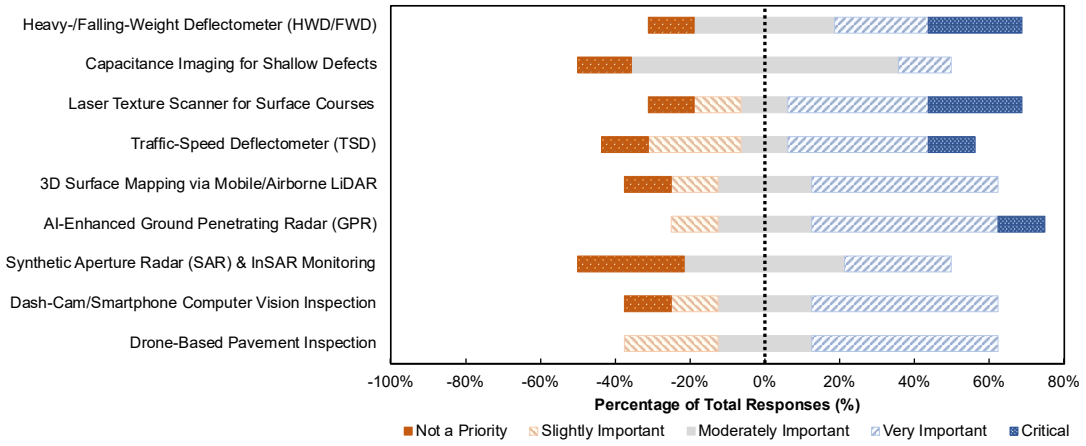
Source: AAPTP

Figure B-7. Panel Survey Results for Pavement Design and Analysis)



Source: AAPTP

Figure B-8. Panel Survey Results for Production and Placement



Source: AAPTP

Figure B-9. Panel Survey Results for Evaluation and Performance Monitoring

Appendix C

Survey introduction

Dear Expert,

Thank you for participating in this research effort to identify and understand asphalt pavement technologies that may be ripe for application in airfield pavements. This survey aims to gather expert insights on advanced asphalt pavement technologies that have been researched, piloted, or implemented on asphalt airfield pavements in recent years. These technologies can include innovations in asphalt materials and modifiers, mix design, specifications, structural design, quality assurance and control, construction methods, production and placement, data-driven tools (including AI and BIM), embedded sensors, procurement and contracting approaches, workforce-enabling technologies, and other novel practices.

The survey will ask you to name the technology, indicate its maturity, and rank its impact, feasibility, benefits, and challenges. The information collected will contribute to a robust methodology to prioritize technologies based on their readiness levels, impact, and feasibility for short-term and long-term implementation. Your input will help ensure the methodology reflects both expert knowledge and contextual sensitivity.

This survey will take approximately 10-15 minutes to complete. All responses will be kept confidential and used solely for research purposes.

If you have any questions or require assistance, please do not hesitate to contact Dr. Nooralhuda Saleh at noor.saleh@continuumis.com, Felipe Do Canto Pivetta at felipe.pivetta@continuumis.com, or Dr. Y. Richard Kim at kim@continuumis.com. Thank you in advance for your participation and contribution to this study.

Thank you for your time and contribution to this important initiative.

Questionnaire Instructions

1. Use the Next and Previous buttons at the bottom of each page to navigate through the questionnaire.
2. On the final page, click Submit to complete the survey. A summary of responses will be available for viewing and printing after submission.
3. While the survey is compatible with mobile devices, completing it on a laptop or desktop computer is recommended for optimal readability and usability.

General Information

1. Organization Type (Multiple choice)
   - ◯ Airport Operator / Owner
   - ◯ Government (DOT, CAA, etc.)
   - ◯ Consultant
   - ◯ Contractor
   - ◯ Academia
   - ◯ Other

2. Role (Multiple choice)
   - ◯ Executive Leadership
   - ◯ Engineering / Design
   - ◯ QC / QA / Testing
   - ◯ Construction Management / Maintenance
   - ◯ Research
   - ◯ Other

3. Location (Multiple choice)
   - ◯ North America
   - ◯ Central America/Caribbean
   - ◯ South America
   - ◯ Europe
   - ◯ Middle East
   - ◯ Africa
   - ◯ Asia/Pacific

4. Years of Experience (Multiple choice)
   - ◯ < 2 Years
   - ◯ 2 – 5 Years
   - ◯ 5 – 10 Years
   - ◯ 10 – 15 Years
   - ◯ > 15 Years

Technology Implementation Screening

5. Has your organization researched, piloted, or implemented any advanced technologies on asphalt airfield pavements within the past 5 years? (Multiple choice)
   Advanced technologies may include innovations in asphalt materials and modifiers, mix design, specifications, structural design, quality assurance and control, construction methods, production and placement, data-driven tools (including AI and BIM), embedded sensors, procurement and contracting approaches, workforce-enabling technologies, and other novel practices.
   ◯ Yes
   ◯ No

Technology Details

Please provide information about any advanced technology your organization has researched, piloted, or implemented on asphalt airfield pavements. You'll be asked to briefly describe the technology, indicate its stage of deployment, and share your experience with its impact and feasibility. This helps us understand how the technology performs in real-world conditions and what challenges or benefits are observed.

6. Technology Name (Short text)
7. Brief Description (Short text)
   A short sentence about what the technology does.
8. Stage of Use (Multiple choice)
   ◯ Concept
   ◯ Lab-Scale
   ◯ Field Pilot
   ◯ Limited Deployment
   ◯ Full Implementation

9. Performance Rating (Multiple choice)
   How well does this technology perform its intended function in comparison to current practices? Consider accuracy, reliability, and overall effectiveness in detecting pavement issues or delivering useful results.
   ◯ 1 (Worse than current practice)
   ◯ 2
   ◯ 3
   ◯ 4
   ◯ 5 (Exceptional performance)

10. Return on Investment Rating (Multiple choice)
How cost-effective is this technology compared to current practice? Consider whether the benefits justify the total cost (equipment, labor, lifecycle, etc.).
◯ 1 (High cost, low benefit)
◯ 2
◯ 3
◯ 4
◯ 5 (Excellent value for cost)

11. Safety Rating (Multiple choice)
How much does this technology improve safety for personnel compared to current methods? Consider exposure to hazards and risk reduction.
◯ 1 (Increases safety risk)
◯ 2
◯ 3
◯ 4
◯ 5 (Eliminates safety risk)

12. Efficiency Rating (Multiple choice)
How efficiently does this technology support operations and project delivery compared to standard practice? Consider speed, coverage, and reduction in work disruptions.
◯ 1 (Slower than current practice)
◯ 2
◯ 3
◯ 4
◯ 5 (Real-time, high-efficiency)

13. Sustainability Rating (Multiple choice)
How well does this technology support sustainability goals compared to current practice? Consider emissions, resource use, and environmental footprint.
◯ 1 (Worse than current practice)
◯ 2
◯ 3
◯ 4
◯ 5 (Exemplary environmental benefit)

14. Technical Barrier Rating (Multiple choice)
How difficult is this technology to implement from a technical standpoint? Consider reliability, integration with current systems, and need for advanced expertise.
◯ 1 (Major technical challenges)
◯ 2
◯ 3
◯ 4
◯ 5 (No technical barriers)

15. Adoption Cost Barrier Rating (Multiple choice)
How accessible is this technology in terms of overall affordability for agencies or contractors?
◯ 1 (Prohibitively expensive)
◯ 2
◯ 3
◯ 4
◯ 5 (Easily Affordable)

16. Regulatory/Operational Barrier Rating (Multiple choice)
How easily can this technology be deployed within existing regulations or operational practices?
◯ 1 (Major regulatory hurdles)
◯ 2
◯ 3
◯ 4
◯ 5 (No regulatory/operational barriers)

17. Stakeholder Acceptance Rating (Multiple choice)
How likely are relevant stakeholders (e.g., owners, operators, crews, regulators) to adopt and support this technology?
◯ 1 (Low stakeholder acceptance)
◯ 2
◯ 3
◯ 4
◯ 5 (Readily accepted)

18. What unmet needs or gaps in airfield pavement practice is this technology intended to address? (Short text)
19. What is the biggest benefit of this technology based on your experience? (Short text)
20. What is the biggest challenge or barrier of this technology based on your experience? (Short text)

21. Do you have any documents, links, or materials you can share to support this submission?
    Your upload will only be used for internal project analysis and will not be shared without permission. (Upload)
22. Would you like to add another technology? (Multiple choice)
    ◯ Yes
    ◯ No

    If "Yes" is selected, jump to Technology Details
    If "No is selected, jump to Focus Group Interest

Additional Input and Interest

23. In your view, what are the most pressing gaps or challenges in asphalt airfield pavement design, construction, or maintenance today? (Short text)
24. Your perspective is valuable. We would greatly appreciate the chance to follow up with you if needed. If you are willing to support us, please share your name and email address below. (Short text)
25. Is there someone else you recommend we reach out to? Please enter their name and email address below. (Short text)
26. Comments (Long text)

Appendix D

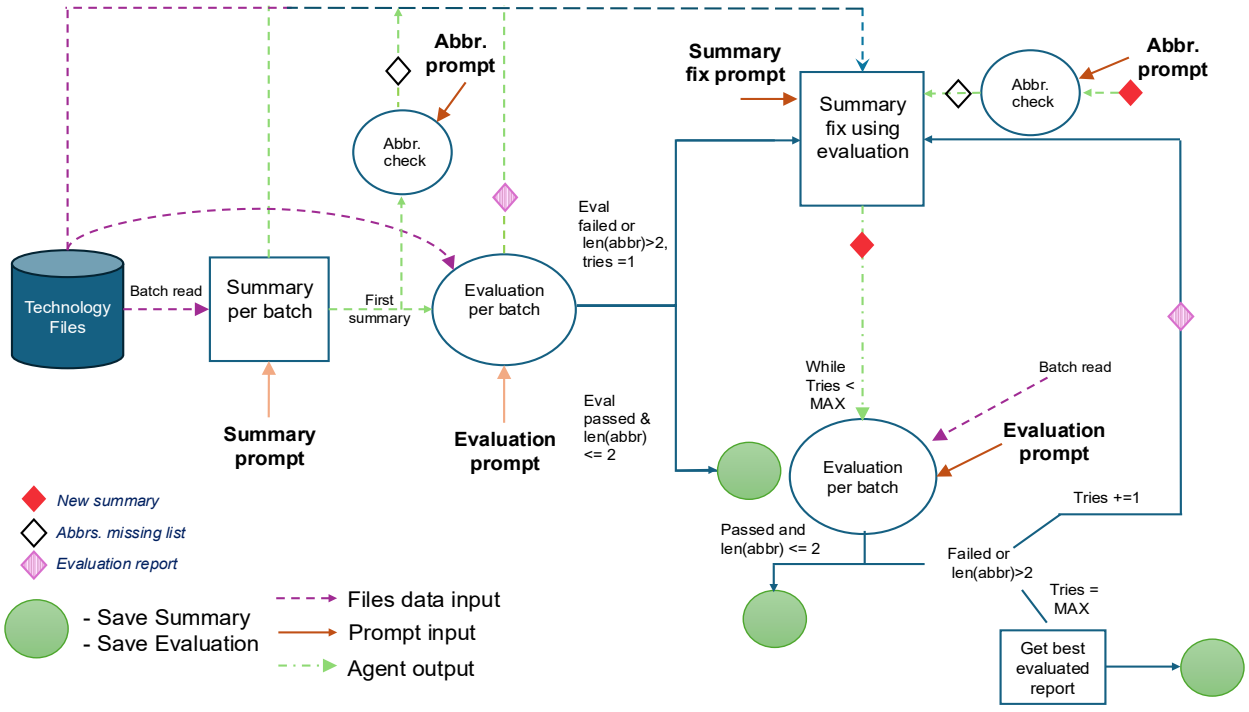
Batch-Level Evaluation Stage

Figure D-1 illustrates the step-by-step process of the Batch-Level Evaluation stage. In this stage, summaries are generated for each technology in batches, depending on the total number of files to be processed. Dividing the files into batches enables the AI system to structure, manage, and retrieve large volumes of information reliably.

The batch-level evaluation process for each technology begins by creating a vector store and uploading the corresponding files. The vector store is configured with a chunk and an overlap so that the text segments maintain sufficient contextual continuity. From this point until the consolidation stage, the following steps are performed for each batch:

1. The batch is read from the vector store, and the corresponding text is provided as input to the summary prompt.
2. This initial summary is then processed simultaneously by two components:

- The evaluation prompt assesses the summary according to the criteria defined in Table D-1.
- The abbreviation checker verifies that all abbreviations appearing in the summaries are properly expanded upon first use.



Source: AAPTP

Figure D-1. Batch-Level Evaluation Stage Pipeline

Table D-26. Summarization Evaluator Scoring Criteria

Criterion	Description	Scoring Guidelines
Factual Accuracy	Measures whether the statements in the summary are supported by the evidence contained in the batch of files. Evaluates citation validity, correctness of claims, and presence of contradictions.	3: All statements supported or only minor inaccuracies. 2: One or two vague or unsupported claims. 1: Multiple errors, contradictions, or false attributions.
Tone Neutrality & Realism	Assesses the neutrality and objectivity of the text, penalizing exaggerations, promotional tone, or speculative language.	3: Completely neutral and analytical tone. 2: One or two mildly promotional or speculative phrases. 1: Repeated bias, exaggerated tone, or unsupported optimism.
Information Completeness	Evaluates how comprehensively the summary covers the key aspects of the topic, including both benefits and limitations.	3: Complete and balanced coverage. 2: Minor omissions or missing details. 1: Major gaps or missing contextual information.
Expert Robustness & Depth	Measures the technical depth and clarity of the summary, checking for appropriate use of terminology, explanation of mechanisms, and acknowledgment of uncertainty.	3: Detailed, accurate, and technically sound explanation with explicit distinctions (e.g., correlation vs. causation). 2: Generally accurate but lacks technical depth or specificity. 1: Contains technical inaccuracies, vague jargon, or missing quantitative details.

After the evaluation and abbreviation checking steps, the results are analyzed to determine whether the summary requires correction. The decision to pass or fail the evaluation is based on quantitative thresholds derived from the evaluator's scoring output.

A summary is considered to fail the evaluation or the abbreviation check if any of the following conditions are met:

- The Factual Accuracy score is below 3.
- The Tone Neutrality & Realism score is below 2.
- The Information Completeness score is below 2.
- The Expert Robustness & Depth score is below 3.
- There are more than two unsupported claims identified in the evaluation.
- There are more than three instances of missing key information detected.
- The abbreviation checker identifies more than four unexpanded abbreviations across the summary (*missed_abbreviations* > *4*).

If none of these conditions are met, the summary is marked as Pass, indicating that it satisfies the quality standards for factual correctness, neutrality, completeness, technical depth, and clarity of abbreviations. If the summary is marked as Fail, the system sends the

current summary, the list of missing abbreviations, the corresponding PDFs, and the evaluator's feedback to a correction prompt, which revises the summary accordingly. This evaluation–correction loop is repeated until either the summary passes the evaluation or a predefined maximum number of attempts is reached.

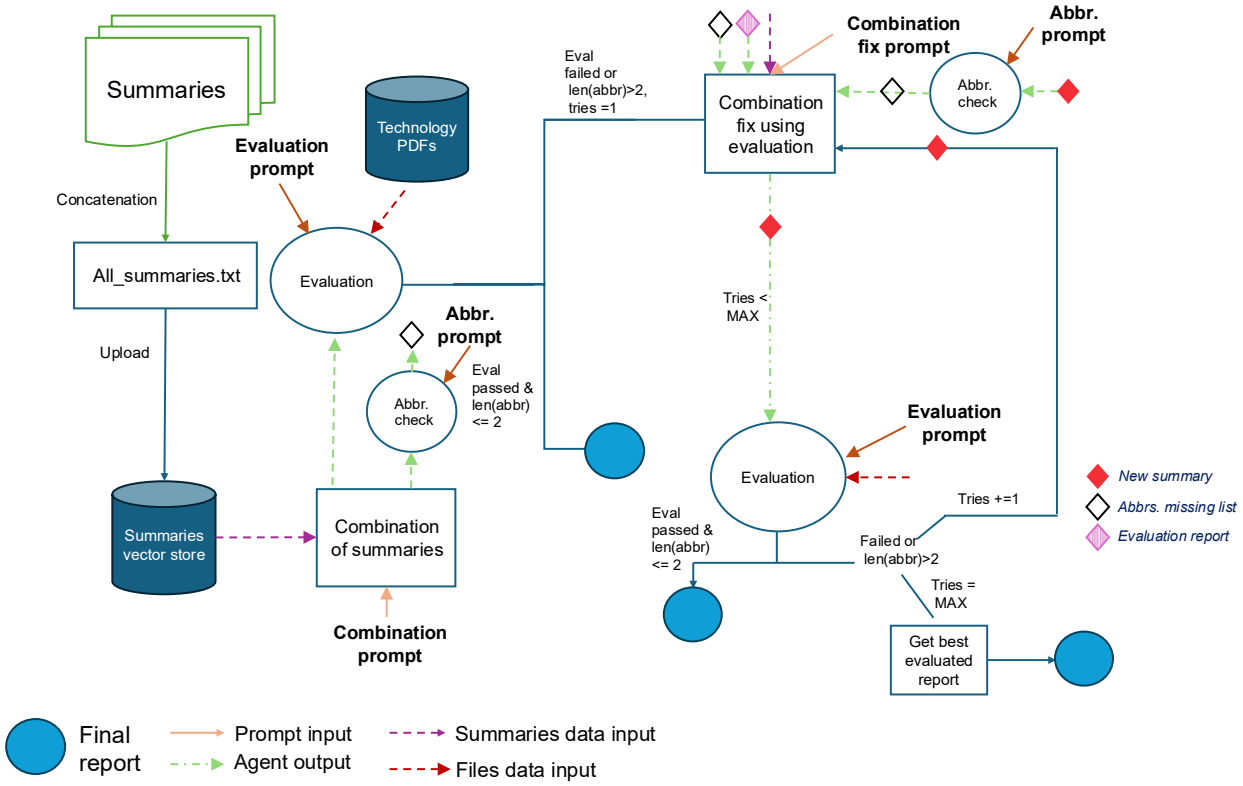
If no version achieves a Pass after the maximum number of tries, a "best" summary is selected among all evaluated versions. The best summary is defined as the one that, in order of priority:

1. Has the lowest number of unsupported claims.
2. Achieves the highest Factual Accuracy score.
3. Achieves the highest Expert Robustness & Depth score.
4. Achieves the highest Tone Neutrality & Realism score.
5. Achieves the highest Information Completeness score.
6. Has the fewest partially supported claims.
7. Has the fewest missing key information items.
8. In the case of a tie on all previous criteria, corresponds to the most recent evaluation.

This procedure guarantees that, even if no summary fully meets all thresholds, the final selected summary is the one with the overall strongest evaluation profile. This process is repeated until all files in the vector store have been processed.

Consolidation Stage

Once all batches have been summarized, the resulting summaries are concatenated into a single file, which is then uploaded to a new vector store. This consolidated vector store, together with the original files, serves as the input for the Consolidation step, as illustrated in Figure D-2.



Source: AAPTP

Figure D-2. Consolidation Stage Pipeline

The concatenated summaries are processed through a combination prompt (using gpt-5) to generate a single report. Once this report is produced, it undergoes both an evaluation and an abbreviation check. The abbreviation check follows the same procedure as in the summarization stage.

However, in the evaluation process, the combined report is evaluated in batches of PDFs, where each batch represents a subset of the documents stored in the vector store. For every batch, the report is analyzed using only the evidence contained within that batch. To ensure that context and continuity are preserved across batches, the output of each evaluation is used as input for the next one. This allows previously unsupported claims to be re-evaluated once the corresponding evidence becomes available in subsequent batches. After all batches have been evaluated, their results are merged into a single consolidated evaluation. This merging process aggregates claim-level data, citation tracking, abbreviation compliance, and rubric scores into a unified assessment of the final report.

The evaluation in the combination stage uses six main criteria, each scored from 1 to 3, where 3 indicates the highest level of quality and 1 the lowest, as shown in Table D-2.

Table D-27. Combination Evaluator Scoring Criteria

Criterion	Description	Scoring Guidelines
1. Factual Accuracy	Validates that all claims in the report are supported by evidence contained in the processed PDFs, without hallucinations, misquotes, or false attributions.	3: All claims supported; no factual or citation errors. 2: Minor unsupported or vague claims. 1: Multiple factual errors, contradictions, or misquotes.
2. Tone Neutrality & Realism	Ensures the text remains impersonal, objective, and free of promotional or speculative language.	3: Entirely neutral and analytical tone. 2: Occasional mild subjectivity. 1: Repeated hype, bias, or persuasive framing.
3. Information Completeness	Measures whether the report provides a balanced overview of the topic, including all relevant benefits, limitations, and details.	3: Complete and balanced coverage. 2: Minor omissions or missing subsections. 1: Major gaps or incomplete lists.
4. Expert Robustness & Depth	Assesses the level of technical rigor, clarity of reasoning, and distinction between correlation and causation.	3: Accurate, detailed explanations with clear methodology and parameters. 2: Generally correct but lacks depth or technical specificity. 1: Technical inaccuracies, misuse of terminology, or superficial analysis.
5. Quantitative Integrity	Verifies that numerical data and ranges are correctly represented, consistently attributed, and free from cross-study conflation or fabricated conversions.	3: All quantitative data properly sourced and consistent. 2: Minor numeric ambiguities. 1: Evidence of conflated or misrepresented quantitative data.
6. Citation Hygiene & Abbreviation Compliance	Ensures that citations follow correct formats, authors are properly attributed, and abbreviations are expanded and used consistently.	3: All citations valid and abbreviations compliant. 2: Minor formatting or abbreviation issues. 1: Missing citations, invented attributions, or inconsistent abbreviations.

Each batch produces an independent evaluation containing the above six scores. Once all batches have been processed, the results are merged into a final consolidated evaluation using a weighted consensus method.

- If all batches show consistent support, the claim is marked as supported.
- If some batches partially support a claim while others do not, it is marked as partially supported.
- Contradictory evidence across batches leads to the status marked as contradicted.
- Claims with insufficient or missing evidence remain unsupported.

During consolidation, a programmatic component aggregates results and overlapping evidence, merges proposed edits, and computes final rubric scores. These are determined

through majority voting among batches and adjusted by detected violations, such as factual misstatements, incomplete lists, or range conflations.

Finally, the system produces a merged evaluation report, which includes:

- Overall rubric scores for each criterion,
- Aggregated counts of supported, partially supported, contradicted, and unsupported claims,
- A summary of missing key information,
- Proposed edits to improve factual accuracy, consistency, or tone, and
- A concise editorial summary describing the main findings.

Once the evaluation and abbreviation checks are completed, the system determines whether the final report passes or fails based on defined thresholds. A report is considered to fail if any of the following conditions are met:

- Factual Accuracy score is below 3.
- Tone Neutrality & Realism score is below 3.
- Information Completeness score is below 3.
- Expert Robustness & Depth score is below 3.
- There are more than two unsupported claims in total.
- There are more than three instances of missing key information.
- The abbreviation checker detects more than three unexpanded abbreviations.

If none of these conditions are met, the report is marked as Pass. Otherwise, the report is considered as Fail and a repair loop is triggered: the evaluation output, the list of abbreviations to fix, the current version of the report, and the concatenated summaries are provided as input to a new prompt whose task is to revise and improve the report. The revised report is then re-evaluated with the same procedure. This process is repeated until the report passes the evaluation or a predefined maximum number of attempts is reached.

If no version achieves a Pass after the maximum number of attempts, the system selects the best-rated evaluation among all attempts. The “best” report is defined as the one whose evaluation satisfies, in order of priority:

1. Fewer unsupported (and contradicted) claims.
2. Higher Expert Robustness & Depth.
3. Higher Information Completeness.
4. Higher Tone Neutrality & Realism.
5. Higher Quantitative Integrity.
6. Higher Factual Accuracy.
7. Higher Citation Hygiene & Abbreviation Compliance.
8. Fewer severe violations, particularly range conflation, factual misquotes, and strong subjectivity.

9. Fewer instances of missing key information.
10. In the case of ties on all previous criteria, the most recent evaluation (newest file) is chosen.

Workflow Performance

The total processing time is approximately 50 min for a batch of about 45 files, though this duration may increase with a larger number of files. The process is subject to OpenAI API rate limits, requiring controlled pauses between requests to avoid exceeding usage thresholds. Because all operations rely exclusively on the OpenAI API, the workflow generates a large number of API calls, which in turn increases cost. The Consolidation stage is the most resource-intensive step of the pipeline. Manual post-processing is still required to refine the final outputs. This includes the removal of non-essential elements such as:

- Coverage logs.
- Checklists or internal tracking data.
- Reference verification notes.
- Extraneous punctuation (e.g., isolated ".").
- Abbreviation handling checks.

This approach is scalable, as multiple batches for the same technology can be processed in parallel, significantly reducing total processing time. Furthermore, consolidation can be executed simultaneously across different technologies, because each process is fully independent. The primary constraint lies in the OpenAI API rate limits, which impose a maximum request frequency. Under the current configuration, it is possible to process three to four technologies concurrently, completing the entire workflow from summarization to combination in parallel without performance degradation.

A total of seven prompts were developed and used throughout the batch-level evaluation and consolidation stages. All prompts share the following guiding principles:

- **Zero Hallucination:** All factual content must come directly from the supplied files.
- **Neutral Tone:** Text must remain analytical and evidence-driven, avoiding promotional or speculative phrasing.
- **Citation Hygiene:** Every claim must be followed by a properly formatted *(Author et al., Year)* citation.
- **Abbreviation Control:** Abbreviations must be expanded on first use and remain consistent throughout.
- **Protected Editing:** Corrections are applied only where explicitly indicated by evaluator feedback to preserve content integrity.
- **Airport Emphasis:** Preference is given to data and evidence relevant to runway, taxiway, and apron applications.