E-Tickets and Advanced Technologies for Efficient Construction Inspections

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Research Report KTC-19-14/SPR18-554-1F

E-Tickets and Advanced Technologies for Efficient Construction Inspections

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16. Abstract			

The Kentucky Transportation Cabinet (KYTC), like many state transportation agencies, has seen demand for highquality infrastructure skyrocket even as it endures reductions in staff numbers. To mitigate the effects of declining staff and bolster construction efficiency, the Cabinet has experimented with a variety of e-construction technologies, the goal of which are to abolish paper-based workflows and improve project-site monitoring activities. This research investigated the performance of three e-construction technologies on KYTC pilot projects — e-ticketing, paver mounted thermal profilers, and intelligent compaction. E-ticketing reduced the amount of time needed to retrieve material tickets and facilitated comparisons of theoretical tonnages to actual tonnages. Inspectors also reduced their exposure to hazardous jobsite conditions through the use of e-ticketing, while contractors strengthened their operational efficiencies. Paver mounted thermal profilers collected temperature data whose accuracy was not significantly different from temperature data gathered using conventional infrared guns. The spatially continuous data generated by profilers can aid in later monitoring of pavement performance and can be used to perform forensic investigations of pavement distress. Although other state transportation agencies have adopted intelligent compaction with considerable success, it produced inaccurate data on asphalt temperature and roller passes. Several factors may have contributed to this unexpected result, such as poor communication between project stakeholders and incorrectly executed equipment setup. The three technologies could potentially be adopted on a more widespread basis; however, it is critical to offer adequate training to equipment and software users, ensure that project stakeholders coordinate and communicate with one another, and be conscientious in the deployment and management of equipment.

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Executive Summary

In response to growing demands for infrastructure as well as staff attrition, many state transportation agencies (STAs) are exploring new technologies that automate construction processes. Specifically, agencies are more aggressively pursuing e-construction technologies, which encompass methods and process that improve construction efficiency and safety by eliminating paper-based workflows and enhancing jobsite monitoring. This research evaluated, on behalf of the Kentucky Transportation Cabinet (KYTC), the performance of three e-construction technologies— e-ticketing, paver mounted infrared temperature sensors (IR) and intelligent compaction (IC). Researchers at the Kentucky Transportation Center (KTC) looked at the performance of each technology and how they can facilitate inspection activities, including the collection of ticket information, monitoring pavement temperatures, and measuring the compaction effort of asphalt, respectively.

Overall, each technology showed considerable promise. The use of e-ticketing significantly reduced the amount of time needed to retrieve material tickets. Another benefit of e-ticketing is that inspectors can more efficiently monitor and compare theoretical tonnage to actual tonnage; doing so helps inspectors verify that crews are paving according to specifications. Adopting e-ticketing also bolsters inspector safety, as they are no longer required to navigate a variety of hazardous situations, such as climbing onto the sides of trucks, walking adjacent to traffic, and working alongside heavy equipment. Contractors also benefited from e-ticketing. Knowing where haul trucks were located in relation to a jobsite helped them avoid paver stops — they could slow down production when incoming trucks were delayed. While e-ticketing performed well, to ensure its viability on future projects it will be critical to train stakeholders on the use of its technologies, confirm that all trucks assigned to a project have GPS transponders installed on them and appropriate geozones have been established, and verify all stakeholders are committed to open and proactive communication.

To evaluate whether IR technologies accurately measure mat temperatures, the Pave-IR system was installed on a paver by a contractor. Temperature data collected using the Pave-IR system were compared to temperatures measured using conventional infrared guns. No significant differences were found between the temperature data gathered using Pave-IR and infrared guns. One benefit of Pave-IR is that it records spatially continuous temperature data across a jobsite, whereas the use of infrared guns only lets inspectors perform spot checks of mat temperatures. Pave-IR is also useful for visualizing the impacts of paver speeds and the use of material transfer vehicles, which promotes the laying of pavement at more uniform (and higher) temperatures. Onsite staff can use real-time temperature data generated by Pave-IR to correct plant temperatures and hauling patterns. Should pavement distresses materialize at some point, data produced by Pave-IR and other sources can encourage a more forensic approach to analysis and the selection of corrective actions. As with e-ticketing, it is imperative that staff receive proper training on the technology and that stakeholders coordinate and communicate with one another to ensure that all interested parties can access data when needed.

Intelligent compaction rollers let roller operators access real-time data to improve compaction operations. To assess the performance of IC, data on temperature and roller passes were recorded using IC and conventional manual methods. Inaccuracies were found in the temperature and pass

data collected on the IC roller. While it is not clear how these errors arose, possible explanations include miscommunication between stakeholders, errors made during equipment setup, or the inherent uncertainties associated with highway construction projects. Many STAs have found success using IC to verify the quality of pavement structures and in eliminating guesswork when compacting fill materials. Because IC generates visualizations of the compaction process in real time, errors such as excessive overlap and incomplete roller passes can be eliminated. The technology can also improve roller patterns, reduce operating costs, improve pavement density and smoothness, and preserve better documentation of project work. Night work is also made easier when IC is used. Effective adoption of IC will require that stakeholders receive sufficient training to operate the equipment and software. Because the expense in purchasing IC equipment is significant, smaller contractors may be unwilling or unable to make those investments.

With respect to scalability and future use, 14 additional KYTC projects are slated to use eticketing. On projects with awarded bids, the average bid price for e-ticketing was \$1.04 per ton of asphalt material. As more suppliers, contractors, and Cabinet staff accumulate experience with e-ticketing, the unit cost and corresponding benefits will continue to improve. If e-ticketing is to be used effectively, suppliers will need capable IT systems and internet access, haulers will need to serve as willing partners and effectively manage GPS devices, and contractors will need to set up equipment and ensure all stakeholders have access to data. Some technical barriers must be overcome to implement e-ticketing statewide. For example, it may not be economical for lowvolume asphalt plants in rural areas to invest in the technology. And in some areas of Kentucky where GPS or internet connectivity is tenuous, leveraging e-ticketing may prove challenging. It may be possible to scale up use of IR and IC more immediately because they have been used more widely. Nonetheless, these technologies have limitations. Because IR equipment costs are significant, it may not be a cost-effective option on smaller projects. IC equipment must have access to accurate geospatial data and be properly calibrated. If operators lack the proper training or projects are situated in remote locations, the results may prove unsatisfactory.

1. Introduction

1.1 Background and Problem Statement

Due to growing infrastructure demands and staffing reductions, state transportation agencies (STAs) are increasingly looking to automate construction processes to increase productivity. NCHRP Synthesis 450 found that "STAs are managing larger roadway systems with fewer inhouse staff than they were 10 years ago. For the 40 STAs that responded to the [study's] survey, between 2000 and 2010 state-managed lane-miles increased by an average of 4.10%, whereas the number of full-time equivalents (FTEs) decreased by 9.68% (1)." STAs can potentially automate highway construction operations through the expanded use of e-Construction technologies. The Federal Highway Administration (FHWA) defines e-Construction as "The creation, review, approval, distribution, and storage of highway construction documents in a paperless environment (2)." E-Construction encompasses a wide range of technologies and processes that aim to improve construction efficiency and safety by eliminating the need to handle and track paper documentation. One collaborative e-construction technology that has shown promising results in the industry is e-ticketing.

Collecting load delivery tickets on highway construction projects is an outdated practice that exposes construction inspectors to many safety hazards. Activities such as walking in close proximity to moving equipment, climbing on the side trucks to retrieve paper tickets, and working next to high speed traffic increases the risk of accidents at construction sites. Additionally, archiving paper tickets for project documentation requires effort and resources to sort, organize, and store. This could be automated easily with a digital project delivery platform. E-ticketing technology lets users collect and document load delivery data electronically, allowing for safer and more efficient construction inspections and management. In addition to load delivery information, e-ticketing systems can provide data on load cycles and material installation (e.g., asphalt and concrete paving, concrete structures, earthwork, millings, and aggregate), which can be tracked through a combination of GPS and GIS technologies. Further, this combination provides crucial quality and productivity data that can be difficult to track using traditional methods.

Despite the benefits of using e-ticketing, implementation has been slow and challenging for many STAs. The Iowa Department of Transportation (DOT) conducted the nation's first eticketing pilot in 2015. This e-ticketing pilot offers lessons the Kentucky Transportation Cabinet (KYTC) can adopt to take advantage of enhanced safety and inspection opportunities. Iowa DOT partnered with industry to improve inspector safety, project documentation, and contractor efficiency. Using GPS and GIS technology tied to electronic scale report-out systems, a fleet tracking system traced haul routes, reported travel time and tonnage, and assisted contractors with equipment matching and balancing (using an efficient number of haulers with place equipment). Data from a system like this would be more thorough, accurate, and collected in a safer manner than current procedures the Cabinet adheres to. Since Iowa DOT's 2015 pilot, many states have tested these technologies as a potential replacement for traditional paper tickets.

Although e-tickets are generally regarded as superior to paper-based tickets, most states are only in the piloting stages of implementation. These pilots typically entail working with local contractors and technology vendors to create systems that meet agency needs. During the testing process, states are facing challenges such as choosing between an outside vendor of the technology or creating an in-house system, internal and/or external resistance to adoption, and a general lack of knowledge of the various uses of the technology in the industry. Beyond the expected challenges, successful implementation of e-ticketing can provide significant benefits to STAs, resulting in greater efficiency and safety improvements on highway construction projects.

E-ticketing is one tool used to perform enhanced asphalt inspection, but there are others with promise: paver mounted thermal profilers (IR) and intelligent compaction (IC). This research project supplements KYTC's ongoing e-construction initiatives, previously funded through the FHWA STIC program. However, this study fills an important void by tying multiple technologies together to achieve safer, more efficient inspection and transferring electronic records from the suppliers to the contractor and Cabinet. The central focus of this research is electronic supplier ticketing and GPS/GIS tracking of materials. Additional analysis examines combining of e-ticketing information with IR and IC.

1.2 Tasks and Objectives

The primary objectives of this research effort are to:

- Evaluate the performance of e-ticketing for construction inspections,
- Evaluate the performance of other e-construction technologies (e.g., real-time temperature readings, smart compaction, other equipment-based technologies),
- Conduct a pilot study rollout of selected inspection technologies, and
- Provide guidance on scalability and implementation of the inspection technologies.

1.3 Report Outline

This report outlines research activities conducted under the auspices of this project. Chapter 2 is an in-depth literature review that provides highlights federal efforts related to e-construction and provides and overview of material tracking technologies, thermal profiling technology, and intelligent compaction. Chapter 3 describes our methodological approach and introduces the pilot projects. Chapters 4 - 6 discuss the results of our pilot studies, which tested three technologies: e-ticketing, paver IR thermal profiler, and IC. The final chapter reviews key conclusions.

2. Literature Review

The research team conducted a review of literature and documented trials relating to e-ticketing, paver mounted thermal imaging devices, and intelligent compaction. The review begins with a broad examination of national initiatives and peer exchanges on e-construction and materials tracking. It then turns to focus on each of the technologies deployed on pilot projects during this research.

2.1 Federal Highway Administration's Everyday Counts (EDC) Initiative

The Everyday Counts (EDC) program began in 2009 as a joint venture between the FHWA and AASHTO and focuses on deploying new innovations, with the goal of accelerating highway project delivery in an economically responsible manner (3,4). The FHWA regards EDC as opening up opportunities for collaborations with state, local, and tribal governments and to promulgate new technologies and practices across the transportation industry (3). EDC runs on a two-year cycle. Wanting to secure buy-in from diverse stakeholders, in anticipation of a new cycle beginning, FHWA publishes a notice in the Federal Register which solicits recommendations for innovations to feature during the upcoming two-year period. The agency also discusses its plans with a stakeholder group whose members are from the transportation industry (3). Ultimately, innovations are chosen with an eye toward their market readiness, potential benefits and impacts, and ease of adoption (4). Once innovations for the impending two-year cycle have been selected. FHWA holds regional summits where they are discussed with state, local, and tribal agencies. The summits also provide a venue in which to begin developing performance goals and identifying opportunities for integrating innovations into agency practices. At the outset of each two-year cycle, FHWA also issues a baseline report which discusses the chosen innovations, the extent to which they have been implemented by U.S. states and territories, and goals for increasing their adoption by the cycle's end. Throughout the EDC process, FHWA tracks the deployment of innovations; this monitoring is used to gauge EDC's performance and the rate of innovation adoption at the state level. Aside from increasing the spread of innovations, a primary goal of EDC is to encourage productive risk taking at public agencies, which can be hesitant to embrace new technologies or practices if they have not yet been proven in the field.

Recognizing the use of paper documentation to administer highway projects made logistics, scheduling, and communications increasingly fraught and untenable, FHWA introduced e-Construction as an innovation during EDC-3 (2015–2016). In making this selection, the agency observed that paper documentation is cumbersome; expensive to create, process, and store; and hampers communication between project stakeholders. For EDC-3, FHWA broadly conceived of e-Construction as "the collection, review, approval and distribution of construction contract documents in a paperless environment" (5). The initiative sought to deploy readily available and already-proven technologies, including digital electronic signatures, electronic communications, secure file sharing, version control, mobile devices, web-hosted data archival and retrieval systems, and RFID tags for tracking the location of resources. In advocating for the use of e-Construction, FHWA cited the positive experiences of several state transportation agencies (e.g., Michigan and Florida's DOTs) as well as its ability to improve the quality, efficiency, environmental sustainability, and productivity of the construction industry. The baseline report

found that as of January 2015, 16 state agencies had institutionalized the use of e-Construction or were at the assessment or demonstration stages of deployment (Figure 1). By the end of EDC-3, FHWA's goal was to increase the number of states at one of these three stages to 36 and dramatically expand the number of states in which e-Construction was institutionalized (5).



Figure 1 Status of e-Construction Implementation Reported in the EDC-3 Baseline Summary

While EDC-4 (2017–2018) retained e-Construction as an innovation, the emphasis shifted to e-Construction and Partnering (eCP). Partnering is a project management technique where transportation agencies, contractors, and other stakeholders form a single team whose foundation is built on shared trust (6). Establishing a team helps to mitigate risk, enhance communication, minimize waste, quickly resolve issues, and fulfill project objectives. The EDC-4 baseline report found that transportation agencies made significant progress incorporating e-Construction into their business practices. By the conclusion of EDC-3, 35 states had reached the institutionalized, assessment, or demonstration stages, which indicates the FHWA nearly met the goals advanced at the beginning of EDC-3 (7). Wanting to sustain this momentum throughout EDC-4 the agency wanted to continue expanding the penetration of e-Construction to nearly all states, including reaching institutionalized status in 22 states (Figure 2) (7). However, there was less widespread use of e-Construction to strengthen partnering on construction projects. The FHWA saw this as a troubling gap, believing that partnering arrangements would become less effective without integrating e-Construction practices. The FHWA hoped to achieve the institutionalization of eCP in 14 states while moving eight additional states to the assessment stage.



Figure 2 Status of e-Construction Implementation Reported in the EDC-4 Baseline Summary

FHWA cited a number of benefits associated with eCP (6, 7). First, it provides greater transparency and gives project stakeholders the means to quickly resolve problems and minimize disputes. Significant time savings can also be realized through eCP by letting inspectors perform data collection and submit reports electronically. Likewise, project managers can more efficiently administer projects when they go paperless. Third, eCP can improve the safety of jobsites by reducing the amount of time inspectors are exposed to worksite hazards; the lack of paper documentation can also bolster safety because project stakeholders no longer have to carry physical records between project sites and offices. In relying on electronic documents, eCP trims project costs, fosters more productive communication, and lowers the number of change orders. Building stronger communication among stakeholders also builds an environment which values respect and mutual trust. Lastly, eCP supports better coordination and collaboration by increasing the transparency of workflows and giving stakeholders rapid access to information.

FHWA outlined a multi-part innovation goal in its EDC-4 work plan (7). A primary goal was to speed up the adoption of e-Construction and forge new standards that would root construction-related project management, communication, and workflows in e-Construction practices. Further, FHWA envisioned growing the use of sophisticated technology applications across state agencies. This included having inspectors adopt survey-grade positioning data on tablets as well as real-time data processing. At the regional summits held in the run up to EDC-4, attendees emphasized the importance of promoting the use of innovations like e-ticketing, remote video monitoring, and seamless data integration across project life cycles. In particular, FHWA viewed EDC-4 as an opportunity to promote e-ticketing to states classified as in the advancing stage. Another area in which the agency identified significant potential of e-Construction was in materials management and asset management, believing it use could produce significant cost savings.

Throughout 2018, FHWA helped organize and convene several peer exchanges that brought together state transportation agencies to discuss their experiences with eCP and future ambitions (8-10). A peer exchange held in Indiana included STAs from Indiana (INDOT), Oregon (ODOT), Pennsylvania (PennDOT), Utah (UDOT), and Wisconsin (WisDOT) (8). At INDOT, the current emphasis is on imagining e-Construction more expansively than as just paperless workflows, viewing it instead as providing the means to transform decision making into a datadriven process. Agency personnel are working to integrate digital data into every aspect of project delivery, including the adoption of 3D models as the legal contract; combining model information with construction inspection applications; developing metrics to calculate return on investment for e-Construction; and identifying new technologies to track material delivery, placement, and conditions. For the latter priority, the agency is interested in determining whether e-ticketing is beneficial for tracking materials and monitoring quantities when laying hot mix asphalt (HMA). INDOT staffers also shared challenges the agency has encountered in shifting toward an operational model founded on data-driven decision making, such as working with 3D models, nurturing an agency culture that embraces change, and investing in change management. Of the agencies participating in the peer exchange, only PennDOT had experience with eticketing for bulk materials. Looking at returns on investment, Ohio DOT has realized significant qualitative and quantitative benefits from mobile mapping systems and 3D engineered models. The key qualitative benefits have been accelerated project delivery and higher quality products while the agency has also accrued millions in savings. Representatives from WisDOT observed their agency has seen meaningful returns on investment from cloud-based plan review and documentation, including a reduction in change orders. Moving forward, stakeholders from all agencies agreed on the importance of devising strategies to integrate disparate e-Construction technologies to facilitate seamless workflows as well as clearly defining why electronic deliverables are important and how they should be used.

A peer exchange hosted by the Alabama Department of Transportation (ALDOT) brought together agency staff from Minnesota (MnDOT), Missouri (MoDOT), Oregon (Oregon DOT), and UDOT to explore how organizations can benefit from unmanned aerial systems (UAS) (9). Four of the six agencies currently have maturing UAS programs, having already selected platforms, sensors, and software for data capture and processing. Participating agencies noted they were able to experiment with and implement UAS technology by taking advantage of pooled fund research, developing partnerships spanning divisions and state agencies, through cost-sharing agreements, and by working with academic researchers and consultants. A particular focus of the peer exchange was discussing how to leverage UAS technologies for bridge inspections, construction quantity measurements, and surveying. In fact, a key motivation for introducing UAS programs — at least in these states — was the search for techniques that would facilitate safer, more efficient bridge inspections. For example, a study in Minnesota found the integration of UAS technologies into inspection practices saved 40 percent on bridge inspection costs. Meanwhile, the Oregon DOT found it can save up to \$10,000 per bridge by relying on UAS systems. Agencies have identified a growing number of use cases for UAS technologies, such as monitoring pavement to identify areas where delamination is occurring, documenting work zone traffic control, and measuring pay item quantities (e.g., earthwork and stockpile volumes, pay items based on area or linear metrics). While UAS technologies may be sufficient for quantifying bulk materials in some circumstances, such as measuring earthwork quantities along short roadway segments, it may not be appropriate for final pavement quantities,

such as where roadway segments are long enough that it is beyond the capabilities of visual-lineof sight flight. Other key advantages of UAS technologies are opening up access to complex terrain and structures, improving documentation through high-resolution imagery, and bolstering the efficiency of agency workflows through automated data collection and feature extraction. For organizations interested in developing a UAS program, agency representatives noted that it is critical to develop standardized procedures to ensure consistency, repeatability, and predictability. Also important for successful implementation is fostering an agency culture in which continuous learning is valued, as this can help key personnel stay informed on new advances as well as changes in regulations affecting UAS deployment.

A third peer exchange between the Virginia DOT (VDOT) and PennDOT focused on mobile technologies (10). Virginia requested the forum because of its recent decision to orient mobile strategies around readily available commercial-off-the-shelf applications; it wanted to glean information from PennDOT on its experience implementing mobile technologies. Despite getting an early start with e-Construction by adopting e-bidding and advertising in 2001, issues with funding and stakeholders have prevented a full rollout of e-Construction initiatives at VDOT. The agency wants to greatly expand its e-Construction footprint over the coming 2-3 years, however, with a focus on using mobile technologies to foster better inspection and testing, construction management, and acceptance and closeout processes. Virginia has funded research to assess the performance of mobile applications for documenting project site activities, accessing electronic plans, and collaborating with stakeholders. PennDOT relies on its Engineering and Construction Management System (ECMS) to support actions from bidding through construction closeout. PennDOT has done in-house development of its mobile computing solutions, which tie in with ECMS. Mobile applications reduce the use of paper, lessen the amount of duplicative data entry, and take full advantage of automated workflows. Cost-benefit analyses presented by PennDOT indicate the agency has saved over \$60 million through its e-Construction programs. Several key takeaway messages were elaborated based on the experiences of PennDOT and VDOT. First it is critical for an agency to develop a roadmap that imagines that status of e-Construction and mobile technologies in 5 to 10 years. Also, beginning small and slowly building a foundation is the surest way to achieve whatever goals are identified. One possible strategy for agencies to consider (and one adopted by PennDOT) is to use an agile method for developing new applications, which is an approach to project management that prioritizes small, continuous improvements. When first starting out, it is critical to focus on developing intuitive processes and workflows that will stimulate personnel to embrace new technologies, and which are also defined by their simplicity and produce consistent results.

2.2 Material Tracking

Technological advances over the past 30–40 years have increasingly sophisticated automated methods of tracking items ranging from packages, retail goods, and vehicles to concrete members, steel beams, and bulk materials. Construction industry stakeholders have gradually embraced an array of technologies such as Radio Frequency Identification (RFID), unmanned aerial vehicles (UAVs; also referred to as unmanned aerial systems [UAS] or drones), GPS, advanced image processing, LiDAR, barcodes, smartphones, and various software apps, seeing in their use the opportunity to shorten project durations, increase productivity, reduce manual labor and data entry, foster greater transparency, and support better recordkeeping (11, 12, 13,

14). Likewise, the highway construction industry, as part of a sweepingly ambitious push to automate more aspects of the construction process, has aggressively implemented many of these technologies (15). The pace of adoption will only accelerate in the coming years. This purpose of this section is to describe technologies used to track the whereabouts of materials on construction projects. For each technology, a concise description is provided along with documented use cases and salient references. The review is not intended to be exhaustive; its aim is to highlight important technologies which have been or could be used in systems for tracking and monitoring bulk materials. The following sections provide details on systems which have been designed or implemented for this purpose.

2.2.1 Barcodes

Barcodes come in one-, two-, and three-dimensional formats. Scanning barcode data is much faster than manually entering data, bolsters data accuracy, and makes the data handling process more secure (16). A one-dimensional (1D) barcode is linear and consists of parallel lines and spaces that are vertically oriented. The Universal Product Code (UPC) is probably the most familiar iteration of a 1D barcode — found on practically any item that can be purchased, they are composed of a 1D barcode plus a 12-digit number that encodes information about the brand owner and item, including a check digit. Two-dimensional (2D) barcodes (also referred to as matrix codes) have an overall square shape, inside of which is a unique arrangement of rectangles; their storage capacity is significantly greater than 1D barcodes. A common example of a 2D barcode is the now-ubiquitous Quick Response (QR) code, which can be scanned with a mobile device or camera; they can redirect users to websites, store personal information, and are commonly used in advertising. Lastly, 3D barcodes resemble 2D barcodes, however, the internal rectangles extend to varying heights, which are measured and interpreted by scanner (15). They are less common than 1D or 2D barcodes. Barcodes have been used in the construction industry to facilitate document management (18, 19), integrated with RFID to improve data acquisition (20), and manage materials and equipment (21). Recently the Iowa DOT piloted a project in which concrete deliveries were tracked with the aid of QR codes affixed to the dashboards of haul trucks (22; see Chapter 4)

2.2.2 Radio Frequency Identification (RFID)

RFID takes advantages of electromagnetic signals to capture and transmit data (23). RFID systems generally have two components: an RFID tag and an RFID reader. The tag contains a microchip that stores data and an antenna for communicating data. Three types of tags are available. Passive tags rely on the electromagnetic field produced by the RFID reader for their activation and have a very long service life but operate over a relatively short range. Active tags include a built-in power source and typically store more data and have the longest range but are most costly and have a limited service life — up to 10 years in most cases (24, 25). Semi-passive tags have an internal power supply which is flipped on when it receives a signal; they are also more expensive than passive tags, have a shorter service life than active tags, and have a moderate range (26). Microchips within tags are read-write; read only; or write once, read many (WORM). RFID readers also have an antenna and communicate data to and receive data from tags. Several RFID frequencies exist, with each being used for a different suite of applications. Unlike barcodes, RFID systems do not require line of sight for scanning (20). While RFID tags are more durable than barcodes, they are also more expensive to produce or purchase. RFID systems have found a number of uses in the construction industry, including the tracking of pipe

spools and steel members, observing the movements of items on construction sites, locating underground assets, tracking materials such as asphalt from suppliers to project sites, performing material control, and inventorying equipment and workers (20, 24, 26, 27).

2.2.3 GPS

GPS is a satellite-based navigation system which can be used to determine the location of objects. GPS satellites broadcast radio signals which include their location, status, and the time. When a GPS receiver picks up these radio signals, it calculates its distance from a satellite. Once a GPS receiver has assessed its distance from four satellites it can derive its location on earth in three dimensions (28). Real-time kinetic (RTK) positioning is often used in the construction industry, particularly for surveying applications as it can provide centimeter-level accuracy. A number of GPS-based systems have been proposed or implemented to facilitate the identification and tracking of materials on construction sites; some systems have combined RFID and GPS technologies to accomplish this (29, 30, 31, 32). GPS, as well as RFID and wireless internet connections, can facilitate materials tracking through the establishment of geofences. Geofences can be set up around different locations (e.g., boundary of supplier facility, entry and exit points of construction sites) and leveraged to record the movements of haul trucks and other vehicles.

2.2.4 Advanced Imaging and Unmanned Aerial Vehicles/Systems (UAVs/UAS)

Many state transportation agencies, consultants, and contractors are incorporating UAS and UAVs (commonly referred to as drones) into workflows to improve the efficiency and safety of activities such as bridge inspections (34, 35), monitoring jobsite safety (36), and improving construction project management (37, 38). Zhou and Gheisari (39) thoroughly reviewed the implementation of UAS in the construction industry. When combined with LiDAR, infrared cameras, sensors, and other advanced imaging technologies, UAVs can help generate precisely detailed maps of project sites and detailed three-dimensional models of buildings, structures, and even stockpiles (e.g., 40). Researchers have also devised methods of estimating stockpile volumes through 2D images and various analytical techniques (41, 42). UAVs and RFID technologies have been paired on an experimental basis to determine the feasibility of using them in combination for materials tracking (43). Because UAVs and remote sensing technologies are best suited to monitoring stationary objects and features, they are probably not the optimal solution for dynamically tracking materials from the point of production to construction sites.

2.2.5 e-Ticketing

Traditionally, materials deliveries have been documented through the use of paper tickets. This unwieldy process is inefficient, potentially endangers workers and inspectors, often requires some form of manual data entry, and can delay invoicing and payment. E-ticketing solves these problems through paperless administration. Information that would otherwise be summarized on a printed document (e.g., batch properties, tonnage, delivery times, asphalt temperature, and signatures) are stored and transmitted electronically (12, 44). Eliminating paper documents fosters greater efficiency, reduces environmental waste, protects against the damage or loss of tickets, and improves project management. Several of the case studies presented in Chapter 4 highlight the implementation of e-ticketing in agency settings. For example, as the Iowa DOT case study demonstrates, when coupled with GPS and Geographic Information Systems (GIS), e-ticketing can support dynamic, real-time tracking of materials.

2.3 Systems for Monitoring the Transportation and Inventory of Bulk Materials

Over the past 25 years researchers have proposed and experimented with a variety of systems to track materials as they are moved from the point of production to construction sites. Technologies like RFID, GPS, and e-ticketing often serve as the linchpins of these systems. Building on the concepts that were described previously, this section highlights examples of systems which have been developed to track bulk materials, or which could be used for this purpose despite not being expressly designed with this goal in mind. Certainly, the innate characteristics of bulk materials pose a number of logistical and procedural challenges for tracking them.

While a technology like RFID tags or GPS units can be used with relative ease with discrete elements (e.g., steel beams, concrete members), they are less well adapted to viscous or flowable materials. Indeed, affixing an RFID tag to a steel beam is a straightforward procedure. Conversely, RFID tags cannot be fitted directly to a batch of aggregate or asphalt. Likewise, a GPS receiver cannot be attached to concrete inside the drum of a concrete mixer. These may seem like intuitive observations, but they are important to keep in mind as most of the systems reviewed in this section do not track the materials per se. Primarily, they track the vehicles or containers in which the materials are being transported. Readers will detect a common system architecture as they gloss over the examples. The following paragraph offers a thumbnail sketch of a basic materials tracking system.

RFID tags are affixed to haul trucks at a plant and information on a batch of materials is downloaded to the tag — systems designed more recently have used bar codes and QR codes in a similar manner. RFID readers at the plant and construction site record when trucks enter or leave the premises. GPS is frequently used to monitor vehicle location and movements. New systems may rely entirely on GPS as well as the establishment of geofences around the perimeters of plants, scales, jobsites, and other features of interest to precisely record where and when haul vehicles are at different locations. Information for each batch of material, including any e-tickets, is transmitted to and stored in a centralized database. Records generated during this process can be used to prepare invoices and serve as documentation that materials were delivered to a construction site. This sketch intentionally elides the nuances of various systems and how frameworks developed for tracking bulk materials have evolved conceptually and in their implementation. The rest of this section presents, in roughly the chronological order they were developed, systems used to track bulk materials. Adopting this sort of genealogical approach helps readers better appreciate how thinking on materials tracking has changed since the 1990s and some of the common problems early adopters have confronted.

Jaselskis et al. (45) proposed three applications for using RFID in the construction industry: 1) monitoring concrete deliveries; 2) tracking the activities of workers and equipment; and 3) managing critical materials. Despite the piece being written in the mid-1990s, it is noteworthy — and therefore merits detailed treatment — because it anticipates quite accurately contemporary trends in e-Construction, down to the types of systems and methods used to trace the locations of vehicles and materials. Our summary focuses on the system for managing concrete deliveries (Figure 3). After a concrete supplier receives a buyer's order electronically, a batch plan supervisor reviews the order and makes truck assignments. Concrete mix requirements and ID numbers for the assigned trucks are sent to a computer at the batch plant. Then, a radio-

frequency (RF) scanner is placed in the loading area; its purpose is to read the RFID unit attached to a truck, verify its ID number, and ensure the truck ID matches its assignment. Next, specifications for the concrete mix, admixtures, loading time, and delivery are programmed into the RFID unit. At this point, a truck is ready to leave the plant. Upon its departure, a centralized computer at the destination jobsite receives notification that the truck is in route. The notification also contains information about the truck ID, concrete mix specification, and departure time. As the truck travels to the jobsite, data are recorded on the number of mixing revolutions, truck speed, and truck location (if the vehicle is equipped with GPS). When the truck arrives at a jobsite, a scanner reads the RFID unit and transmits information to the centralized computer, the job of which is to confirm that the number of revolutions and mix time align with specifications. Workers who have access to handheld computers enter into them the results of air tests and slump tests, while the truck's RFID unit is used to link test data with the truck ID. RFID tags are then affixed to concrete test cylinders and associated with the delivery by truck ID and time of deliver. Once the delivery wraps up, the completion time is transmitted to the batch plant, so planning can begin for the next truck assignment. Upon arriving the truck arriving at the batch plant, the scanner at the batch plant collects data on truck speed and route information. Meanwhile, the RFID tags placed on concrete cylinders are essential for coordinating the lab testing process. Test results can then be used to streamline invoicing and payments to the concrete supplier, contractor, and testing lab.



Figure 3 RFID-Based Tracking System Proposed by Jaselskis et al. (43)

Beginning in the mid-1990s, Alberta Transportation sought to develop an automated system capable of tracking construction materials from their point of origin to the jobsite (46). A 1993 pilot project partially automated the process by installing RFID tags on haul tucks. Load data were captured at weight scales and stored on a computer, while at the job site road checkers (i.e., personnel responsible for verifying and recording load weights) used handheld portable readers to communicate with RFID tags. However, manual data entry and checks were still required, data capture at the scale proved inconsistent, and partial automation did not reduce engineering staff costs. Following a 2000 feasibility study that surveyed other transportation agencies to understand their use of automated data collection on truck hauls, Alberta Transportation piloted a new project focused on automating materials tracking. The agency contracted with a private firm it had previously partnered with to devise and test an automated data collection system. The system design consisted of a computer enabled with satellite communications and equipment at the scale house, two handheld computers (one equipped with GPS, the other enabled with

satellite communications) and an off-site server. When a tuck entered a scale, the computer recorded its ID number, net load weight, material type, and time; the truck driver received a load receipt before exiting. These data were then transmitted to the server and a handheld computer stationed aboard the paver. In turn, this handheld device tied into the server and the road checker's handheld computer. The road checker could use their device to view a list of incoming trucks. Once a load arrived, the road checker's device recorded GPS coordinates of the delivery location; the system was also capable of generating tonnage spread rate calculations in a separate report. Load and unload data were transmitted to the home server at 10-minute intervals and GPS coordinates converted to highway kilometer values. While Alberta Transportation deemed the pilot successful, the reliability of handheld devices was inconsistent. Among the benefits noted with the system were that consultants gained access to real-time data, letting them monitor progress on construction activities remotely, improvements in safety, more accurate haul data (due to less manual data entry), and better monitoring and enforcement of overweight loads. A preliminary cost-benefit analysis also suggested investment in the automated monitoring system produced net financial benefits.

Another early illustration of RFID and GPS technologies being used to track materials from the plant to job site is Peyret and Tasky's Material Traceability System (47). For each batch of asphalt, the system automatically collects data related to fabrication characteristics from a plant's existing monitoring and quality control systems. Data are then downloaded into an RFID tag mounted on the haul truck. For the pilot study described, information on quality parameters sourced from the plant's computers, the weighing station, and other miscellaneous data (e.g., type of mix design, coordinate information) were loaded onto the RFID tag. Once a haul truck arrives on the construction site, batch information is automatically transferred to the paver information system; GPS locates where material is being laid on the roadway. Software developed for the pilot was capable of visualizing where different batches of asphalt were placed using graphical plots which traced the paver movements.

When they proposed a tracking system using barcoding technologies in 2008, Lee and McCullouch (16) could identify no transportation agencies that had in place automated materials tracking systems. Their proposed system relies on handheld computers and pen-based bar code scanners to produce material delivery records. Figure 4 illustrates the automated procedure for tracking materials delivery. Once a contractor places an order with a materials supplier, the supplier adds order information (e.g., quantities, delivery dates, number of deliveries) to their database. Delivery tickets with corresponding barcodes are printed for each delivery. Drivers receive a ticket once material is loaded into their vehicle. When they arrive on a construction site, drivers present the barcoded ticket to an inspector, who is responsible for collecting all tickets and scanning them into a computer. Records maintained by the contractor, supplier, and owner are updated through this process. Suppliers can then create an invoice, expediting the payment process. Because physical tickets would still be printed, the system is not paperless and only partially automates tracking. Nonetheless, prototypes of barcoded tickets were field tested on an Indiana DOT project, with agency staff expressing interest in expanding the system's use. It thus provides an interesting example of incorporating barcodes into materials tracking.



Figure 4 Proposed Materials Tracking System from Lee and McCullouch (16)

Blending field research and conceptual model building, Nasir et al. (48) put forward an implementation framework for automated materials tracking. Fieldwork took place in the context of two construction projects where materials were tracked — one a combined cycle generating plant and the other a coal-fired power plant. Onsite, RFID tags were affixed to construction components while data collectors bearing mobile reader kits consisting of a GPS unit, RFID reader, and handheld computer walked through the material storage facility. As the data collector moved around, the GPS receiver recorded their location while the RFID reader documented which tagged items were near them. Maps indicating the locations of tagged materials were distributed to workers so they could quickly identify tagged components. At one pilot study site, the amount of time required to locate an item with the automated tracking system fell from approximately 36 minutes before adoption to just under five minutes after. Foremen noted using the system increased labor productivity and reduced the number of materials classified as temporarily lost because they could not be located quickly. Building on the success of this field trial, Nasir et al. proposed an implementation model for automated materials tracking, the purpose of which is to help stakeholders determine whether a project is a viable candidate for adoption of automated materials tracking. They specify conditions under which it is appropriate to use an automated system, methods for evaluating different tracking systems, how to perform a cost-benefit analysis, and strategies for installing and deploying a tracking system. While their model is geared more toward identifying and tracking discrete elements, several of the field deployment options discussed — such as the use of gates or portal structures at construction sites, warehouses, and suppliers — are salient in a transportation context and suitable for working with bulk materials.

Arguing that previous RFID-based methods of tracking materials were inadequate, Kassim (49) described a prototype system — Integrated Materials Tracking System — which synchronizes materials tracking and resource modeling. The integrated system leverages commercially available project management software and encompasses the registration of materials in a database system, materials tracking, and automated identification of materials during installation; the latter functions are integrated with resource modeling. System users are grouped into two

categories: manufacturers and contractors. Manufacturers can register construction materials and associated with particular RFID tags, while contractors have the ability to view the status of materials and RFID tag information. When trucks are loaded with material, the date, time product, location, and other information are written to RFID tags by a reader. Although conceptually similar to other systems described in this section, the integration of information into project management software and its use in resource modeling calls to attention the importance of developing a holistic approach to materials tracking and using knowledge generated through this process to strengthen project management.

Several researchers have proposed systems which measure the quantity and track the movement of bulk materials on construction sites. Shahab (41) presented a system which automates the measurement of conical stockpiles. The system's design is intended to minimize human involvement in monitoring activities, support heightened surveillance of earthmoving operations, and give workers and managers rapid access to valuable information that can be used to inform corrective actions. Relying on a combination of automated distance measurement technologies, image analysis, and artificial intelligence, the system has three modules: 1) data acquisition, 2) data transfer, and 3) data analyses. The data acquisition module leverages a wireless digital camera and RFID-RTLS (real-time location services). As materials are added to or removed from a stockpile, the camera snaps pictures — which capture the changing shape and volume of a stockpile — while the RFID-RTLS system measures a stockpile's distance from the camera. Data are then transferred to a field host server. The data analysis module encompasses image enhancement, which isolates stockpiles, eliminates noisiness, and measures associated attributes (e.g., area, major and minor axis length), and a neural network system. The neural network processes the measured parameters and distinguishes stockpiles from background objects. Stockpile volumes are calculated by converting 2D features into volumes reported in cubic yards or meters. On its own, a system like this would not be sufficient to materials tracking, but it highlights an innovative approach to inventorying materials that could be incorporated into a tracking system (see also 42 and the final paragraph of this section).

While not focused explicitly on materials tracking, Hubbard et al.'s (43) investigation of pairing off-the-shelf RFID systems and unmanned aerial vehicles (UAVs) is informative, as this combination of technologies could plausibly be leveraged to measure and monitor bulk material quantities. As part of the proof-of-concept study, RFID readers were installed on a UAV and three RFID tags with initial read ranges of over 1 m on the floor of an indoor facility. Three test flights were conducted, with an overall success rate of 56 percent. Manually controlling the UAV made it challenging to maintain consistent speed and height, while the RFID's weight (attributable to the payload) reduced flight time. Possible use cases for UAV–RFID pairings include identifying material on jobsites, integrating them with BIM models to generate 3D representations of components with an RFID tag, and facilitating project control and management.

Taiwan has established a system for tracking the disposal of surplus soil generated on project sites that relies heavily on manual inputs. The system is cumbersome because it requires significant labor for reporting data, and errors creep into reporting, due to both unintentional and intentional actions. Seeking to circumvent problems with this system, Huang et al. (50, 51) designed and piloted an RFID-based tracking system. The system shares many commonalities

with others that have been described in this section. Fully automated, it takes advantage of RFID technologies, cameras, and real-time data transfer so regulators and stakeholders can remain knowledgeable of disposal activities. Before moving any soil, a contractor submits a project application which contains information about haul vehicles, disposal sites, and the amount and types of soil that will be moved. Upon approval, the contractor receives RFID tags, which they apply to a truck's windshield. At the construction site, RFID equipment and a computer system are installed. As a truck enters the site the RFID reader notes the time and cameras take photos of the vehicle. Upon exiting the facility, the RFID reader again records the time and cameras acquire more imagery. A similar process is used to document truck and load information at disposal sites. Once all of the soil has been unloaded a control server determines the amount of surplus soil the project has produced in real time and generates a report. While piloted the system generally performed well, equipment was prone to overheating, unstable internet connections at times created problems related to data transfer and processing, and the performance of RFID tags was degraded by interference from metal surfaces and moisture (however, there are RFID tagging solutions which minimize the problem of metal interference [53]).

Several commercial vendors offer products that facilitate the automation of materials tracking. Their platforms have affinities with the conceptual, experimental, and piloted systems described above. Stockpile Reports has developed an inventory system which takes imagery generated from a smartphone or UAV and calculates stockpile volume and condition; it can be used to facilitate holistic management of stockpiles. Another player in the materials tracking space is Earthwave Technologies, which the Iowa DOT partnered with on its e-ticketing initiative. Full details of this case study can be found in Chapter 4. The company's approach involves its software processing data from GPS transponders located onboard vehicles. GPS transponders record time-stamped data on when a vehicle moves across geofences and into or out of designated areas (e.g., plant, scale, project site, paver). Inspectors located onsite equipped with tablet computers can thus monitor the location of trucks as they travel from the plant, which enables better monitoring of delivery timing and quality control (52). Arguably, in the coming years, keeping apprised of the latest developments in materials tracking will require paying close attention to innovations from private firms and how they are being adopted by transportation agencies and other stakeholders.

2.4 Paver Mounted Thermal Profiler

A paver mounted thermal profiler is an infrared scanner placed on the back of a paver. Profilers use infrared sensors to create a live thermal profile of the asphalt mat. Inspectors can view temperatures across the mat at any station. Infrared scans identify any cold spots or streaks in the mat, which coincide with lower density sections (53). Monitors are placed on the paver that can show real-time scan results; each scan records thermal data of the mat. Figure 5 shows the equipment that produces real-time visualizations of thermal profile (54). Pave-IR is a system for process optimization and documentation in road construction. And because density segregation significantly impacts pavement performance, thermal profilers are a critical tool for eliminating this process.



Figure 5 Smart Paver (54)

Additional sensors can be placed on equipment (e.g., on the compactor, on the back of dump trucks, on the screed, in the hopper). Thermal visualization provides insights into the quality of the material being laid. For example, MOBA Mobile Automation delivers a breakdown of the system's components, accurately depicting what each component can sustain and deliver to the entire innovative technology (Figure 6) (54). If there are differences in the material being laid, immediate measures can be taken to correct a road. This technology is compatible with every paver. An infrared scanner has three principal competencies: "high-precision data acquisition with innovative cloud solution linked to open interfaces for current asphalt logistics and process systems as well as a highly scalable reporting system" (54). These competencies facilitate accurate depictions of measurements.



Figure 6 MOBA System Components (54)

Several DOTs have successfully used infrared temperature monitoring on pilot projects, including those in Iowa and Texas. Pave-IR (MOBA Mobile Automation) appears to be the only system in the field that displays temperatures in real time using a monitor onboard the paver. The entire system costs roughly \$34,000 for each pavement operation, or it can be rented for two months at a cost of \$18,000. The price for rental equipment includes a \$3,000 installation charge plus an additional \$7,500 charge per month of rental. Devices such as a Microsoft Tablet let inspectors view pavement data if, Java, Adobe, and MOBA Pave Project are installed on the device. Aided by this equipment, technicians will be able to monitor and inspect resurfacing projects without being onsite, thereby increasing their efficiency and empowering them to inspect multiple projects simultaneously (54).

Using an infrared scanner behind pavers can help contractors identify poorly constructed sections and therefore fix them immediately — rather than after failure. Adopting this method could also increase the safety of paving operations by eliminating the requirement for inspectors to walk alongside the operation as well as the need to record pavement temperatures inside the truck. Mapping temperature contours fosters quicker and more accurate evaluation of materials and identification of variations in surface temperature. Thermal profilers can help prevent cold spots, such as, fatigue cracks, raveling, and potholes (53). Increasing the life of the road directly translates into lower maintenance costs. Figures 7 - 9 are screen captures from the US24 Project Report submitted to the Missouri DOT. They portray multiple forms of IR data analysis, including paver stops, passes, and temperature profile readings [53].



Figure 7 Thermal Profile of Mat



Figure 8 IR Data Analysis



Figure 9 IR Expanded Analysis

Data processing and reports maintain the raw temperature profile of the analysis zone, paving area, and sensor width. Three steps can be taken to remove invalid temperature measurements: 1) Eliminate measurement locations within two feet of the mat's edge, 2) Eliminate temperature readings less than 170° F and greater than 400° F, and 3) Eliminate data with paver stops more than 60 seconds (53). Studies identified by the SHRP2 RO6C found that "properly installed and maintained tarps significantly reduced the temperature differentials by about 40%," which could show advantage in our study. Feedback posted during the SHRP2 RO6C *Technology to Enhance Quality Control on Asphalt Pavements* webinar quoted two noteworthy reviews from customers. For example, "the scanner helps in adding trucks for increased uniformity, adjusting practices, and shows the benefits of short hauling; the scanner data is a vivid tool for showing how readability is influenced by the uniformity of temperatures" and "the IR scanner technology saves one grind of a project, the equipment paid for itself" (Maine DOT) (53). Nonetheless, to obtain high-quality thermal readings, it is critical to adopt the proper equipment. Trucks with good beds, MTVs with remixing capability, paved automation, and so forth will facilitate the performance of paver mounted thermal profilers.

2.5 Intelligent Compaction

Intelligent Compaction (IC) technologies were first studied by Heinz Thurner of the Swedish Road Administration in 1974. Thurner installed a Dynapac vibratory roller with an accelerometer (55). His results found a relationship between the amplitude of the vibration induced and the excitation frequency affected the soil stiffness. While this early experiment was done on soil compaction, further work was later completed on the use of IC in hot mix asphalt (HMA) applications. Swanson's 1998 patent application, "Compacted material density measurement and compaction tracking system," laid the conceptual foundations of IC by combining GPS technologies with a method of measuring the compaction density of asphalt. Modern sensor technologies now allow the combination of sensors, computers, and GPS units, allowing for the collection, transmission, and visualization of compaction measurements in real time (56).

FHWA defines IC as "vibratory rollers equipped with accelerometers mounted on the axle of drums, survey-grade global positioning systems (GPS), infrared temperature sensors, and onboard computers that can display IC measurements as color-coded maps in real time" (57). IC technology provides information on the precise location of compaction equipment on a project site, compaction response data (including compaction roller speed, number of passes, and frequency), material surface temperature, and corresponding amplitude (55). Making these data available to compaction roller operators allows them to quickly adjust the compaction process in the field, resulting in a better final product.

With conventional compaction processes, roller operators receive little feedback about materials undergoing compaction, especially during the first roller pass (58). Roller operators rely strictly upon predefined, quality-control produced roller patterns for a given area. Data from portable gauges record density information at spot locations (58). Using IC roller operators can visually discern how the predefined compaction roller pattern is affecting the underlying material. Quick alterations can be made to ensure material is placed at its prime density and temperature. The use of IC affords roller operators the opportunity to act somewhat independently of quality control personnel because they receive firsthand knowledge of how asphalt material is responding to the compaction process. This is not to suggest quality control personnel are unneeded —spot testing remains necessary to verify results.

2.5.1 Intelligent Compaction Measurements

All compaction measurements taken by IC rollers rely on the same principle: the vertical acceleration at the center of the vibrating drum of the roller (64). The roller drum applies a compactive force to materials; materials react back onto the roller drum. The reactive force is captured in terms of vertical acceleration and converted to an intelligent compaction measurement value (ICMV); methodologies and models for calculating this value differ among vendors . Figure 10 lists some common, vendor-specific ICMVs (59).

IC Measurements	Units	IC Systems	Model Definition
Compaction Meter Value - CMV	None	Caterpillar, Dynapac	$CMV = C \frac{A_{2\Omega}}{A_{\Omega}}$
Machine Drive Power - MDP	None	Caterpillar	$MDP = P_g - Wv \left(Sin\alpha + \frac{A'}{g}\right) - (mv + b)$
Compaction Control values - CCV	None	Sakai	$CCV = \left[\frac{A_{0.5\Omega} + A_{1.5\Omega} + A_{2\Omega} + A_{2.5\Omega} + A_{3\Omega}}{A_{0.5\Omega} + A_{\Omega}}\right] \times 100$
Stiffness - K _b	MN/m	Ammann/Case	$\mathbf{k}_b = \omega^2 \left[m_d + \frac{m_0 e_0 \cos(\phi)}{z_d} \right]$
Vibration Modulus - E_{vib}	MN/m ²	Bomag	$\frac{\Delta F}{\Delta z_1} = \frac{E_{ub} \cdot 2 \cdot a \cdot \pi}{2 \cdot (1 - v^2) \cdot \left(2, 14 + 0, 5 \cdot \ln(\frac{\pi \cdot (2 \cdot a)^3 \cdot E_{ub}}{(1 - v^2) \cdot 16 \cdot (m_b + m_e + m_r) \cdot g \cdot (d/2)}\right)}$

Figure 10 Common Intelligent Compaction Measurements

The most commonly used IC measurements for HMA materials are compaction meter value (CMV) and compaction control value (CCV). Other measurements do exist for soil applications, such as machine drive power (MDP). Several factors affect ICMVs, including machine weight, size, compacting energy, operational speed, vibration amplitude and frequency, compacted material properties (moisture, soil type, particle shape for soils/bases and temperature for asphalt materials, asphalt mixture material proportioning), underlying support conditions, and location of the water table in the area of compaction (62). Compaction measurements are generally either accelerometer-based (CCV and CMV) or energy-based (MDP) (60).

CMV is a dimensionless value whose measure is contingent on roller dimensions (drum diameter and weight) and roller operation parameters (frequency, amplitude, and speed); it is a product of the roller's dynamic response (59). Additional factors that affect ICMV calculations include the vibration type and eccentric forces found within the roller drum (64). Drum-mounted accelerometers measure g-force at vibratory frequency and harmonics due to vertical acceleration of the drum (60). Aspects of drum behavior, such as continuous contact, partial uplift, double jump, rocking motions, and chaotic motion are captured in the resonant meter value (RMV), which is simultaneously calculated by roller's computer system (61). The CMV measurement at a certain point indicates the "average value over an area whose width equals the width of the drum and length equal to the distance the roller travels in 0.5 seconds" (61). Drum behavior can affect the calculation of CMVs, and therefore must be interpreted alongside typical intelligent compaction measurements. Dynapac, Caterpillar, and Trimble Intelligent Compaction system integrated rollers all report the CMV measure (58). One disadvantage of the CMV is that it is highly variable, meaning correlations are difficult to produce with standard compaction measurements (60).

The CCV is a relative stiffness index calculated from the measured acceleration data (59). Sakai compaction rollers — like other IC rollers — use the mounted accelerometers to record the roller drum's interaction with the material being compacted. The conceptual foundation of the CCV measure is that as ground material stiffens, the roller drum begins moving in a jumping manner, which results in various changes in the drum acceleration.

Computing ICMV measurements presents several challenges. (64). The first is that compaction force are vibratory force are not equivalent. The vibration force from the eccentric weight in the roller drum is not equivalent to the effective compaction force applied to the materials being compacted. The compaction force changes as the vibration frequencies increase. Conversely, vibration force increases monotonically as the vibration frequency increases.

A second challenge is the discrepancy between actual strain measurements and theoretical computations. While the actual measurement is constant, the theoretical computation is variable due to a cylindrical drum of finite length on compacted materials (64). The observed error results from an incorrect assumption about the model's theoretical contact area, which is intended to mimic the field drum contact condition. As such, the theoretical computation requires corrections if it is to match field measurements.

IC measurement values can be related to various spot tests. Conventional methods that are potentially correlated include lightweight deflectometer, dynamic cone penetrometer, and plate loading tests (62). While these correlations may not always be as high as desired, IC systems can be an invaluable method of proof rolling or mapping the project area to locate areas where soft spots may already occur or are likely to appear. Using IC systems can lead to more effective and efficient corrective actions and ensure that a project area is covered completely by the roller, which may also reduce the areas where further corrective action is needed.

2.5.2 Intelligent Compaction Measurement Correlations

Existing ICMV models are based on either a multilayer pavement system or a single soil foundation with a certain influence depth; therefore the ICMV model is unable to capture the stiffness of a certain pavement layer (59). Figure 11 illustrates how the effect of an IC roller's influence depth compares to other density testing devices, such as geophones, soil stiffness gauges, nuclear density gauges, and dynamic cone penetrometers.



Figure 11 Effect of Density Testing on Influence Depth

Several problems follow from attempting to correlate the ICMV with an in situ measurement of a soil or pavement layer (59). Several demonstration projects have found weak correlations between core density and compaction response values, including ICMV, frequency, amplitude, and temperature, indicating that the compaction values produced by an IC roller are not significantly correlated with core density (55). Many empirical correlations have been developed to capture the relationship between ICMVs and traditional spot measurements. The correlations have been weak due to the narrow measurement range (65). Correlations have improved when data are used from project-wide measurements, due to the wider range in measurements collected (65). Other factors that potentially influence correlations include:

- Heterogeneity in underlying support layers,
- High moisture content variation,
- Machine operation setting variation (amplitude, frequency, speed, and roller jumping),
- Uncertainty in spatial pairing of point measurements and ICMVs,
- Limited number of measurements, and
- Intrinsic errors associated with the collection of ICMV measurements and in situ point measurements (61).

Various IC roller demonstrations have found that different ICMV models can produce similar trends within the same compaction area (59). An IC demonstration project in Maryland focused primarily on HMA construction indicated similar trends when the existing HMA layer on the project site was mapped using both Sakai and Bomag IC rollers. All major vendors produce rollers capable of accurately capturing weak or strong compaction, although several problems persist. First, there is no consistent linear relationship between the ICMVs developed by different IC manufacturers because vendors use dissimilar algorithms and definitions/ Achieving standardization within the industry may only be possible once a single definition for each ICMV measurement has been adopted. A harmonized model or a standardized definition of ICMVs may improve project evaluation and lead to broader acceptance of IC technology throughout the industr.

Due to few correlations being available that relate ICMVs to in situ pavement measurements, there is a limited interest in replacing traditional in situ measurements with ICMVs. Even though there is a reluctance to change industry standards because of the poor correlations discussed, IC has provided widespread benefits.

2.5.3 Intelligent Compaction Major Research Findings

Mapping is one of the greatest benefits of IC technology; successful demonstration projects have mapped the granular subbase, stabilized subbase, and milled asphalt surfaces with IC rollers set at low vibration amplitudes and low frequencies (59). IC technologies can help establish better roller patterns, while mapping underlying materials facilitates corrective actions (58). When IC systems are used, rolling patterns tend to be more consistent and uniform, as seen an Indiana FHWA demonstration project (59).

Demonstration projects have found IC mapping can identify weak areas on milled asphalt surfaces, Portland Cement Concrete pavements, and both stabilized and untreated bases (58). IC mapping has also proven useful for monitoring the gain in strength of a stabilized base layer, enabling contractors to determine when a layer had sufficient strength to be built upon. Mapping can also let contractors and agency personnel acquire a more clearly defined picture of subgrade conditions, allowing them to determine when they comply with standards. Once conditions meet that threshold construction operations can resume without negative impacts to the project timeline.

IC-equipped rollers have also been used to identify mix tender zones and sensitive periods when roller passes are not effectively compacting materials (58). Knowing pavement temperature conditions in real time can help operators determine the compaction mode (static or vibratory) during the intermediate or finishing compaction operation while avoiding premature material failure (vibratory compaction at low temperatures can damage HMA materials) (59).

Correlations between ICMVs and falling weight deflectometer/light-weight deflectometer-based measurements are stronger than correlations between ICMVs and HMA core density measures (59). One study characterized the correlations between ICMVs and light-weight deflectometer base layer modulus as generally fair — ICMVs increased alongside layer modulus, however, the sensitivity of the correlation was low and there was significant scatter in the data (58). Weak correlations between ICMVs and nuclear/non-nuclear density gauge measurements may be due

to the fact that IMCVs reflect the stiffness of the entire pavement system while density gauges only measure the top six inches of HMA layers (59). However, multilinear regression has improved our understanding of the relationship between ICMVs and in situ spot tests by detecting the influences of factors such as machine settings (amplitude, vibration frequency), conditions of underlying support layers, and HMA temperature.

The quality of the correlations between ICMVs and HMA density range from poor to good. Various data sources indicate pronounced scatter (58). Correlations between ICMVs and HMA density derived from asphalt cores are inconsistent, as results show that ICMVs can increase or decrease with increasing density. With no definitive correlations between IC measurements and density available, additional research is needed before correlations are used in the field or IC measurements completely replace traditional quality assurance methods.

2.5.4 Specification Needs for Intelligent Compaction

Based on demonstration projects, FHWA has proposed general IC specifications for HMA construction. Specifications address equipment, GPS, documentation, mapping, and machine settings (59).

Equipment

A smooth double-drum vibratory roller is suggested, with preferred rollers being Sakai SW880 and SW990 series and Bomag tandem IC vibratory rollers. Other IC vendors have been used on demonstration projects, although their produces have not been endorsed by FHWA.

GPS

A Real-Time Kinetic (RTK) system accurate to within 5 cm should be used; the roller must be equipped with a receiver which can communicate with the project base station. The GPS system must be checked daily to ensure communication between the project base station and IC rollers/GPS rover units is accurate before compaction operations begin.

Documentation

The computer system and software adopted should be able to present color-contoured ICMV measurements; pass counts; HMA surface temperatures; and machine settings, such as frequency, amplitude, and speed in real time. The roller should be able to export data to an online database or USB device in a format (ASCII or binary) that can be read by software such as Microsoft Excel. Exported data should include time stamps, GPS location (northing, easting, and elevation), vibration amplitude, vibration frequency, pass counts, speed, roller direction, ICMVs, and HMA temperatures. Veta is the standardized tool for geospatial data management, viewing, analysis, and reporting. It was developed by the Minnesota DOT and FHWA (62). Veta lets users import and analyze IC data from different vendors. Figure 12 is a screen capture from Veta depicting the variation in CCV measurements along a portion of a project (57).



Figure 12 Intelligent Compaction Data Viewed Using Veta Software

Mapping

Mapping is required before HMA paving operations begin, with either a single or double drum vibratory roller. At least one pass of the paving area should be completed and weak spots identified. Treatments and corrective action may be taken before HMA material is placed on top of weak spots. Corrective actions vary among agencies, as there is no industry-defined standards yet established. For example, the Indiana DOT conducts dynamic cone penetration (DCP) tests on weak areas in proposed pavement areas (62). If the test fails, contractor options include drying and compacting the subgrade again or replacing the weak subgrade with better fill material before asphalt paving operations commence.

Machine Settings

The minimum vibration frequency should be 2,500 vpm. A lower frequency (2,500 vpm) represents a higher vibration amplitude (0.6 mm), while a higher frequency (3,500 vpm) is a low vibration amplitude (0.3 mm). Additionally, the roller should be maintained at a relatively low speed (e.g., 3 mph).

Specification alternatives for the compaction of HMA materials have been advanced as well: 1) Roller-based quality control with ICMV target values determined from project test strip results, 2) Using ICMV maps to select areas for quality assurance tests, and 3) The selection of optimal roller passes and ICMV target value from compaction curves. For roller-based quality control using ICMV target values, an ICMV measurement is selected and compaction tests run on a test strip of a designated length (usually 100 feet). In situ nuclear gauge tests are completed while following the breakdown roller at a predetermined distance (e.g., 10 test locations with 20-foot spacing between test locations). Nuclear gauge density results are plotted against the recorded ICMV measurements for all passes to determine if the ICMV target value corresponds to the density value defined in contract requirements. Multivariate linear regression can also be applied to the data set to account for multiple factors, such as machine settings (frequency, amplitude, speed), environmental conditions (HMA surface temperatures), and pavement conditions within the supporting base and subbase layers (ICMVs for layers beneath HMA). The rolling procedure would need to attain a certain percentage of the target ICMV for quality control purposes (e.g., 90% of compaction on the project must meet the target ICMV).

Georeferenced maps of ICMV data can also be used to identify weak spots, so that quality assurance spot tests can be reduced in number and focused on weak areas. The contractor should provide a ICMV map to the field inspector to select where to perform quality assurance spot tests (e.g. 2-3 tests per weak area). Figure 13 depicts the mapping potential of an IC system (Sakai in this example). Variations in chromatic value indicate the relative hardness of material in a given area.



Figure 13 Mapping Potential for an Intelligent Compaction System

Final acceptance is based on the target quality assurance spot tests measurements in rolleridentified weak area. This could take the form of the example set forth by the Indiana DOT some other practice, which may vary by agency.

Once a compaction curve has been used to establish the optimal number of roller passes as well as an ICMV target value, successive passes of the compaction roller can serve as an indicator of compaction quality. As the number of roller passes increase, typically ICMVs increase at first and then decrease, or increase continuously before reaching a relatively constant value. Figure 14 captures such a trend; it depicts a simple case of identifying target pass counts based IC data.


Figure 14 Identifying Target Pass Counts from Reported ICMV Measurements

Determining where the ICMV measurement begins to reach equilibrium on a test strip can help avoid over-compaction or under-compaction (59). In one study that conducted a roller-blind operator test that lasted 20 working hours, 23% of the paved area was over-compacted, 40% of the paved area was under-compacted, and 37% of the area was at the target compaction level (66). The test strip area can also be monitored for changes in ICMVs between passes. When the change in ICMVs is less than 5% between successive passes, the optimal pass count and target ICMV can be determined for the project compaction procedure (59).

2.5.5 State DOT Case Studies on Intelligent Compaction

Several states have published case studies detailing how IC technology can be used to improve quality control processes on asphalt paving projects. These projects include Wisconsin's HMA overlay on I-39, Iowa's HMA overlay of US 218, California's Asphalt IC Demonstration on I-80, and Maine's IC Demonstration on I-95.

The Wisconsin demonstration project on I-39 was completed in May 2010. The project was approximately 5 miles long and focused on constructing two southbound lanes (67). The existing HMA layer was milled, while the underlying PCC slabs were cracked and seated. Next, a 25 mm HMA base course was applied, followed by a 19 mm HMA intermediate layer and a 12.5 mm HMA surface layer. Two Sakai IC equipped rollers were used for compaction operations (SW880 with 76" wide drum, SW990 with 84" wide drum). The Sakai rollers were used to map cracked and seated concrete pavement and compact the asphalt material placed on top of the concrete pavement. The smaller SW880 roller was used to collect ICMV measurements on concrete. By collecting ICMV measurements, the support condition of the broken concrete section could be analyzed before paving operations commenced (weaker areas were identified along concrete joints and stiffer areas were located where full-depth patches had been done during previous repairs).

CCV maps created using IC technology were critical for identifying areas needing attention before the HMA layer was placed (67). Repairing soft spots improved the support condition and made the compaction operation more effective, almost certainly increasing the density of the HMA layer . The Veta software also proved beneficial for handling the massive amounts of data collected by the roller during compaction. The software can also be used to conduct a statistical analysis of IC data.

The Iowa demonstration project on US 218 was completed in September 2009. Histogram plots of roller pass coverage data, temperature and CCV data were developed based on three days of paving operations. No statistical differences were found between traditional compaction and IC (68). Geostatistical semivariograms of roller pass coverage indicated more uniform coverage in areas treated using IC than locations where traditional compaction methods were used. A strong relationship between falling weight deflectometer measurements and CCV was identified ($r^2 = 0.8$) while the association between CCV and relative compaction was weaker ($r^2 = 0.4$). This result was expected — CCV measures the stiffness of a material and is not necessarily related to material density, as relative compaction is.

The California demonstration project faced challenges related to data loss and GPS offsets. During the first night of paving operations, the Bomag Intelligent Compaction roller failed to collect any data due to GPS connection issues (69). Data were also lost on the second night of paving from a Hamm IC roller because of a lapsed software subscription. A Caterpillar IC roller experienced GPS offset issues. These incidents were believed to be isolated and thus fixable. Despite the malfunctions, the IC systems proved valuable for tracking roller passes and surface temperatures of the asphalt. They enhanced quality control by improving asphalt consistency and the uniformity of compaction.

The California study also examined whether a linear relationship was present between core data and nuclear gauge density data. Regression analysis found a low r^2 value of 0.08, with a bias toward core density values (69). All-pass IC data (data collected containing measurements from all equipment passes) was able to predict in-place asphalt density while final coverage data (data collected containing measurements from only the last pass of the equipment) did not show this. This may be due to the hardening states of asphalt at lower temperatures, although this will require further investigation.

The Maine demonstration project used both the Caterpillar and Hamm Intelligent Compaction rollers; data were exported from the roller systems to the standardized Veta tool for further analysis (69). The Caterpillar data suffered from a GPS offset issue, however, and therefore were not analyzed statistically. The IC systems did not achieve their full potential on this project as roller patterns were dictated by the onsite quality control personnel instead of taking advantage of the IC system's real-time data reporting, which can guide adjustments to the predefined patterns. Core data and nuclear gage density were linearly associated ($r^2 = 0.55$). A multivariate nonlinear stochastic model was also developed to relate predicted density to core density (69). Data used to create the multivariate model were the combined Hamm final coverage and pass-by-pass data.



Density Proportion properties measured by laboratory bulk density tests or nuclear density gauge.



Stiffness Mechanical properties measured by accelerometers to reflect drum rebounds during vibratory compaction.

Figure 15 Difference Between Density and Stiffness Parameters

Because stiffness is a measurement of the ratio of the force required to create a desired deflection or movement within a part of the pavement layer, stiffness may not be accurately recorded if an asphalt material has been properly compacted. In this case, the value reported may only account for the surface portion of the asphalt lift (75). This explains why asphalt density is currently sought after, since density is the measurement of mass per unit volume. Asphalt density is a measure of the amount of compaction that has occurred throughout asphalt material; density measures are tied to the amount of air voids within a pavement layer. By approximating the amount of air voids through a specified target density, the negative effects associated with asphalt material that has not been compacted properly can be avoided. Project contractors also benefit from knowing asphalt density directly in the field because it is the true metric by which their work is evaluated and compensated for (76).

Volvo has proposed a *Density* Direct technology, which would let roller operators interact with an Android-based touch screen monitor (like a smartphone screen) that displays color-coded density readings, pass counts, and recorded temperatures, which are common in other IC rollers (74). The Density Direct technology was developed and tested as part of the FHWA for LIFE Technology Partnerships Program 2003 -2015 [76]. The Density Direct technology was tested on full-depth and asphalt overlay projects before undergoing independent evaluations by users around the U.S. Calculations obtained through Direct Density are accurate to within 1.5% of the measured value of core samples at 180 test locations (76).

The Density Direct tool can calibrate to each lift required for a project. For example, a 3 inch asphalt binder lift can be stored separately from a 2 inch asphalt surface lift; when the operator returns to work compacting the 3 inch asphalt binder lift several days later on another portion of a project, the Direct Density technology does not require recalibration, saving on time and increasing worker efficiency (75). The screen displays a project map gridded into segments of 1 square foot; squares are color coded based on the numerical density values displayed on the right

of the screen. The system can hold approximately 14 GB of data (equivalent to approximately seven months of five-day work weeks). Files are specific to certain lifts on individual projects and will not be automatically deleted from the system, although the operator will be prompted when memory is low. Density Direct data, like general IC data, can be exported by USB, since most state DOTs require daily data downloads onto project information storage locations.

Density Direct was released in fall 2015 and is available on the Volvo DD110B, DD120B, and DD140B compaction rollers in North America (75). The technology is proprietary and not compatible with other IC vendors like Amman/Case, Bomag, Caterpillar, Dynapac, Hamm, and Sakai. No other IC manufacturers currently offer a tool to calculate density in real time, only stiffness measurements calculated through proprietary ICMVs. As with any new technology, using a product like Density Direct will require a contractor to receive approval from the resident engineer or state agency engineer.

The utility of density measurements and stiffness measures is immense, as they could potentially reduce the need to conduct core sampling on the asphalt mat, allowing roller operators to work more quickly and realize the full benefits of an IC system (i.e., visualizing density and stiffness information about the complete asphalt mat area rather than just a small sample size that is tested when using traditional spot tests, such as a nuclear density gauge). Reductions in coring will produce greater asphalt mat uniformity, as there is less need to disrupt a monolithically laid mat. It could mitigate potential safety risks that arise when quality control personnel conduct the in situ testing that is currently required.

3. Methodology

This study aimed to improve the overall efficiency and safety of highway paving projects through the introduction of e-construction technologies. Our research team anticipated that analyzing data collected on pilot projects would demonstrate e-construction technologies can reduce inspector workload and improve project safety. To limit project size and timeline of the study, we only examined resurfacing projects. For simplicity and to achieve better control, our research focused solely on the asphalt pavement operations in the field, excluding plant operations, milling, maintenance of traffic, striping, and other operations typically included in a paving project. As such, project inspection was not entirely supplemented, but the goal was to reduce inspection staff workloads, increase inspector safety, let inspection focus on areas that are more experience-based (visual inspection), and augment data collection.

Field inspection requirements of paving operations typically include:

- Ticket receipt and acceptance
- Tracking theoretical tonnage
- Visual inspection for segregation in the truck
- Temperature monitoring in the truck bed and paver hopper
- Temperature monitoring behind the paver and screed
- Monitoring paver gates and material loss
- Checking pavement depth
- Monitoring roller operation (as per test strip)
- Visual inspection of pavement during rolling
- Communicating with contractor quality control for nuclear density measurements
- Marking verification core locations and core possession (if needed)

Table 1 describe how the inspection requirements were monitored on the pilot projects.

Ingrastion	Inspector	Study Investigator	Technology
Inspection	Inspector Degrade sibility	Study Investigator	Free layed
Ticket Receipt & Acceptance	Collect tickets and communicate with Study Investigator	Compare paper ticket information, delivery and dump times with	Employed Fleetwatcher Technology (e- ticketing: Integrated GPS, GIS, and plant
Tracking Theoretical Tonnage	Determine theoretical tonnage by station and communicate with Study Investigator	Compare theoretical tonnages as determined by Fleetwatcher and inspection staff.	weighing operations) Fleetwatcher Technology (e- ticketing: Integrated GPS, GIS, and plant weighing operations)
Visual Inspection for Segregation in the Truck	Inspect for segregation	N/A	N/A
Temperature Monitoring in the Truck Bed & Paver Hopper	Take temperature readings as normal and communicate with Study Investigator	Track temperatures by station and location to compare to PaveIR data	PaveIR (temperature sensors mounted on paver)
Temperature Monitoring Behind the Paver and Screed	Take temperature readings as normal and communicate with Study Investigator	Track temperatures by station and location to compare to PaveIR data	PaveIR (temperature sensors mounted on paver)
Monitoring Paver Gates and Loss of Material	Review theoretical tonnage and check paver	Communicate with inspection staff and review Fleetwatcher tonnage data. Does theoretical tonnage raise red flags?	N/A
Checking Pavement Depth	Check as normal	N/A	N/A
Monitoring Roller Operation (as per test strip)	Check as normal	IC roller should illustrate rolling needed to operator	IC
Visual Inspection of Pavement during Rolling	Check as normal	N/A	N/A
Communicating with Contractor Quality Control for Nuclear Density Measurements	Check as normal and communicate with Study Investigator	Compare densities and locations to data should be available by IC roller	IC
Marking Verification	Check as normal and	Compare core density	N/A

Table 1	Typical Ins	pector Res	ponsibilities	Manned
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Core Locations and	communicate with	and location to IC data	
Core Possession (if	Study Investigator		
needed)			

Given the breadth of the field data collection effort, we established a plan, which included a number of sub-tasks, to effectively control and manage the process:

Sub-Task 1: Work with District 7 management to identify 3 – 5 test projects.

Sub-Task 2: Add the special notes for using e-ticketing, PaveIR, and IC to the bid packages of the selected test projects.

Sub-Task 3: Work with the District 7 staff and contractors (including the asphalt plant) to initiate the study plan, acquire data, and communicate schedules and timelines.

Sub-Task 4: Communicate schedules of paving operations with the Study Investigators.

Sub-Task 5: Study Investigators observe and collect data during paving operations of the test projects (see Table 1).

Sub-Task 6: Tonnage, delivery, temperature, and compaction data are compared and reported. Sub-Task 7: A final evaluation of the data and technology used is developed.

Special notes were developed each technology tested; these are presented in Appendices A, B, and C. Two projects were let with lump sum bid items for each of the special notes and put out for bid in spring 2018. Resurfacing took place in summer 2018. The projects were based in KYTC District 7 (Lexington, Kentucky Central Office) in Fayette County. Project A focused on New Circle Road (KY 4) and required approximately 7,500 tons of asphalt. Project B was on Newtown Pike (KY 922) with needed approximately 2,700 tons of asphalt. Data were collected using conventional methods and via e-construction technologies. Conventional methods entailed collecting data as inspectors traditionally do (e.g., collecting a paper ticket, using an infrared gun to measure surface mat temperatures, noting roller patterns). These data were also collected using e-construction technologies. The accuracy of data collected using conventional and advanced methods were compared and the time savings associated with e-construction technologies determined. Our findings are outlined in Chapters 5, 6, and 7.

4. E-ticketing

4.1 Background

Over the past 20 years, STAs have looked to automate more construction processes in order to increase productivity while coping with growing infrastructure demands and staffing reductions. NCHRP Synthesis 450 found that, "STAs are managing larger roadway systems with fewer inhouse staff than they were 10 years ago. For the 40 STAs that responded to the survey, between 2000 and 2010 state-managed lane-miles increased by an average of 4.10%, whereas the number of full-time equivalents (FTEs) decreased by 9.68%. STAs can automate more highway construction processes by integrating e-construction technologies into their business operations. FHWA defines e-construction as "The creation, review, approval, distribution, and storage of highway construction documents in a paperless environment" E-construction encompasses a range of technologies and processes that aim to improve construction efficiency and safety by eliminating paper documentation. One such technology — e-ticketing —has shown promising results in.

Collecting load delivery tickets on highway construction projects is an outdated practice that exposes construction inspectors to many safety hazards. Activities such as walking in close proximity to moving equipment, climbing on the side trucks to retrieve paper tickets, and working next to high speed traffic increases the risk of accidents at construction sites. Additionally, archiving paper tickets for project documentation requires effort and resources to sort, organize, and store. This could be automated easily with a digital project delivery platform. E-ticketing technology lets users collect and document load delivery data electronically, allowing for safer and more efficient construction inspections and management. In addition to load delivery information, e-ticketing systems can provide data on load cycles and material installation (e.g., asphalt and concrete paving, concrete structures, earthwork, millings, and aggregate), which can be tracked through a combination of GPS and GIS technologies. Further, this combination provides crucial quality and productivity data that can be difficult to track using traditional methods.

Despite the benefits of using e-ticketing, implementation has been slow and challenging for many STAs. The Iowa DOT conducted the nation's first e-ticketing pilot in 2015; since then many states have pilot tested e-ticketing to determine whether it is a viable replacement for traditional paper tickets. These pilots have typically entailed working with local contractors and technology vendors to create systems tailored to agency needs. During testing, states face many challenges, such as choosing between an external vendor or creating an in-house system, internal and/or external resistance to adoption, and a general lack of knowledge of how the technology can be used. Looking past the expected challenges, successful implementation of e-ticketing can provide significant benefits to STAs, bolstering efficiency and improving safety on highway construction projects.

KYTC is considered an early adopter of e-ticketing. After hearing a presentation on the use of eticketing in Iowa, the Cabinet's Division of Construction staff thought held promise for Kentucky, especially with inspection staffing resources in decline. The Cabinet undertook its first pilot studies in summer 2018, which focused on asphalt resurfacing projects. The pilot projects sought to evaluate the e-ticketing, paver mounted thermal profilers, and IC to determine the viability of collecting inspection data remotely and automatically. KYTC used a special note and bid item to include the e-ticketing solution with these projects. The initial pilots, as well as a second round of pilot projects have adopted EarthWave's FleetWatcher e-ticketing software solution. Stakeholder feedback, which was gathered through debriefings as well as at an asphalt contractor summit, has been largely positive. KYTC's Division of Construction organized a summit with the Plant-Mix Asphalt Institute of Kentucky to gather asphalt material suppliers and contractors from across the state. The purpose of this meeting was to discuss e-ticketing and the benefit and challenges of implementing e-ticketing on a large scale. Based on discussions at the summit, KYTC decided to conduct a broader range of pilot projects so that a larger segment of contractors could work with e-ticketing. Further details from the e-ticketing pilot are discussed in the following sections.

4.2 Data Collection

E-ticketing is used during construction to improve efficiency through the use of a paperless system for material delivery tickets. For the pilot projects, KYTC personnel and the contractor's team worked with EarthWave Technologies to set up an e-ticketing program. EarthWave installed GPS tracking units on all equipment (pavers and haulers) used during the projects. All GPS units could be tracked on the FleetWatcher web-based system. This system let parties track trucks, view e-tickets, and retrieve other important details regarding the cycle times during operations.

GPS transponders were installed on all company-owned and third-party haul trucks and pavers. Additionally, geozones were established around the pavers and project sites. When a truck with a GPS transponder crosses the boundary of a geozone a notification it generated documenting its location (e.g., when a truck leaves the plant, enters the jobsite, is in close proximity to the paver, or dumps the mix in the paver). When a truck exits the perimeter of a paver geozone, the time is recorded, and it serves as a record that the mix has been delivered. Figures 16 and 17 illustrate geozones in the FleetWatcher interface.



Figure 16 Static Geozone Around the Project Site (FleetWatcher)



Figure 17 Mobile Geozone Around the Paver (FleetWatcher)

The software records and updates transponder locations every minute, displaying them on a webbased GIS map. Inspectors and contractor personnel can examine this map to confirm equipment is being used appropriately. The software leverages a a shift system — an EarthWave employee or contractor must set up project shifts prior to the project start date for the software to organize data correctly. The system records information for a wide range of data categories (Table 2). Key categories include: Ticket Number, Ticket Date/Time, Material Name, Cumulative Tons, Net

Tons, and Dump Coordinates. The system can also be accessed through a mobile app, giving inspectors the option to multitask using their mobile devices.

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Table 2 Freet Watcher Data Categories	Table	2 F	leetW	atcher	Data	Categories
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For this study, traditional ticket information was manually recorded. We also noted the amount of time required for inspectors to acquire data. Additionally, the times when the trucks entered job sites and the times when the trucks dumped the asphalt mix were recorded throughout the paving operations. These data were compared to information collected by hand to evaluate the software's accuracy as well the time savings that can be realized by incorporating the technology into operations.

4.3 Results

Data collected electronically by FleetWatcher aligned perfectly with data obtained through traditional tickets in the following categories: Truck Number, Mix Design, Ticket Number, Net Tons, and Cumulative Tons. Table 3 presents a small sample of data. *Conventional Data* are those recorded on physical tickets, while *Technology Data* are those recorded with FleetWatcher. Although Table 1 shows a small sample of data collected during a single shift of one project, it is representative of all 75 load delivery tickets.

Data	Truck Number	Mix Design	Ticket Number	Net Tons	Cumulative Tons
Conventional	CB35	CL4.S.38 A 76	868794	25.72	51.30
Technology	CB35	CL4.S.38 A 76	868794	25.72	51.30
Conventional	PR10	CL4.S.38 A 76	868807	26.06	103.48
Technology	PR10	CL4.S.38 A 76	868807	26.06	103.48
Conventional	H98	CL4.S.38 A 76	868811	25.30	155.13
Technology	H98	CL4.S.38 A 76	868811	25.30	155.13

 Table 3 Sample Ticket Alignment from 07/05/2018

Improving inspector safety was a main driver of this study. Highway construction inspectors face many hazards when collecting delivery tickets. Activities such as walking adjacent to traffic, climbing onto the sides of dump trucks, and working next to heavy equipment expose inspectors to risk. Data indicate the amount of time needed to obtain and process traditional ticks was significantly longer than what was required for FleetWatcher to record data. During this shift, 19 tickets were collected from delivery trucks; it took the inspector 54 minutes to collect these tickets. The same data were retrieved from FleetWatcher in 18 minutes. FleetWatcher data were also retrieved in the inspector's truck, which eliminated hazards associated with collecting paper tickets. Retrieving e-ticketing data can also be done in a safe environment away from jobsite hazards.

Another benefit of e-tickets is they let inspectors track theoretical tonnage in a much more efficient manner. Theoretical tonnage is a calculation DOT inspectors perform to estimate how much material should be used for a given pavement length. Examining the number of tons delivered to a project site in relation to the theoretical tonnage can confirm if crews are paving in accordance with the specifications, and ensures material is not being dumped along the process. Equation 1 is the calculation for theoretical tonnage. Note that the calculated theoretical tonnage rarely matches the cumulative tons delivered to the project site perfectly due to the many errors and uncertainties associated with construction projects. Nonetheless, significant differences between the values can signal the pavement is too thin, too thick, or that material has been lost during the process. Several theoretical tonnage calculations were performed using the dump coordinates recorded by FleetWatcher, the information in the specifications. Table 4 shows the results of the calculations.

Theoretical Tonnage(tons)

$$= Mix Density\left(\frac{lb.}{sy.in.}\right) * Pavement Thickness(in.) * \frac{1(sy.)}{9(sf.)}$$

* Pavement Width(ft.) * Pavement Length (ft.) * $\frac{1(ton)}{2000(lb.)}$ (1)

Date (m/d/y)	Approx. Dist (ft)	Lane Width (ft)	Thickness (in)	Density (lb /sy in)	Theoretical Tons	Cumulative Tons
$\frac{7}{2}$	3205.49	14	1.25	110	342.81	381.60
7/3/2018	3219.49	14	1.25	110	344.31	358.88
7/6/2018	7634.74	14	1.25	110	816.49	801.26
7/7/2018	6954.89	14	1.25	110	743.79	754.44

Table 4 Theoretical Tonnage Inputs Per Shift

To further investigate differences between theoretical tonnage and actual tonnage, a theoretical tonnage was calculated for each load delivery ticket and compared to the values on the ticket. A paired sample t-test was used to evaluate if the values differed significantly. The null hypothesis is that the population means are equal. Because of the high p-value (0.768), convincing evidence does not exist to reject the null hypothesis. Practically speaking, theoretical tonnage and actual ticket tonnage are not significantly different. Notwithstanding various sources of error that can creep into measurements, theoretical tonnage calculations embedded in the e-ticketing software were effective at reporting accurate quantities.

Pair	Mean	Std. Deviation	Std. Error Mean	t	df	P (2- tailed)
Theoretical - Actual	-0.710	20.810	2.403	-0.296	74	0.768

Table 5 Statistical Results from Theoretical Tonnage Comparison

4.4 Lessons Learned

E-Ticketing is still a relatively new concept in the highway construction industry, and so it is important to catalogue lessons learned. First, it is critical to set up all aspects of an e-ticketing system before a project starts. One problem encountered during the pilot was that the contractor did not establish a static geozone until after the project had concluded, meaning no data were recorded for this category. Second, GPS transponders play a key role in capturing all necessary data, but we noticed throughout the project that the system failed to track some dump trucks. The mobile geozone established around on the paver is ineffective if the trucks entering and exiting it do not have transponders attached to them. Figure 18 shows the Load Cycle Analysis tool used to track dump trucks for Day 4 of the project. Gray lines represent the times when trucks dumped loads into the MTV. Table 6 lists all of the trucks that were recorded manually at the job site on the same day. Comparing Figure 18 and Table 7, it is evident that several trucks were not tracked by the system, and therefore the dump times for those trucks could not be retrieved.

		07 PM	08 PM	09 PM	10 PM	11 PM	12 AM	01 AM	02 AM	03 AM	04 AM	05 AM
FW Unknow	vn Loads	:				T.						
PR06	32	34 36	22 32	32 118 5	188 29	364	34 <mark>3</mark> 1 17	42 4	31 31	40 61 8	61	59
RR57	19	108	6 3	7 27 1:9	2823 22	2 <mark>531:62</mark> 2	5 21 <mark>,</mark> 2468	20 27 7	27, 19, 2	7 848 37	8 1;	96
H99	21	85	9 1275	49 <mark>26</mark>	14 16 20	34 82 2	29 25 18	42 6 2	4 28 <mark>29</mark>	84 20 44	4 65	5
H93	7	116		28 <mark>2</mark> 5 1:1	8 1 <u>5</u> 18	35, 18 <mark>4</mark> 14	29 23	37 7 25	33 <mark>26</mark> 1	14 64	1 .9	66
H98	20	113		37 <mark>25</mark> 1	:1355 19	235 1475	29 <mark>,</mark> 25 3	5 8 23 2	2 <mark>26</mark> 7122	21 30,7 1	65	
PR08		102	21 20 1	1:7 39	8321:112	2 31 6	35 21 3	3 <mark>5</mark> 7 23 1	17 <mark>24</mark> 71111	25 87 3	65	9(
H97	5	81	148 108 1	§ 14 14 34	1; 20, 2	26 1976 2	22 19 <mark>25</mark> 5	119 236	31, 22	30 <mark>766 - 36</mark>	5 44	
PT155		4 194 20	23 42	22 1-1:5	1 20 1 5	1,646775:	25 19 <mark>1</mark> 9 2	8,5 23 18	<mark>25</mark> 71:18	34, 1117	1546	
H94			7	43 <mark>₃23</mark> 1:	1115 18 <mark>1</mark>	39 <mark>6</mark> 4 -	ε 29, 22 ₃	37 <mark>7</mark> 28	3 20 27 ₅ 85	23 2 57	98 32	1242
				- and the second	Aw	-	Say -	and the	mand	an Adam	Ser .	
	Animat	e from 07/0	6 06:00P	M to 07/07	05:57AM	focus on u	nit None		▼ Start			

Figure 18 Load Cycle Analysis Graph (FleetWatcher)

Table 6 Dump Times							
Project A Date: 07/06/2018							
Data	Truck Number	Ticket Number	Time Dumped				
Conventional	H94	868973	22:43				
Technology	H94	868973	-				
Conventional	CB25	868996	0:12				
Technology	CB25	868996	-				
Conventional	RH3	869019	0:46				
Technology	RH3	869019	-				
Conventional	RH2	869020	0:51				
Technology	RH2	869020	-				
Conventional	H87	869030	1:35				
Technology	H87	869030	-				
Conventional	RR57	869071	2:53				
Technology	RR57	869071	2:54				
Conventional	RH2	869045	2:08				
Technology	RH2	869045	-				
Conventional	PT155	869050	2:14				
Technology	PT155	869050	2:15				
Conventional	PR08	869052	2:19				
Technology	PR08	869052	2:20				
Conventional	H98	869053	2:22				
Technology	H98	869053	2:23				
Conventional	PR10	869056	2:27				
Technology	PR10	869056	-				
Conventional	CB25	869060	2:32				
Technology	CB25	869060	-				
Conventional	H87	869063	2:37				
Technology	H87	869063	-				
Conventional	H93	869064	2:43				
Technology	H93	869094	2:44				
Conventional	H99	869068	2:47				
Technology	H99	869068	2:48				
Conventional	PT155	869083	3:24				
Technology	PT155	869083	3:25				
Conventional	RH2	869084	3:28				
Technology	RH2	869084	-				
Conventional	H98	869086	3:37				
Technology	H98	869086	3:38				
Conventional	PR10	869087	3:45				
Technology	PR10	869087	-				

Most of the issues encountered during the study could have been resolved easily if there was open communication between all stakeholders. If used properly, e-ticketing can benefit all stakeholders. Therefore, it is crucial for DOTs, contractors, and all other stakeholders to work together to take advantage of this technology.

4.5 E-ticketing Benefits

E-construction presents an opportunity to lighten the workload of KYTC's already-overtaxed inspection staff. Using e-tickets, tracking temperatures with a thermal profiler, and leveraging IC ensures quality control measures are immediately captured and stored, letting inspectors focus on observing field activities. As noted, e-ticketing reduces exposure to workplace hazards and improves the safety of vehicles passing through work zones. KYTC inspection staff and engineers found e-ticketing to be very beneficial as they could check quantities and assemble pay estimates from reports generated by the e-ticketing software. Additionally, lost paper tickets were easily recoverable by printing the e-ticket. In the field, personnel benefitted from knowing where the next or last asphalt loaded truck was in relation to the jobsite. As a result, contractors avoided paver stops and were able to merely slow production when trucks were delayed. Further the contracting community was very interested in tracking third-party hauling contractors and more efficiently assigning trucks to avoid bottlenecks and backups. KYTC administration found benefit in e-ticketing information as well. They could quickly determine where a particular mix design was placed, aiding future analysis and forensics and enhancing the performance and monitoring of pavements.

4.6 E-Ticketing Challenges

Several challenges arose during the pilot projects, and some additional issues were noted during the Cabinet's meeting with external stakeholders. Internet accessibility at asphalt plants was an issue during the pilots, as was having these plants run the most recent software. One plant had to be upgraded from a legacy system. While the contractor noted this was a needed upgrade, it was nonetheless a challenge and expense. This highlighted that there could be little-used plants in rural areas that may not warrant such upgrades. Further, both KYTC and contractor staff required training to adopt e-ticketing. In some cases, staff were added or removed from pilot projects, requiring additional training and access. Without training and access e-ticketing will not deliver on its promised benefits. Data ownership was another challenge. The contractor worked directly with EarthWave, but there was no contractor to approve data access. Following construction, data remained within the FleetWatcher system which does not meet the Cabinet's records retention requirements.

Challenges emerged on the jobsite as well. One pilot project used a material transfer vehicle (MTV) while the other did not. At the site where an MTV was used, the truck (and therefore its GPS transponder) never entered the paver geozone because the truck dumped material into the MTV. A potential solution would be to increase the size of the geozone size at the paver or create an additional geozone around the MTV. Another project-level challenge was ensuring all trucks had GPS units installed and recognized by the e-ticketing system. Because many of the trucks hauling material were part of third-party agreements, trucks varied from day to day and sometimes even within the same day. Challenges resulted when trucks were not equipped with GPS devices or not correctly set up in the tracking software. These issues were mentioned at the contractor summit. Because third-party trucking companies often work for multiple contractors, trucks could have multiple GPS devices onboard. For example, the potential exists for devices to

be confused as does the possibility that one contractor could track the haul routes of other contractors. This issue will need to be resolved by e-ticketing vendors. Another problem that could arise is having multiple e-ticketing software vendors. Existing procurement rules and the avoidance of sole-source procurement dictate that contracting with a single vendor is not a feasible arrangement.

4.7 Future Work

KYTC has moved forward with 14 additional e-ticketing pilot projects. The goal of these projects is to give multiple contractors and the Cabinet districts the opportunity to experiment with e-ticketing. Another goal is to work through some of the challenges discussed above. While no long-term plans for e-ticketing at KYTC have been set, feedback so far indicates many stakeholders would like to see its use continued and expanded. Extending the use of e-ticketing to additional materials has been mentioned as well, but the short-term focus will remain on asphalt pavements.

5. Paver Mounted Thermal Profiler

5.1 Background

Several DOTs have successfully used infrared temperature monitoring on pilot projects, including those in Iowa and Texas. Pave-IR by MOBA Mobile Automation is the main vendor of infrared monitoring systems; its equipment takes temperature readings across the asphalt mat in real time on a monitor displayed onboard the paver. Tablet devices let inspectors see pavement data using a MOBA Pave Project application, supporting data transmission in close to real time. Personnel can thus monitor and inspect pavement temperatures without other devices that measure temperatures. Using infrared technology generates a view of temperatures across the pavement mat at any station. Infrared scans identify cold spots or streaks in the mat, which directly relate to lower density sections or segregation, both of which significantly impact pavement performance. Pave-IR facilitates continuous pavement temperature monitoring and provides the means for automatically storing project data and recordkeeping.

For the pilot study, MOBA Mobile Automation was contracted to set up a Paver-IR program. The contract stipulated that MOBA would set up thermal sensors on the back of the paver (to track mat temperatures) and thermal sensors atop the screed and hopper (to monitor temperatures of loads delivered to the projects). Unfortunately, due to communication issues between parties, only the sensors on the back of the pavers were installed before the projects started. The installed cameras displayed mat temperatures in real-time on LED screens mounted on the pavers, letting crews identify and fix cold spots on the mat. The thermal recordings were either uploaded to MOBA's online cloud storage system or preserved on a remote storage device (USB drive) if the cellular signal was lost.

To assess the accuracy of the data captured by Pave-IR, mat temperatures at various locations were measured using traditional infrared guns; the GPS coordinates at these locations were also recorded. Once the pilot projects ended, temperature data from the MOBA Cloud were retrieved and compared to manually recorded temperatures. Pave-IR eliminates the need for manual inspection of mat temperatures throughout the project, saving considerable time and reducing inspector exposure to hazards (e.g., moving traffic, high mat temperatures, heavy moving equipment). Additionally, Pave-IR supports better a recordkeeping system and lets agencies review data if there are pavement failures.

5.2 Data Collection

Components of the Pave-IR system include an onboard computer, an infrared temperature scanner, and a GNSS (Global Navigation Satellite System) antenna. The active scanner gives full-width temperature readings at locations whose coordinates are recorded by the GNSS receiver. The system tracks paver speed and converts locations to mile points or project stations. Data are collected, displayed, and transmitted (near real-time to a cloud-based database) via the onboard computer. Figure 19 illustrates data output and shows temperature and paver speed.



Figure 19 Pave-IR Output

The Pave-IR system records data for the entirety of a project (except for structures). Thus, it collects significantly more data than is possible through spot checking temperatures. Although temperature sensors were not installed to collect data at the hopper or screed, what data were generated proved valuable. Had these sensors been installed, the only location where temperature data would not have been collected was the truck bed — whose temperatures would be nearly be identical to those of the hopper.

To compare Pave-IR system data to the temperature data gathered manually, temperatures were recorded using a handheld infrared thermometer gun at the approximate right wheel-path, left wheel-path, and center of the paved lane at specific locations. Manually collected temperature data were averaged and compared to the average temperatures measured by the Pave-IR system at the same locations. We could not compare temperature data at exactly the same locations due to small inaccuracies between geospatial information collected from a mobile GPS device and the high-density data collected by the Pave-IR system.

5.3 Results

Use of Pave-IR proved much more efficient and safer than the traditional method of collecting temperature data. The system captured continuous and accurate mat temperatures. Figure 20 is a screenshot from the Pave-IR interface that displays a continuous reading of temperatures.



Figure 20 Pave-IR Interface

To evaluate data accuracy, we mapped locations where manual temperature checks were done onto the Pave-IR interface to retrieve the Pave-IR temperatures at those points. Table 7 shows a small sample of the data where the *Conventional* temperatures were recorded using a standard temperature gun; *Technology* refers to data captured via Pave-IR. As indicated by the figures in the *Percent Difference* column, there were no significant differences between the two methods.

	T 4'4 1	T '4 1		
Method	Latitude	Longitude	Average Temp	Percent
			(°F)	Difference (%)
Conventional	38.043	-84.567	297.33	0.78
Technology	38.043	-84.566	299.67	
Conventional	38.0417	-84.567	290.00	1.78
Technology	38.042	-84.567	295.27	
Conventional	38.0396	-84.568	293.00	1.12
Technology	38.04	-84.57	296.33	
Conventional	38.0338	-84.5663	298.67	0.11
Technology	38.034	-84.566	298.33	
Conventional	38.0313	-84.5641	306.67	0.65
Technology	38.0313	-84.5642	304.67	
Conventional	38.0253	-84.558	296.33	3.16
Technology	38.0253	-84.558	306.00	
Conventional	38.024	-84.5562	303.67	2.57
Technology	38.024	-84.553	311.67	

 Table 7 Temperature Alignment

5.4 Lessons Learned

Pave-IR data are highly accurate and beneficial to project stakeholders. Where differences exist between temperature data collected via Pave-IR and data procured through manual spot checks, they are likely more related to locational inaccuracies than real discrepancies in the temperature measurements. Pave-IR is also very beneficial for visualizing the impact of paver speed and the use of material transfer vehicles (MTVs). Figure 21 displays the impact of using an MTV. The top portion of the figure displays the temperature signature of a paving operation using an MTV; the lower portion of the figure represents an operation without an MTV. It facilitates pavement placement at more uniform, higher temperatures. Without an MTV, a distinct pattern of cooling in the material toward the end of each truck is noticeable. Cooling is also related to paver speed

(e.g., each time the paver must slow to back a truck into the hopper) (see Figure 22). As Figure 22 demonstrates, use of an MTV fosters greater more even temperatures by helping ensure more consistent paver speed.



Figure 21 Pave-IR Comparison of MTV Usage



Figure 22 Pave-IR Paver Speed with MTV Usage

Pave-IR can also help workers correct plant temperatures or hauling patterns. And when pavement distresses materialize, reviewing temperature data generated though Pave-IR and other sources can inform selection of corrective actions. Such a forensic approach will also improve our understanding of pavement performance and its relationship to material temperatures and paver speeds.

Other lessons learned pertain to communication and data ownership. As with e-ticketing, the relationship between the technology vendor, equipment, and KYTC creates issues related to data access and ownership. Careful project communication and coordination must be normalized to ensure login information is available to KYTC staff who require data access. This was a concern noted during the pilot projects, because data could not be accessed until the work was completed. This was due primarily to Cabinet personnel lacking training and delays in communication. If the use of Pave-IR becomes more routine, making sure that staff have the appropriate level of knowledge about and training in the system's operation will alleviate these concerns, as will adhering to clear communication protocols. A final concern is that, pursuant to a Special Note, it is the contractor that owns the equipment and service needed to collect data through Pave-IR — they are compensated by KYTC. This arrangement is not ideal for ensuring access to data. One potential solution is to establish a data access chain of command between the technology vendor and KYTC.

Except for these minor challenges, the Pave-IR system garnered accolades from the users. It is a user-friendly system able to gather critical and impactful data on paving projects.

6. Intelligent Compaction

6.1 Background

Intelligent Compaction (IC) rollers help operators achieve better compaction, which improves the mat's service life. For this study, SITECH Solutions was contracted to retrofit rollers on the projects where IC technology was used. IC technology tracks roller movements, displaying them on an LED screen in the roller hub. It also records temperatures of the mat at breakdown. Like the Pave-IR technology, data are uploaded to a cloud server. IC automates what has traditionally been manually tackled by inspectors — monitoring roller movements during resurfacing to ensure proper compaction is achieved. Freed from tracking these activities, inspectors can focus on more demanding tasks.

While IC does rely on a unique method for compacting asphalt — compaction still depends on the combination of the roller machine's weight and the vibratory system — it can yield a better product. Roller operators can determine where the last roller pass stopped, whether the return pass covered the proper area, and if the previous pass had the proper overlap (60). They can also monitor the asphalt mat temperature to determine the best time to begin rolling without having to seek confirmation from other project personnel who may be unavailable. For paving work done at night, IC has multiple benefits, including letting roller operators evaluate the progression of compaction work in real time, which is challenging under poor lighting conditions. By incorporating measurement capabilities within the compaction roller, it is possible to ensure project specifications and requirements are met in real time. Meeting specifications during the initial compaction process improves overall quality, maximizes productivity, reduces rework, and minimizes costs (61).

6.2 Data Collection

Roller passes and the temperatures at various locations were recorded manually throughout the project. The same information was recorded using IC and was viewable by roller operators in real time. Following project completion, manually recorded data were compared to the IC data to determine the latter's accuracy. Data for the pilot studies were not available during construction. This was due to a lack of training and communication between KYTC, contractor, and research team. Another reason is that e-ticketing was the primary focal point of the study, with IC being of tangential interest. But the project team had only anticipated using the IC data to draw conclusions about roller coverage. It was thus sufficient to compare IC data on roller coverage (pass counts) to data collected manually.

6.3 Results

During retrieval of IC data from SITECH's online portal (VisionLink), we noticed that only data from the New Circle Road (KY-4) project had been captured. Analysis indicated IC data for both mat temperatures at breakdown and roller passes were less accurate than manually collected data. Figure 23 shows temperature data recorded by the IC sensors mounted on the breakdown roller. Over 95% of the mat temperatures were under 200° F. Figure 24 shows breakdown temperatures that were manually recorded. Mat temperatures were in fact 200°F or above during breakdown.



Figure 23 Breakdown Temperature Summary — IC



Figure 24 Breakdown Temperature Summary — Manual

A comparison of pass counts also turned up inaccuracies. Figure 26 displays the manually recorded data. As with temperature, IC captured significantly different readings. While IC did not perform as anticipated, many DOTs have found it useful for improving project efficiency and safety. Inaccurate IC data could have resulted from miscommunication between stakeholders, errors during equipment setup, and uncertainties associated with highway construction projects.



Figure 25 IC Pass Counts



Figure 26 Manual Pass Counts

6.4 Lessons Learned

The proper equipment set up, robust training, and sound communication are all instrumental for collecting accurate data using IC.

6.4.1 Importance of Intelligent Compaction Training

Since IC is a relatively new process, training is often needed to ensure roller operators and supervisors understand its functionality. Roller operator training is normally straightforward and requires only one to two hours to complete (62). Additional training on effectively utilizing the software portion of IC systems is available to field supervisors and agency personnel. FHWA is sponsoring IC data management workshops that include training on Veta software, which is used to visualize the records created by the IC measurement system. Contractual language can mandate IC training, and should be viewed as a positive aspect of a construction project. By ensuring roller operators and quality control personnel know how to use the selected IC system to the best of their abilities, the compaction process will be enhanced, leading to fewer weak areas and a higher quality final product.

6.4.2 Intelligent Compaction Field Calibration

To ensure an IC system operates properly, daily field calibration and verification are needed. There is no standard procedure for calibrating temperature measurements recorded by the roller, but it requires an independent temperature gauge to verify the measurements being reported (62). To ensure accuracy of the GPS data, daily GPS verification is needed and is specified by FHWA in its generic IC specifications.

The quality control technician must ensure an IC system is properly linked to the GPS base station on the project site each day before work begins (63). Distance offsets must be corrected before beginning work each day. A hand-held GPS rover should be used to double check measurements collected from the GPS rover on the IC integrated roller. FHWA specifications state that the differences between the roller GPS and the IC rover measurements are to be within 12 inches for both northing and easting before compaction processing can begin.

6.4.3 Benefits of Intelligent Compaction

Several agencies have observed the benefits of the project-wide adoption of IC. The Minnesota DOT completed a six-mile long project on Highway 64, which was the first project to use IC in a project-wide scenario (70). Use of IC eliminated guesswork from compacting fill materials; the technology also enabled the collection of a constant stream of data points rather than having to check compaction density at static locations. IC generated time and cost savings and facilitated the more uniform distribution of materials.

Contractors can use IC to verify the quality within a pavement structure and to eliminate risk factors before problems arise. IC systems require an initial investment to pay for the necessary software, but the positive returns on investment are significant (70). Depending on the equipment manufacturer, an IC-integrated roller may command an initial investment that is 3-5% higher than a conventional compaction roller; retrofitting a conventional compaction roller to be an IC-capable roller costs between \$50,000 and \$75,000 (71). In addition to initial investment costs, the equipment must be maintained and calibrated, although traditional compaction rollers often require the same. The more efficient roller patterns made possible through the use of IC rollers lowers fuel consumption, saves, money, and has environmental benefits. Additionally, when the equipment is operating for less time, labor, equipment, and maintenance costs are reduced. Finally, if IC results in more uniform compaction, larger pay incentives related to meeting target densities may be collected by the project contractor.

IC eliminates many of the disadvantages associated with traditional compaction evaluation (e.g., measurements capturing a small portion of the work area, delays in construction operations for testing and analysis, safety hazards). IC systems have the ability to perform pass-count mapping, which shows where the roller has operated in the project area. This mapping can help achieve target densities and increase roller efficiency when proper planning occurs (selection of IC roller, vibratory selection, and speed) (60). Being able to visualize the compaction process eliminates other common errors, such as excessive overlap and incomplete roller passes. As noted, working at night is also easier when IC is employed. Heightening the roller operator's awareness, as well as improving roller patterns, reduces operating costs, preserves better documentation of project conditions, and improves pavement density and smoothness. Currently, IC for soil applications is

used as a direct measure of compaction, while asphalt applications are focused more on process control than direct compaction measurement.

Another benefit that IC systems monitor the temperature of the asphalt material (71). Monitoring asphalt temperatures ensures that compaction occurs within the effective temperature range of 190° F to 300° F (lower and upper limits permitting compaction, respectively)) to avoid tender zones of the pavement structure (60). This is a surface temperature reading collected by the IC system's integrated infrared sensors, however — ideally this temperature measurement would come from within the asphalt material layer (62).

IC's continuous monitoring of interactions between the roller and compacted material can control the intensity of the vibrations and avoid damaging the pavement structure (71). GPS capabilities ensure roller patterns are more precise with the corresponding correct amount of compactive effort being applied. IC also affords roller operators the chance to make midcourse corrections if onboard sensors indicate problems. For example, it can prevent problems in a localized area or with a material lift from reflecting through and compromising the entire road surface. With electronic data collection, better construction records can be maintained and therefore consulted in the future. Multiple IC rollers can be linked to one another so that each roller operator (i.e., breakdown and finishing rollers) continuously sees measurement results from the other rollers through the use of a WLAN network. Operators can view the progress by a group of rollers, sorting the data measurements by the number of passes or asphalt temperature (72).

6.4.4 Challenges to Implementing Intelligent Compaction

A principal challenge with IC is that initial equipment investments may not be recuperated in a single project. As it may take several projects to recoup an investment in IC, smaller construction companies may less willing or able to invest in the technology (71).

Most IC vendors lack a prominent rental option for IC-equipped compaction equipment (62). Options may exist for retrofitting a conventional compaction roller to be an IC-equipped roller, although this option varies among vendors. However, there are few IC vendors, limiting the availability of equipment that can meet FHWA specifications (67). A lack of easily accessible rental options may prompt companies to purchase IC rollers, which could financially strain smaller contracting firms.

Another hurdle is that personnel lack requisite training to operate IC equipment and software. There are insufficient educational opportunities to learn about IC systems and their potential benefits as well as a lack of training materials (68). Thus, some portion of the industry is still unaware of the benefits IC systems confer. Furthermore, there are no widely accepted standards or specifications to guide stakeholders when they want to implement IC on new projects. While FHWA has provided general specifications, individual state DOTs must tailor them to meet their general guidelines. Workshops can familiarize attendees with the fundamentals of IC, show how it can be implemented successfully, and encourage attendees to serve as IC champions in their organizations (59). Beyond education, improvements to several areas of the IC process remain necessary, including simplification of the roller setup, standardizing measurement definitions and data formats, and updating analysis software required to visualize and store data, and the (67).

An action plan has been put forward to advance the use of IC for both soil and HMA applications. A past industry goal was to establish a Technology Transfer Intelligent Compaction Consortium (TTICC) to identify gaps within published research, determine implementation needs, develop problem statements for research, identify key partners, and form a national-level Specifications Technical Working Group to coordinate efforts (68). The first TTICC was held in Des Moines, Iowa, in December 2010 with representatives from 14 different agencies across the nation (73). Another possibility to accelerate the implementation of IC is holding one-day National Highway Institute trainings at conferences (68). Published case histories may also be useful to demonstrate the technical aspects of and project benefits realized by using IC technologies. For industry members who do not regularly attend conferences, webinars may be useful to promote technology and knowledge transfer. Giving more industry stakeholders access to published work on IC will increase the likelihood of growing its constituency.

6.5 Intelligent Compaction Conclusions

FHWA has concluded that IC is very effective for achieving the target level of compaction in HMA as well as increasing the uniformity of the asphalt material (58). Roller demonstrations show that IC technology can track roller passes, monitor HMA surface temperatures, and report an ICMV that roller operators can use to better control compaction within the asphalt material. Rollers are an effective tool for mapping the surface before HMA placement so that corrective measures can address soft spots or weak areas before construction operations progress too far. Finally, IC rollers have a demonstrated ability to generate compaction curves, which can be used to determine the optimal number of roller passes, whereas conventional methods set the number of roller passes based on the results taken from a test strip.

Studies have found a correlation between ICMVs collected by various equipment and the in situ measurements traditionally collected during the quality assurance process (58). Specifically, linear relationships have been identified between HMA density (from nuclear and non-nuclear density gauges) and deflection-based parameters, such as maximum deflection or layer modulus. But the strength of these relationships has varied. Further research must be carried out on these associations before there are enough data to determine whether they can be used to relate IC data to traditional compaction measurements. A lack of regression equations relating field-collected ICMVs to traditional compaction in-situ measurements, such as asphalt core density, remains a weakness.

A major stumbling block for IC systems is that the measured stiffness of the mat is less accurate than that of asphalt density, but these systems cannot provide instantaneous density measures. See Figure 15 for the difference between the parameters of density and stiffness (57).

Published literature contains few best practices for using IC on highway construction projects. Three key factors impact compaction efforts (regardless of technology used): mat temperature, mat depth or thickness, and compactor rolling pattern (74). As discussed previously, IC helps roller operators control two of the three factors. IC systems equipped with thermal sensors inform operators of the instantaneous surface temperature of asphalt material, enabling them to begin working the mat as soon as is safely possible. IC systems also let operators monitor rolling

patterns over the project area, ensuring that each area of the asphalt is properly rolled and that it complies with project specifications for density.

7. Conclusions

7.1 Project Summary and Lessons Learned

Incorporating e-construction technologies into paving operations could significantly improve project efficiency and safety. All of the technologies tested as part of this study revealed many areas to improve upon for future projects.

With inspection staffing a being persistent challenge at KYTC, e-construction technologies present an opportunity to lighten their workloads. Using e-tickets, monitoring temperatures with thermal profilers, and adopting IC enables the immediate capture and storage of quality control measures, freeing inspection staff to observe field activities. E-ticketing carries notable safety benefits, as it reduces worker exposure to equipment, vehicles traveling through work zones, and the dangers associated with climbing on equipment to retrieve tickets. Cabinet inspection staff and engineers found e-ticketing to be very beneficial as they could quickly check quantities and assemble pay estimates from reports generated by the e-ticketing software. With e-ticketing, lost paper tickets are no longer a concern — they can be easily recovered by reprinting the e-ticket. While in the field, staff benefitted from having knowledge of where the next or last asphalt loaded truck was in relation to the jobsite. Contractors with recourse to this knowledge were able to avoid paver stops and merely slowed down when trucks were delayed. The contracting community was also very interested being able to track their third-party hauling contractors and more efficiently assigning trucks to projects so as to avoid bottlenecks and back-ups. KYTC's administration found benefit in e-ticketing information, particularly in data on where a particular mix design was placed, as this can aid future analysis, monitoring, and forensics and enhance pavement performance.

Several challenges arose during the pilot projects, and some additional issues were noted during the Cabinet's meeting with external stakeholders. Internet accessibility at asphalt plants was an issue during the pilots, as was having these plants run the most recent software. One plant had to be upgraded from a legacy system. While the contractor noted this was a needed upgrade, it was nonetheless a challenge and expense. This highlighted that there could be little-used plants in rural areas that may not warrant such upgrades. Further, both KYTC and contractor staff required training to adopt e-ticketing. In some cases, staff were added or removed from pilot projects, requiring additional training and access. Without training and access e-ticketing will not deliver on its promised benefits. Data ownership was another challenge. The contractor worked directly with EarthWave, but there was no contractual relationship between EarthWave and KYTC. As such, the Cabinet required the contractor to approve data access. Following construction, data remained within the FleetWatcher system which does not meet the Cabinet's records retention requirements.

Because resurfacing jobs are fast-paced, the set-up of many parts of the e-ticketing system was delayed until right before the projects began, leading to many unnecessary problems that showed a lack of preparation on the part of all stakeholders. Creating a static geozone around project sites proved challenging. This geozone plays a critical in that it can facilitate delivery schedules so wait times in front of the paver are reduced. On both pilot projects, a static geozone was never set up, preventing the system from collecting arrival time data. A second challenge with e-ticketing was that some asphalt delivery trucks did not have GPS transponders installed, which

meant they were not tracked by FleetWatcher. Correct set-up of the e-ticketing system could have avoided these issues.

Challenges emerged on the jobsite as well. One pilot project used a material transfer vehicle (MTV) while the other did not. At the site where an MTV was used, the truck (and therefore its GPS transponder) never entered the paver geozone because the truck dumped material into the MTV. A potential solution would be to increase the size of the geozone size at the paver or create an additional geozone around the MTV. Another project-level challenge was ensuring all trucks had GPS units installed and recognized by the e-ticketing system. Because many of the trucks hauling material were part of third-party agreements, trucks varied from day to day and sometimes even within the same day. Challenges resulted when trucks were not equipped with GPS devices or not correctly set up in the tracking software. These issues were mentioned at the contractor summit. Because third-party trucking companies often work for multiple contractors, trucks could have multiple GPS devices onboard. For example, the potential exists for devices to be confused as does the possibility that one contractor could track the haul routes of other contractors. This issue will need to be resolved by e-ticketing vendors. Another problem that could arise is having multiple e-ticketing software vendors. Existing procurement rules and the avoidance of sole-source procurement dictate that contracting with a single vendor is not a feasible arrangement.

With respect to Pave-IR, the thermal sensors for the paver screed and hopper were not installed on either pilot project. The goal behind having the additional sensors was to record temperatures of the loads being delivered to the project from the plant to monitor effective workflows and future pavement failures. Data analysis was delayed because our research team lacked access to information on the Pave-IR interface.

IC presented the most significant challenges. No IC data were collected for the Newtown Pike (KY 922) project; the data retrieved from the New Circle Road (KY 4) project were inconsistent with the manually recorded data. Several factors may have contributed to the issues with IC, including a compressed project schedule, poor communication among stakeholders, and errors during equipment set up.

Many of the problems during this study could have been resolved if there were open channels of communications between stakeholders. The technologies are designed to benefit all parties, but everyone involved must be willing to collaborate to take full advantage of these tools.

7.2 Scalability

As with any pilot study, the goal of this study was to assess whether e-construction technologies are ready for broader use. E-ticketing is the most practice-ready technology. Several vendors offer tested solutions for e-ticketing, and some DOTs are developing their own systems. The technologies which underpin e-ticketing have existed for some time; thus, e-ticketing is mostly a repackaging of existing tools rather than something completely new to industry stakeholders. Fourteen additional KYTC projects are slated to use e-ticketing. On projects with awarded bids, the average bid price for e-ticketing works out to \$1.04/ton of asphalt material. As more suppliers, contractors, and Cabinet staff gain experience with e-ticketing, the unit cost and corresponding benefits will continue to improve. To use effectively use e-ticketing more broadly and under similar contracting methods, suppliers will need capable IT systems and internet access, haulers will need to serve as willing partners and effectively manage GPS devices, and contractors will need to set up equipment and provide stakeholders with appropriate access. Significant technical barriers must be overcome to implement e-ticketing statewide. It would not be economical, currently, for asphalt plants in rural locations to invest in plant upgrades if their sales volumes are small. Additionally, the potential loss of GPS or internet connectivity and outfitting brokered truck companies are issues that may make e-ticketing unattractive in certain parts of the state. If the only application is the electronic transfer of ticket data, some of these concerns are alleviated, but plant upgrade costs remain a hurdle. Ultimately the Cabinet, like other DOTs, will need to establish a vision for e-ticketing in the state. A pressing question is: Should e-ticketing be viewed as a collaborative technology that provides fleet optimization for the contractor or should it be regarded as strictly the electronic transfer of material information to construction administration systems in the agency? The answer to that question will greatly influence future of e-ticketing at the state and national levels.

The other technologies piloted in this study — the paver mounted thermal profiler (IR) and intelligent compaction (IC) — have deeper histories of being used and therefore could be more immediately scaled up. But they have limitations. Because IR equipment costs are significant, it may not be cost-effective on smaller projects. Meanwhile, IC equipment requires accurate geospatial data and proper calibration; if operators lack the proper training or projects occur in remote locations, the results may be poor.

7.3 Current and National Trends

This study and subsequent discussions with construction industry stakeholders in Kentucky indicate there is a strong interest in e-construction. Users have reported consistent satisfaction with the technologies while only expressing a few concerns. At the national level, the focus is shifting toward e-ticketing while setting aside tracking capabilities. Dropping the GPS tracking component, which is of significant value to contractor and hauling companies, sacrifices the collaborative nature of e-ticketing initiatives. However, it circumvents often-voiced DOT concerns such as problems sole sourcing software and liability privacy issues of suppliers and contractors. Nonetheless, e-ticketing is expected to continue to technically develop, change processes, and increase non-user interest given the value it provides.

With advanced tools and technologies proliferating the construction industry, e-ticketing is bound to continue gaining momentum as material tickets often remain the last information still collected by paper. There has been widespread use of IR and IC in the United States, however, the value proposition has not been well documented.

A pooled fund study has supported the initial and ongoing development of Veta, a map-based tool for viewing and analyzing geospatial data imported from IC machines and MOBA, Pave-IR scanners. It is required in the AASHTO PP81-70 specifications and most IC specifications put out by DOTs [77]. Although Veta provides useful platform for analyzing IC and IR data, it does not yet incorporate e-ticketing. Integrating fleet tracking and an electronic documentation system would position VETA as an ideal solution for tracking paving projects. Taken together, e-ticketing, IR, and IC can have a tremendous impact on highway construction projects in the United States by bolstering project efficiency and improving the safety of highway inspectors.

Contractors and equipment vendors will be more open to using these technologies if they only have to manage one system rather than relying on a software solution for each system.

7.4 Future Work

As noted, KYTC has moved forward with 14 additional pilot projects using e-ticketing. The goal of these projects is to give multiple contractors and Cabinet districts experience with e-ticketing. A second goal of launching more pilot projects is to work through the challenges highlighted in this report. While the Cabinet has not yet settled on a long-term approach for e-ticketing, IR, and IC, feedback gathered so far indicates the desire exists among stakeholders to continue their use. Expanding the use of e-ticketing to additional materials has been discussed, but the current and short-term focus is on asphalt pavements.

Another future development opportunity is a proposed asphalt inspector dashboard displayed in real-time on a mobile computing device. This device would enable remote inspection of asphalt paving projects, letting the Cabinet provide high-quality inspections with limited staffing.

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Appendix A – e-Ticketing Special Note

SPECIAL NOTE FOR HMA ELECTRONIC DELIVERY MANAGEMENT SYSTEM (HMA e-Ticketing)

This Special Note will apply when indicated on the plans or in the proposal. Section references herein are to the Department's Standard Specifications for Road and Bridge Construction current edition.

1.0 DESCRIPTION. Incorporate a GPS Fleet Management System for all HMA delivered to the project in order to monitor, track, and report loads of HMA during the construction processes from the point of measurement and loading to the point of incorporation to the project.

2.0 MATERIALS AND EQUIPMENT. Submit to the Engineer for approval, no fewer than 30 days prior to HMA placement activities, a GPS fleet management system supplier that can provide a qualified representative for on-site technical assistance during the initial setup, pre-construction verifications, and data management and processing as needed during the Project to maintain equipment.

Provide operator settings, user manuals, training videos, and required viewing/export software for review. Provide equipment that will meet the following:

- 1. A wireless fleet management or GPS device that is capable of tracking all delivery trucks (both company-owned and third-party) must be installed on all trucks and equipment (dump trucks, belly dumps, side-load dumps, transfer vehicles, pavers, or any other trucks/vehicles) used to transfer and incorporate HMA into the project. KYTC personnel shall have the ability to access Real Time monitoring through the use of a mobile device such as an iPad, smartphone, etc.
- 2. The fleet management system shall be fully integrated with the Contractor's Load Read-Out scale system at the HMA plant site.
- 3. The fleet management system shall have the ability to measure and track vehicles and their contents (weights and material types) continuously from the plant site to the project site. The system shall have internal battery backup capabilities due to loss of power, and have the ability to store data if GPS connectivity is lost and transmit that same data when unit re-establishes connectivity. To be considered continuous, no two data points shall be more than 60 seconds apart unless the vehicle is stopped. Duration of stop time for any reason shall be recorded.

3.0 CONSTRUCTION. Provide the Engineer with the manufacturer's specifications and all required documentation for data access at the pre-construction conference.

A. Construction Requirements

- 1. Install and operate equipment in accordance with the manufacturer's specifications.
- 2. Verify the GPS is working within the requirements of this Special Note.

B. Data Deliverables

Provide to the Engineer a means in which to gather report summaries by way of iOS apps, web pages, or any other method at the disposal of the Engineer. The Engineer may request data at any time during paving operations.

1. Real-time Continuous Data Items

Provide the Engineer access to a GIS map-based data viewer which displays the following information in real-time with a web-based system compatible with iOS and Windows environments.

- Each Truck
 - UniqueTruck ID
 - Truck status
 - Time At Source
 - Time At Destination
 - Time At Paver
 - Time At Scale
 - Time to and from plant/job
 - Time Stopped with Engine Running
 - Time of last transmission
 - Location (Latitude and Longitude in decimal degrees to nearest 0.0000001) every 60 seconds
 - Description of Material being transported (i.e. asphalt base, asphalt surface)
 - Mix Design Number
 - Net Weight of material being transported to the nearest 0.01 ton
 - Running Daily Total of Net Weight of material being transported to nearest 0.01 ton.
 - Project Number
- Scale Location
- Project Location
- Point of Delivery (i.e. paver)

2. Daily Summary

The following summary information shall be provided to the Engineer electronically within 4 hours of beginning operations on the next working day

- For each Material
 - List of Individual Loads
 - Contractor Name
 - Project Number
 - Unique Truck ID
 - Net Weight For Payment (nearest 0.01 tons)
 - Date
 - Mix Temperature at Time of Loading, Fahrenheit (to be key

entered by plant)

- Time Loaded
- Time Unloaded
- Delivery Location (Latitude/Longitude in decimal degrees to nearest 0.0000001)
- For each Bid Item
 - Total Quantity for Payment (nearest 0.01 tons)

4.0 MEASUREMENT. The Department will measure the HMA electronic delivery management system as a lump sum item.

5.0 PAYMENT. The Department will make payment for the completed and accepted quantities under the following:

- 1. Payment is full compensation for all work associated with providing all required equipment, training, and documentation.
- 2. Delays due to GPS satellite reception of signals or equipment breakdowns will not be considered justification for contract modifications or contract extensions.
- 3. Payment will be full compensation for costs related to providing the GPS system, including all equipped pavers and transfer vehicles, integration with plant loadout systems, and any software required for the construction and reporting process. All quality control procedures including the GPS systems representative's technical support and on-site training shall be included in the Contract lump sum price.

Code	Pay Item	<u>Pay Unit</u>
24986EC	HMA ELECTRONIC DELIVERY MANAGEMENT SYSTEM	LS

Appendix B – Paver Mounted Thermal Profiler Special Note

SPECIAL NOTE FOR PAVER MOUNTED TEMPERATURE PROFILES

This Special Note will apply when indicated on the plans or in the proposal. Section references herein are to the Department's Standard Specifications for Road and Bridge Construction current edition.

1.0 DESCRIPTION. Provide paver mounted infrared temperature equipment to continually monitor the temperature of the asphalt mat immediately behind all paver(s) during the placement operations for all driving lanes (including ramps for Interstates and Parkways) within the project limits. Provide thermal profiles that include material temperature and measurement locations. Provide equipment measuring material temperature within the paver hopper and at the vibratory screed.

2.0 MATERIALS AND EQUIPMENT. In addition to the equipment specified in Subsection 403.02 utilize a thermal equipment supplier that can provide a qualified representative for onsite technical assistance during the initial setup, pre-construction verification, and data management and processing as needed during the project to maintain equipment within specifications and requirements.

Provide operator settings, user manuals, required viewing/export software for analysis. Ensure the temperature equipment will meet the following:

- 1. A device with one or more infrared sensors that is capable of measuring in at least 1 foot intervals across the paving width, with a minimum width of 12 feet, or extending to the recording limits of the equipment, whichever is greater. A Maximum of two (2) brackets are allowed in the influence area under the sensors. A temperature profile must be made on at least 1 foot intervals longitudinally down the road;
- 2. Infrared sensor(s):
 - Measuring from 32°F to 400°F with an accuracy of \pm 2.0% of the sensor reading;
- 3. Ability to measure the following:
 - The placement distance using a Global Positioning System (GPS) or a Distance Measuring Instrument (DMI) and a Global Positioning System (GPS)
 - Stationing;
- 4. GPS: Accuracy \pm 4 feet in the X and Y Direction;
- 5. Latest version of software to collect, display, retain and analyze the mat temperature readings during placement. The software must have the ability to create and analyze:
 - Full collected width of the thermal profiles,
 - Paver speed and
 - Paver stops and duration for the entire Project;
- 6. Ability to export data automatically to a remote data server;

At the preconstruction meeting, provide the Department with rights to allow for web access to the data server. This web-based software must also provide the Department with the ability to download the raw files and software and to convert them into the correct format.

The thermal profile data files must provide the following data in a neat easy to read table format:

• Project information including Road Name and Number, PCN, Beginning and Ending

MPs.

- IR Bar Manufacturer and Model number
- Number of Temperature Sensors (N)
- Spacing between sensors and height of sensors above the asphalt mat
- Total number of individual records taken each day (DATA BLOCK)
- Date and Time reading taken
- Latitude and Longitude
- Distance paver has moved from last test location
- Direction and speed of the paver
- Surface temperature of each of the sensors

3.0 CONSTRUCTION. Provide the Engineer with all required documentation at the preconstruction conference.

- 1. Install and operate equipment in accordance with the manufacturer's specifications.
- 2. Verify that the temperature sensors are within \pm 2.0% using an independent temperature device on a material of known temperature. Collect and compare the GPS coordinates from the equipment with an independent measuring device.
 - Ensure the independent survey grade GPS measurement device is calibrated to the correct coordinate system (using a control point), prior to using these coordinates to validate the equipment GPS.
 - The comparison is considered acceptable if the coordinates are within 4 feet of each other in the X and Y direction.
- 3. Collect thermal profiles on all Driving Lanes during the paving operation and transfer the data to the "cloud" network or if automatic data transmission is not available, transfer the data to the Engineer at the end of daily paving.
- 4. Contact the Department immediately when System Failure occurs. Daily Percent Coverage will be considered zero when the repairs are not completed within two (2) working days of System Failure. The start of this two (2) working day period begins the next working day after System Failure.
- 5. Evaluate thermal profile segments, every 150 feet, and summarize the segregation of temperature results. Results are to be labeled as Minimal 0°-25°F, Moderate 25.1°-50°F and Severe >50°. Severe readings over 3 consecutive segments or over 4 or more segments in a day warrant investigation on the cause of the differential temperature distribution.

4.0 MEASUREMENT. The Department will measure the total area of the driving lanes mapped by the infrared scanners. Full payment will be provided for all driving lanes with greater than 85% coverage. Partial payment will be made for all areas covered from 50% coverage to 85% coverage at the following rate Coverage area percentage X Total bid amount. Area with less than 50% coverage will not be measured for payment.

5.0 PAYMENT. The Department will make payment for the completed and accepted quantities under the following:

- 1. Payment is full compensation for all work associated with providing all required equipment, training, and documentation.
- 2. Delays due to GPS satellite reception of signals or equipment breakdowns will not be considered justification for contract modifications or contract extensions.

<u>Code</u>	Pay Item	<u>Pay Unit</u>
24891EC	PAVE MOUNT INFRARED TEMP EQUIPMENT	SQFT

Appendix C – Intelligent Compaction Special Note

SPECIAL NOTE FOR INTELLIGENT COMPACTION OF ASPHALT MIXTURES

This Special Note will apply when indicated on the plans or in the proposal. Section references herein are to the Department's Standard Specifications for Road and Bridge Construction current edition.

1.0 DESCRIPTION. Provide and use Intelligent Compaction (IC) Rollers for compaction of all asphalt mixtures.

2.0 MATERIALS AND EQUIPMENT. In addition to the equipment specified in Subsection 403.02, a minimum of one (1) IC roller is to be used on the project at all times. The Contractor may elect to only use one (1) IC roller for compaction, but two (2) IC rollers are preferred as any combination of the breakdown, intermediate and finish rollers in the roller train. All IC rollers will meet the following minimum characteristics:

- 1) Are self-propelled double-drum vibratory rollers equipped with accelerometers mounted in or about the drum to measure the interactions between the rollers and compacted materials in order to evaluate the applied compactive effort. The IC rollers must have the approval of the Engineer prior to use. Examples of rollers equipped with IC technology can be found at www.IntelligentCompaction.com.
- 2) Are equipped with non-contact temperature sensors for measuring pavement surface temperatures.
- 3) The output from the roller is designated as the IC-MV which represents the stiffness of the materials based on the vibration of the roller drums and the resulting response from the underlying materials.
- 4) Are equipped with integrated on-board documentation systems that are capable of displaying real-time color-coded maps of IC measurement values including the stiffness response values, location of the roller, number of roller passes, machine settings, together with the material temperature, speed and the frequency and amplitude of roller drums. Ensure the display unit is capable of transferring the data by means of a USB port or through wireless transmission.
- 5) Are equipped with a mounted Global Positioning System GPS radio and receiver either a Real Time Kinematic (RTK-GPS) or Global Navigational Satellite System (GNSS) units that monitor the location and track the number of passes of the rollers. Accuracy of the positioning system is to be a minimum of 12 inches.

3.0 WORK PLAN. Submit to the Engineer an IC Work Plan at the Preconstruction Conference and at least 2 weeks prior to the beginning of construction. Describe in the work plan the following:

1. Compaction equipment to be used including:

- Vendor(s)
- Roller model(s),
- Roller dimensions and weights,
- Description of IC measurement system,
- GPS capabilities
- Documentation system,
- Temperature measurement system, and
- Software.

2. Roller data collection methods including sampling rates and intervals and data file types.

3. Transfer of data to the Engineer including method, timing, and personnel responsible. Data transfer shall occur at minimum twice per day or as directed by the Engineer and is to be electronic.

4. Training plan and schedule for roller operators, project foreman, project surveyors, quality control technicians, and Cabinet personnel including project engineers and field inspectors; including both classroom and field training. Training should be conducted at least 1 week before beginning IC construction. The training is to be performed by a qualified representative(s) from the IC Roller manufacture(s) to be used on the project. The training should be 4-8 hours in duration and minimum training topics shall include:

1. Background information for the specific IC system(s) to be used

2. Setup and checks for IC system(s), GPS receiver, base-station and hand held rovers

3. Operation of the IC system(s) on the roller; i.e., setup data collection, start/stop of data recording, and on-board display options

4. Transferring raw IC data from the rollers(s)

5. Operation of vendor's software to open and view raw IC data files and exporting allpasses and proofing data files in Veta-compatible format

6. Operation of Veta software to import the above exported all-passes and proofing data files, inspection of IC maps, input point test data, perform statistics analysis, and produce reports for project requirements

7. Coverage and uniformity requirements

4.0 CONSTRUCTION. Do not begin work until the Engineer has approved the IC submittals and the IC equipment.

Follow requirements established in Section 400 for production and placement, materials, equipment, acceptance plans and adjustments except as noted or modified in this Specification. Provide the Engineer at least one day's notice prior to beginning construction or prior to resuming production if operations have been temporarily suspended. Ensure paving equipment complies with all requirements specified in Section 400. The IC roller temperatures will be evaluated by the Department with the data from a Paver Mounted Infrared Temperature Gauge.

A. Pre-Construction Test Section(s) Requirements

1. Prior to the start of production, ensure the proper setup of the GPS, IC roller(s) and the rover(s) by conducting joint GPS correlation and verification testing between the Contractor, GPS representative and IC roller manufacturer using the same datum.

- 1. Ensure GPS correlation and verification testing includes the following minimum processes:
 - a. Establish the GPS system to be used either one with a base station or one with mobile receivers only. Ensure all components in the system are set to the correct coordinate system; then,
 - b. Verify that the roller and rover are working properly and that there is a connection with the base station; then,
 - c. Record the coordinates of the two edges where the front drum of the roller is in contact with the ground from the on-board, color-coded display; then,
 - d. Mark the locations of the roller drum edges and move the roller, and place the mobile receiver at each mark and record the readings; then,
- 2. Compare coordinates between the roller and rover receivers. If the coordinates are within 12.0 in. of each other, the comparison is acceptable. If the coordinates are not within 12.0 in., diagnose and perform necessary corrections and repeat the above steps until verification is acceptable.
- 3. Do not begin work until acceptable GPS correlation and verification has been obtained.

- 4. The Contractor and the Department should conduct random GPS verification testing during production to ensure data locations are accurate. The recommended rate is once per day with a requirement of at least once per week.
 - 5. All acceptance testing shall be as outlined in Standard Specifications Section 400.
 - B. Construction Test Section(s) Requirements

Construct test section(s) at location(s) agreed on by the Contractor and the Engineer within the project limits. The test section is required to determine a compaction curve of the asphalt mixtures in relationship to number of roller passes and to the stiffness of mixture while meeting the Department in-place compaction requirements. All rollers and the respective number of passes for each is to be determined via control strip each time a material change, equipment change or when the Engineer deems necessary.

Conduct test section(s) on every lift and every asphalt mixture. Ensure test section quantities 1,000 tons of mainline mixtures. Operate IC rollers in the low to medium amplitude range and at the same settings (speed, frequency) throughout the section while minimizing overlapping of the roller, the settings are to be used throughout the project with no changes. After each roller pass, the qualified technician from the contractor observed by the Department will use a nondestructive nuclear gauge that has been calibrated to the mixture to estimate the density of the asphalt at 10 locations uniformly spaced throughout the test section within the width of a single roller pass. The density readings and the number of roller passes needed to achieve the specified compaction will be recorded. The estimated target density will be the peak of the average of the nondestructive readings within the desired compaction temperature range for the mixture. The IC roller data in conjunction with the Veta software will create an IC compaction curve for the mixture. The target IC-MV is the point when the increase in the IC-MV of the material between passes is less than 5 percent on the compaction curve. The IC compaction curve is defined as the relationship between the IC-MV and the roller passes. A compaction curve example is as follows:



Subsequent to the determination of the target IC-MV, compact an adjoining > 250 < 500 tons section using same roller settings and the number of estimated roller passes and allow the Department to verify the compaction with the same calibrated nondestructive nuclear gauge following the final roller pass. The Department will obtain cores at 10 locations, uniformly spaced throughout the test section within the width of the single roller. Obtain GPS measurement of the core locations with a GPS rover. Use the Veta software to perform least square linear regression between the core data and IC-MV in order to correlate the production IC-MV values to the Department specified in-place air voids. A sample linear regression curve example is as follows.



C. Construction Requirements

Use the IC roller on all lifts and types of asphalt within the limits of the project.

During construction, the Quality Control Technician shall be responsible for the following minimum functions:

1. Daily GPS check testing for the IC roller(s) and rover(s).

2. Test section construction to establish target compaction pass counts and target values for the strength of the materials using the standard testing devices; i.e., Nondestructive density gauges, pavement cores, and IC roller(s).

3. Monitoring of the construction operations and the IC roller(s) during production and final evaluation operations.

4. Quality control testing to monitor the pavement temperature and the required level of compaction.

5. Daily download and analysis of the IC data from the roller(s).

6. Daily set-up, take down and secure storage of GPS and IC roller components

Ensure the optimal number of roller passes determined from the test sections has been applied to a minimum coverage of 80% of the individual IC Construction area. Ensure a minimum of 75% of the individual IC Construction area meets the target IC-MV values determined from the test sections.

Do not continue paving operations if IC Construction areas not meeting the IC criteria are produced until they have been investigated by the Department. Obtain the Engineer's approval to resume paving operations. Non-IC rollers are allowed to be used as the third roller on the project; one of the breakdown or the finish rollers is to be equipped with IC technology.

The Contractor shall coordinate for on-site technical assistance from the IC roller representatives during the initial seven (7) days of production and then as needed during the remaining operations. As a minimum, the roller representative shall be present during the initial setup and verification testing of the IC roller(s). The roller representative shall also assist the Contractor with data management using the data analysis software including IC data input and processing.

IC Construction areas are defined as subsections of the project being worked continuously by the Contractor. The magnitude of the IC Construction areas may vary with production but must be at least 750 tons per mixture for evaluation. Partial IC Construction areas of < 750 tons will be included in the previous area evaluation. IC Construction areas may extend over multiple days depending on the operations.

The IC Construction Operations Criteria does not affect the Department's acceptance processes for the materials or construction operations

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5.0 MEASUREMENT. The Department will measure the total tons of asphalt mixtures compacted using the IC roller(s). Compaction is to be performed by a minimum of one IC roller, material compacted by rollers not equipped with properly functioning IC equipment will not be accepted for payment of the bid item asphalt mixtures IC rolled. Use of non-IC rollers can be accepted on small areas due to equipment malfunctions at the written approval of the Engineer. Paving operations should be suspended for equipment malfunctions that will extend over three days of operation.

6.0 PAYMENT. The Department will make payment for the completed and accepted quantities under the following:

- 1. Payment is full compensation for all work associated with providing IC equipped rollers, transmission of electronic data files, two copies of IC roller manufacturer software, and training.
- 2. Delays due to GPS satellite reception of signals to operate the IC equipment or IC roller breakdowns will not be considered justification for contract modifications or contract extensions.

Code	Pay Item	Pay Unit
24781EC	Intelligent Compaction for Asphalt	TON

May 4, 2015