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Consuming Pavement Engineering Research through Software:  
An Empirical Investigation of Software Value  
in Transportation Agency Practices

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**Abstract**

Consuming Pavement Engineering Research through Software:  
An Empirical Investigation of Software Value in Transportation Agency Practices

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State transportation agencies have an established interest in funding pavement research that inform design and construction best practices. Seldom however does research result in development efforts that mobilize their findings into digital services (e.g. software or web-based applications), despite their perceived benefits in such form. When pavement research does result in software, tools are often limited in scope and may not be practice-ready despite their potential as proofs of concept. Consequently, research-based software is rarely the subject of further research and it is unclear whether additional investigations would result in additional academic or business value. This dissertation discusses how state agencies might further extend the value of research by

translating its contents into to digital, web-based services and subsequently, benefit from its consumption.

Ultimately, the body of work applies the findings from three separate research efforts to recommend best practices for managing and mobilizing research knowledge into practice. To establish the state of practice, the research begins with an empirical assessment of research knowledge, information technology, and software consumption patterns among transportation agencies. The work then identifies and characterizes how users consume research knowledge through web-based mediums by examining the performance of two existing web-based services. These efforts inform the development of a research and web-based decision support tool, which aims to document and identify how value is produced in the process of strategically translating research into development-ready formats. This third study identifies software characteristics and competencies that can be used to assess how effectively a software (or service) enables it consumers to leverage research concepts.

Finally, this research synthesizes the findings from the three investigations to address specific research concepts the pavement industry has historically struggled to incorporate into workflows as digital support tools. The outcomes examined include how software development may add value to existing research efforts by improving the analytical capacity of its end-users as well as accessibility to research knowledge.

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## **DEDICATION**

This dissertation is dedicated to all of my teachers, professors, and mentors who have taught me never to give up what I love, but to find love in what I do. You have helped me carve a path I never thought possible and realize that I have choice in my identity.

## Chapter 1. INTRODUCTION

*If a software is the product of valued research,  
how can the software in turn produce additional value?*

Transportation agencies are seeking to improve their workflows and capacity to strategize the preservation of 8.8 million lane miles of pavement infrastructure in the United States as of 2017 (FHWA 2018a, b). This dissertation examines a subset of software and services based on research and primarily intended to facilitate pavement design, construction and management. Particularly in these cases, knowledge or information is consumed through a digital software or service medium and relies on users with limited expertise to provide context through inputs. Because agencies change their preferences for consuming technology and software over time, this research primarily addresses three key questions:

- How do agencies use (or intend to use) information technology and software, and how has this changed over the last decade?
- How do users consuming research through software and how do we develop software to address trends in user behavior?
- What are development best practices and software characteristics that competent research-based software should demonstrate?

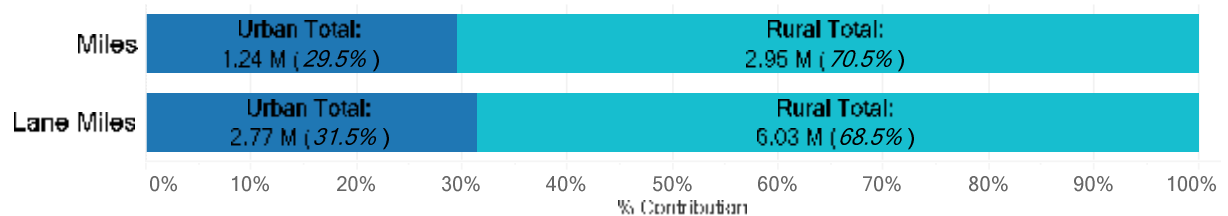


Figure 1.1. 2017 National Statistics for Public Road Length (FHWA 2018a, b)

Accordingly, this research explores the concept of value generated by developing and consuming research-based software in three contexts:

1. **Platform:** Refers to value realized through the technology platform on which a software or service is consumed. The platform may provide inherent benefits regardless of the software's intended use, such as improved functionality. For example, a web-based service (referred to in this work as a web-app) may require no installation, regardless of the software's intended function.

2. **Development:** Refers to value incorporated by a well-designed product that results in a functional, well-received experience by consumers. For example, a web-app service with best practices is thought to affect users' ability to consume information more effectively and produce meaningful results (Wang et al. 2016).
3. **Research:** Refers to value added when software informs or expands upon the underlying research. Benefits may also include opportunities to reuse otherwise archived data or identifying additional avenues of useful research. For example, a web-app can present concepts from research contextually through in-app features such as tooltips.

## 1.1 PROBLEM IDENTIFICATION

Transportation agencies (DOTs and STAs) are concerned that pavement-related responsibilities must be addressed with fewer financial and human resources in the foreseeable future. (AASHTO 2016; Olsen et al. 2013). DOTs are experiencing an evolution in traditional agency practices and business models driven primarily by concerns for funding, staffing requirements, and staff experience levels (Mahoney et al. 2010; Taylor et al. 2013; The PFM Group 2016). Based on the responses representing 40 STAs, Taylor and Maloney (2013) found that:

- Engineer workloads will likely increase, as most states are experiencing increases in population, lane miles of pavement, annual vehicle miles travelled, and capital budgets (Figure 1.2).
- Fluctuations in funding levels have affected the ability of DOTs to predict future staffing levels and overall have resulted in a reduction of full-time employees (FTEs) (Figure 1.3). DOTs predominantly address staffing shortfalls through outsourcing, allowing them to reduce the number of FTEs and acquire missing in-house expertise as needed.
- DOTs are also uncertain how outsourcing will affect traditional job responsibilities. Changes in job definitions blur roles, rendering titles incomparable across agencies across states and among other in-state agencies.
- A so-called retirement bubble is looming in which the most experienced workforce will retire, resulting in a younger, less-experienced one that faces greater responsibilities earlier in their service career

Measure	0-20% (increase)	> 20% (increase)	< 0% (decrease)
Population (Thousands)	<b>36 States</b> Avg Change: 8.4% Total Change: 18,143.00	<b>3 States</b> Avg Change: 26.2% Total Change: 1,490.00	<b>1 States</b> Avg Change: -0.8% Total Change: -75.00
Lane-miles (Thousands)	<b>37 States</b> Avg Change: 4.2% Total Change: 217.00	<b>1 States</b> Avg Change: 25.9% Total Change: 54.00	<b>2 States</b> Avg Change: -7.8% Total Change: -19.00
Annual Vehicle Miles Travelled (Thousands)	<b>34 States</b> Avg Change: 9.1% Total Change: 120.00	<b>1 States</b> Avg Change: 28.7% Total Change: 44.00	<b>5 States</b> Avg Change: -1.4% Total Change: -3.00
Disbursement on Capital Outlay (\$1000)	<b>6 States</b> Avg Change: 6.7% Total Change: 350.00	<b>31 States</b> Avg Change: 69.2% Total Change: 17,230.00	<b>3 States</b> Avg Change: -30.7% Total Change: -1,506.00

Description: Each bar groups states by their corresponding level of increase / decrease for a given measure in 2010. For example, 37 states experienced a (0-20)% increase in lane-miles, totaling 217 lane miles with an average increase of 4.2% over 2000 levels.

Figure 1.2. 2000-2010 Changes in Scope of Service (Taylor et al. 2013)

Change in Full Time Employee (FTE) Levels (N =16)					Change in FTE / Million USD in Capital Overlay				
State	% Change	2010	2005	2000	State	% Changes	2010 FTE / Million USD	2005 FTE / Million USD	2000 FTE / Million USD
Illinois	-34.1%	5,270	5,750	8,000	Illinois	-60.5%	1.96	3.49	4.96
Florida	-28.1%	7,443	7,579	10,354	Florida	-59.8%	1.72	2.20	4.28
Kentucky	-19.4%	4,814	5,108	5,972	California	-59.0%	3.73	8.65	9.10
Georgia	-16.0%	4,950	5,807	5,895	Oregon	-54.3%	6.04	7.43	13.21
Michigan	-11.7%	2,863	2,872	3,244	North Dakota	-52.1%	3.17	4.32	6.62
Kansas	-11.7%	2,916	3,247	3,304	Georgia	-47.7%	3.14	5.91	6.00
California	-11.3%	20,796	21,035	23,444	Utah	-46.4%	1.49	4.48	2.78
Utah	-8.7%	1,753	1,820	1,920	Kentucky	-41.7%	3.82	7.10	6.55
Maine	-5.7%	2,260	2,390	2,396	Wyoming	-39.2%	5.14	8.81	8.45
West Virginia	-3.9%	4,900	5,000	5,100	Maine	-38.5%	6.83	10.98	11.11
Oregon	-3.7%	4,550	4,559	4,727	Oklahoma	-36.5%	1.91	5.79	3.01
North Carolina	-3.5%	13,957	14,544	14,457	North Carolina	-28.9%	7.02	8.26	9.87
Nebraska	0.0%	2,200	2,200	2,200	Michigan	-26.1%	2.10	2.57	2.84
Oklahoma	0.0%	2,350	2,350	2,350	Kansas	-13.7%	4.84	5.41	5.61
Wyoming	0.0%	2,000	2,000	2,000	West Virginia	-13.3%	6.56	8.75	7.57
North Dakota	1.4%	1,055	1,044	1,040	Nebraska	-0.7%	5.72	6.71	5.76

Figure 1.3. Changes in FTE and FTE / Capital Overlay Costs (Taylor et al. 2013)

In addition to concerns regarding lower FTE levels, the Washington Department of Transportation (WSDOT) also shares additional concerns (The PFM Group 2016):

- Projection of 2013 WSDOT employee attrition rates imply that the agency will lose 45% of its current engineering and technical workforce by 2026, requiring the replacement of up to 1,153 FTEs over the next 10 years (Figure 1.4)

- non-competitive compensation and career development opportunities compared to other state transportation agencies contributed to high attrition rates among employees with 6-10 years of experience

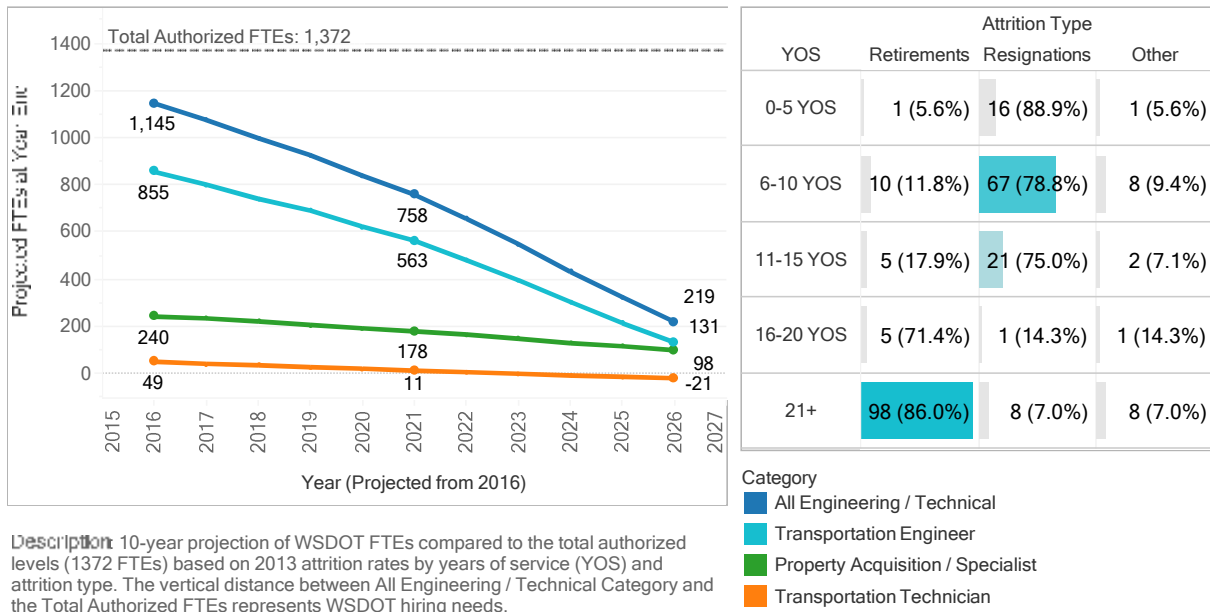


Figure 1.4. 10-Year FTE Projections for WSDOT (The PFM Group 2016)

Amid concerns regarding workforce retention and capabilities, DOTs may feel added pressure to leverage technology to maximize their productivity in practice. Overall, literature establishes that agencies commonly believe resource limitations can be partially overcome using information technology (Boddy et al. 2007; Chong et al. 2007; Son et al. 2012; Wang et al. 2016; Yang et al. 2017). This trend reflects both the general cultural belief that technology can improve worker productivity (economics), and trends of increasing worldwide access to internet and computing technologies (The Global Village Online 2019). Despite the clear interest in IT, agencies approach software and technology adoptions with caution over concerns about lasting investment value and realizing tangible production gains (Taylor et al. 2013). Other concerns include wasted or inefficient use of resources, unrecoverable data (obsolescence), and loss of competitiveness for not investing (Chong et al. 2007).

Agencies leverage technology with varying success rates and are unclear on best practices for selecting products (Vaughan et al. 2013). Some researchers have previously considered the construction and pavement industry among the slowest to adopt and integrate IT compared to other engineering disciplines (Boddy et al. 2007; Rezgui et al. 2011). Others believe that hesitations

indicate resistance to organizational change or changes in business models, which potentially shifts attention and resources away from IT needs (Taylor et al. 2013).

While general strategies for technology adoption exist (Moore 2014), there are few case-studies specific to the paving industry from which agencies can derive actionable best practices to strategize technology adoptions (Janssen et al. 2016). Thus, investigations are warranted to better understand how software integrations can assist agency goals of fostering a more capable workforce. Investigations are also timely because they capture how agencies utilize technology amidst pavement funding cycles likely to reoccur in the future.

## 1.2 SCOPE OF WORK AND CONTRIBUTING INVESTIGATIONS

This research explores how developing research-based software can extend the value of underlying pavement research. The study focuses on web-based platforms and identifies integration issues pertinent to this form of software delivery. To accomplish these research goals, the scope of work is divided into self-contained research investigations connected through their examination of the development and consumption of software based on research supporting the paving industry. These empirical investigations collectively assess how state transportation agencies consume research knowledge through software, and consequently how researchers can impact how users consume research through strategic development choices. Ultimately, these investigations inform best practices for future development efforts by demonstrating and generalizing characteristics of effective software featuring research methods.

The first investigation effort (Chapter 2) is a literature review that updates the state-of-the-practice regarding IT and software adoptions by STAs over the last decade. Ultimately, this effort provides a literature review of how public and private entities leverage information technology to assist pavement engineering workflows. The investigation also attempts to understand how agencies have attempted to leverage research through software development and infer lessons learned from such attempts.

The second investigation effort (Chapter 3) characterizes trends in user behavior when they consume pavement research through web-based mediums. The effort then rationalizes advantages and limitations of consumption research through such mediums. These goals are accomplished by examining Google Analytics (GA) data available for two web-based tools developed by Pavia Systems: a wiki-style knowledge repository, and a pavement design application based on

established empirical design practices. The data availability extends between five to ten years, providing a rare opportunity to examine challenges associated with research-based web services over an extended period. Accordingly, these efforts provide insight regarding how research content can be incorporated into software more effectively to align with user consumption habits. As well, this investigation highlights persisting issues regarding knowledge transfer through web-based mediums.

The third investigation effort (Chapter 4) applies recommendations from literature and inferences from the previous two chapters (Chapter 2 and Chapter 3) to the development of a research-based web-app named RxPave. This research subsequently provides a structured assessment of the development process. RxPave was proposed by the Washington State Transportation Improvement Board (TIB) to assist small cities with determining viable pavement rehabilitation strategies for low-volume roads. The software's embodied research concepts have only been incorporated into TIB's practices since 2015 and have no software predecessors. Users must primarily consume research knowledge through the software itself and so, perceptions regarding the software's usability can be associated with researcher efforts during development. Drawing lessons learned from RxPave's development, the investigation then identifies characteristics of software that specifically address issues critical to researchers and generalized development best practices for research-based software intended for the pavement industry. Lastly, this investigation defines how software development can inform and extend the value of its underlying research.

### 1.3 PROJECT CIRCUMSTANCES

This work is motivated by specific circumstances that provides additional context for understanding the connection between software referenced in this work, as well as interpreting potential author bias.

#### 1.3.1 *Partnership Among Academic, Private, and Public Entities*

This research is made possible by the author's ongoing partnership with Pavia Systems, Inc., a private construction software development company has previously collaborated with UW to develop research-based web-based tools. Pavia's projects are primarily funded by various

transportation agencies (including state and federal) and so this partnership provides a rare opportunity to examine how paving research can impact software development.

### 1.3.2 *Involvement with Ongoing Development*

The author has been involved in the ongoing development, technical writing, and validation of multiple software models referenced in this research over the last four years. This experience provides insight regarding development challenges across stakeholders.

### 1.3.3 *Previous Research with TIB*

The author has previously partnered with TIB to perform research updating the organization's project selection process for grant funding. Consequently, the author is familiar with the research leveraged by RxPave (discussed in Chapter 5) and updates the model as part of an ongoing contract.

### 1.3.4 *Teaching Experience with Concepts from Research*

The author was a teaching assistant at both the UW and UC Berkeley for multiple courses featuring construction and computer science concepts featured in this research. At UC Berkeley, this included an engineering programming course that trains student to code abstract answers to engineering problems as generalizable solutions. At UW, this includes construction courses that focus on using software to facilitate pavement design, project engineering, quantity estimation, scheduling and productivity, economics, and traffic impacts from construction. Consequently, the author's teaching experiences influence his interpretation of findings pertaining to knowledge transfer, training, and usability issues for research-based software.

## 1.4 MOTIVATION FOR RESEARCH

### 1.4.1 *Three Pavement Research Concepts in Software Practice*

This dissertation focuses specifically on research-based software / services and the potential advantages of consuming research knowledge through mediums including web-based apps. The

author has extensive experience with three research methods fundamental to pavement engineering analysis and observed the following similarities (Figure 1.5):

1. They have an established research history;
2. They intend to mobilize research concepts into practice;
3. The paving industry dedicated resources towards translating the research into a software or service in some form;
4. Multiple attempts have been made to adapt the research into a software/service
5. Adaptations have struggled with sustaining continued use or development, but efforts to do so are ongoing (and consequently still relevant to research).

The subsequent sections provide addition background regarding the treatment of research concepts presented in Figure 1.5 through software, including the fate of related development and implementation efforts.

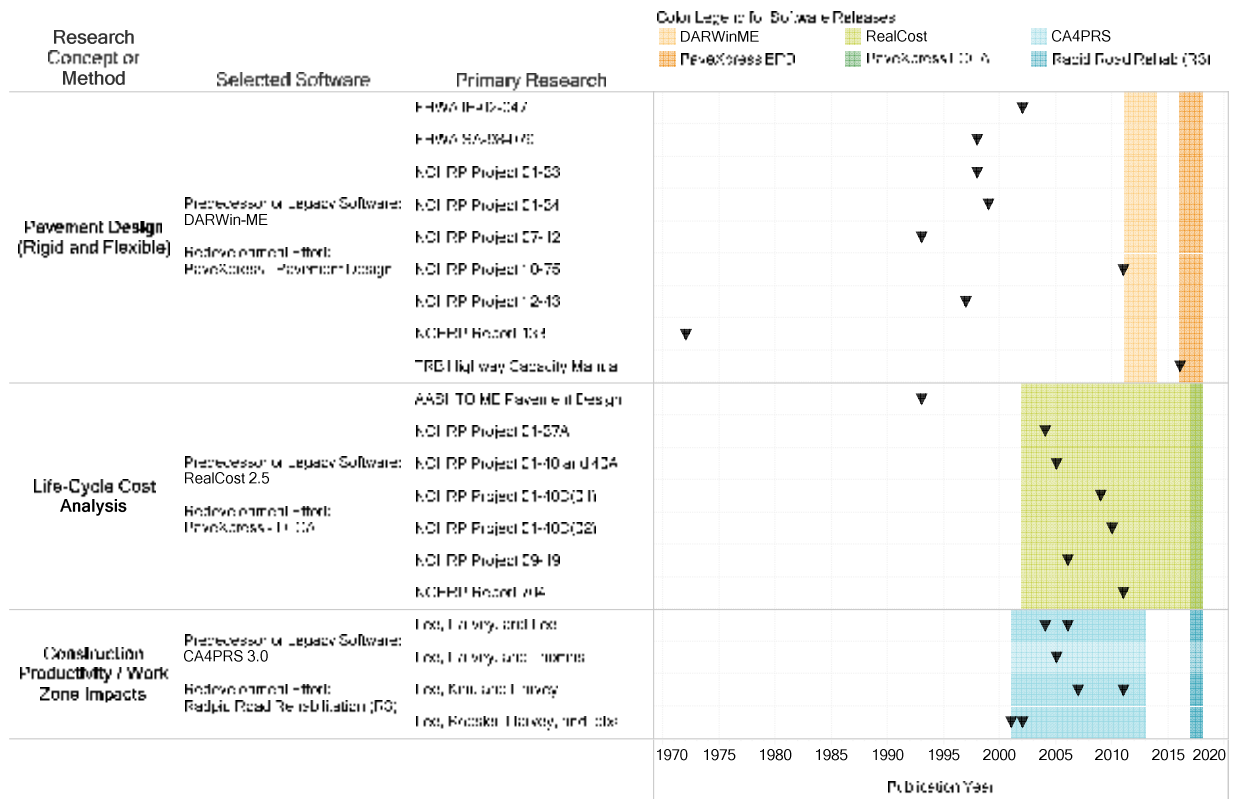


Figure 1.5. Timeline of Three Pavement Research Concepts

### 1.4.2 Exhibit 1: Pavement Design Methods

The outputs of pavement design inform resulting quantifications of physical material, scope of construction work, and cost estimation. Design methods have evolved substantially since the original AASHTO Road Tests conducted in the early 1950s, and state agencies currently adopt a

wide range of methods (Chris Wagner 2007; Crawford 2008; Pierce and McGovern 2014; Timm et al. 2014; FHWA 2004). Empirical design methods were continuously subject to revision over decades of subsequent research and culminated in the 1993 AASHTO Flexible Pavement Structural Design equations (referred to here as AASHTO93 flexible) and the 1998 Rigid Pavement Structural Design equations (referred to here as AASHTO98 rigid). This author was particularly interested in the shift in attitudes towards pavement design to incorporate mechanistic methods through software in the early 2000. Mechanistic methods attempt to include relationships guiding physical phenomena to generate pavement designs that meet structural requirements (rather than solely experimental data). Commonly referred to as Mechanistic-Empirical Pavement Design (MEPD), these resulting methods are considered the most accurate once calibrated locally.

NCHRP research on MEPD eventually resulted in the joint-development of software ultimately named DARWin-ME by AASHTO and the FHWA. Released commercially in 2011, DARWinME is the second iteration of MEPDG software developed in 2004. DARWinME was developed in C++ and Fortran90 and delivered as free on-premise software for the Windows operating system. By 2014, DARWin-ME became inaccessible and was redeveloped directly by AASHTOWare into Pavement ME, a paid subscription-based software service. Around this same time, and motivated to replace the by-then defunct DARWin-ME with a free web-based service, the National Asphalt Pavement Association (NAPA) and Asphalt Pavement Alliance (APA), and other state pavement associations funded the development of PaveXpress by Pavia Systems. In contrast, PaveXpress supports empirical design methods only: it is based on a modified version of AASHTO93 for flexible methods and AASHTO98 for rigid methods.

The industry predominantly uses empirical methods in practice, despite the increased accuracy promised by a calibrated MEPD model (Chris Wagner 2007; Crawford 2008; Pierce and McGovern 2014; Timm et al. 2014; FHWA 2004). This is evident in Figure 1.6, which compares results of nation-wide surveys regarding agency use of pavement design methods since 2003. Moreover, only 3 DOTs have reported implementing MEPD since 2003; nearly all other responding agencies indicated plans to implement but have been repeatedly forced to delay or extent their implementation schedule (Crawford 2008; Pierce and McGovern 2014; FHWA 2004). A full list of self-reported MEPD implementation timeframes by DOTs can be found in Appendix B (Figure 5.2). MEPD implementation appears to require more time or resources than agencies originally anticipated, and consequently, DOTs continue to rely on empirical design methods

(AASHTO93 and 98). This example demonstrates a research concept which agencies are eager to mobilize through software, but few have managed to do so in practice.

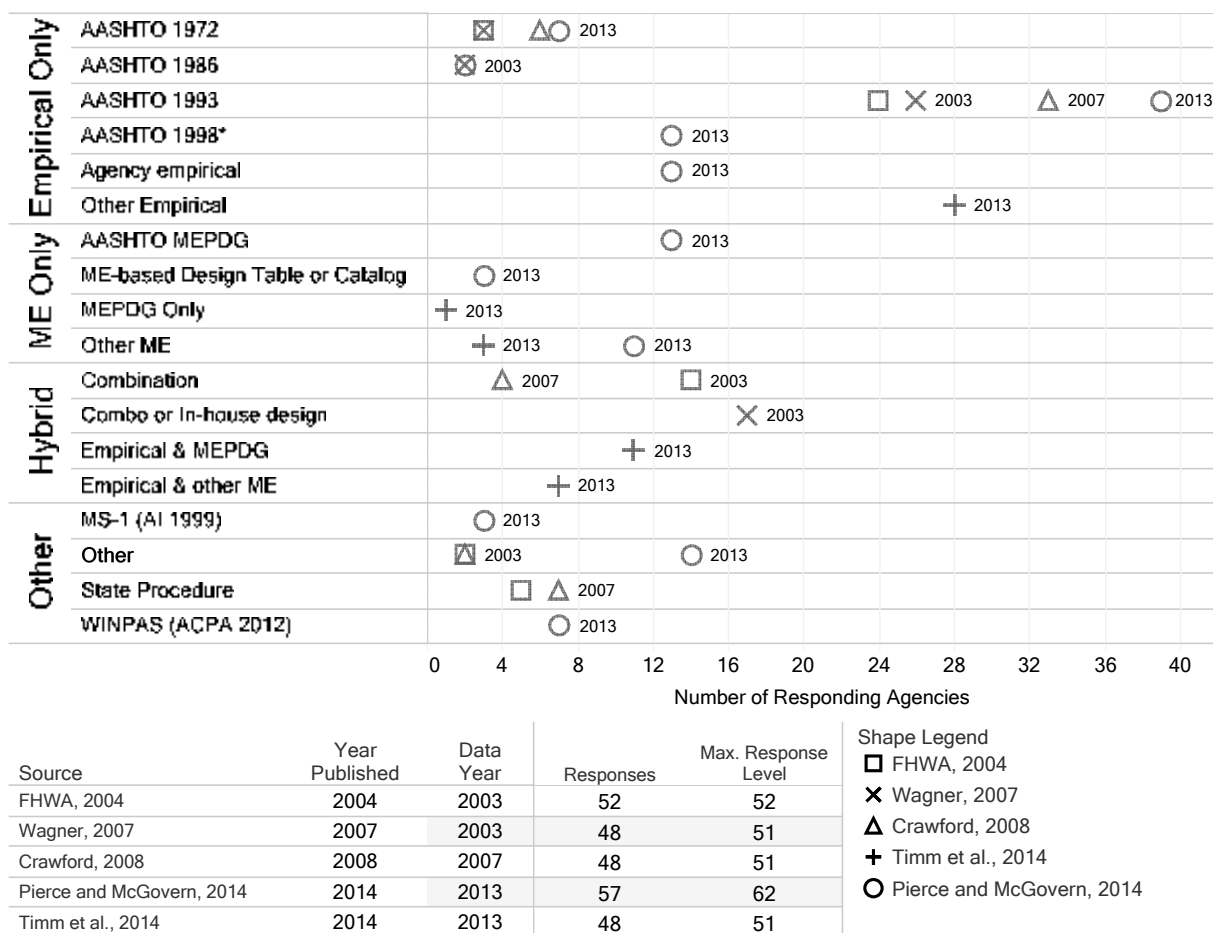


Figure 1.6. Pavement Design Methods used by DOTs over the last 15 years

#### 1.4.3 Exhibit 2: Life-Cycle Based Analysis

Life-cycle cost analysis (LCCA) methods attempt to quantify explicit agency costs and implicit opportunity costs (i.e. user costs) incurred by users impacted by construction decisions over the pavement's intended service life. LCCA can be generalized as a type of life-cycle based analysis intended to quantify the cradle-to-gate impacts resulting from construction decisions, including financial, material, or environmental impacts. To support decision-making, these methods rely heavily on the accuracy of historical data and expectations of future conditions (e.g. traffic growth, price inflation, climate change). As well, LCCA is influenced by road geometry and traffic levels

determined from pavement design methods and traffic demands. LCCA is also related to construction planning algorithms, whose methods affect agency and user costs generated from construction productivity and scheduling.

The LCCA method's underlying concepts are partially based on FHWA research resulting from AASHTO Road Tests and original concepts of user and vehicle operation costs defined in NCHRP Report 133 (Curry and Anderson 1972). Subsequent revisions to the model incorporated additional processes based on updates references to the TRB's Highway Capacity Manual (HCM), and time-sensitive parameters such as currency and traffic inflation. The methods were ultimately popularized in FHWA's LCCA Technical Bulletin in 1998. Following this, RealCost was developed into a free LCCA tool developed by the FHWA beginning in 1998 and publically released in 2002. It is built in the Microsoft Excel 2000 environment as a macro-enabled software extension but packaged as on-premise software with a graphical user interface. The software includes both deterministic and probabilistic scenarios, as well as the ability to compare multiple user-defined scenarios through automatically generated reports and figures. Overall, RealCost attempts to provide a structured framework for quickly completing LCCA methods that are heavily data driven and iterative by nature.

In 2008, South Carolina's DOT released a report and found that while most states practiced LCCA (30 of 33 responding), only 14 used a form of LCCA software in practice (Rangaraju et al. 2008). Of these respondents, most used RealCost (5), in-house developed spreadsheets (4), DARWin (1) or a combination of the three (5). In a similar FHWA report based on 2009 data (NCHRP Report 703), the researchers surveyed 35 state DOTs regarding the use of LCCA and found that 30 indicated use of one or more software tools (Hallin et al. 2011; Mallela et al. 2011). Figure 1.7 shows that most DOTs (28) used a single software tool, and that about half of respondents (18) reported using in-house developed software. This is compared to compared to FHWA's RealCost (10 states), AASHTO's DARWin-ME or AASHTOWare Pavement ME (5 states), or other industry software (1 state).

While Flannery et. al (2016) cites user costs as critical to advancing the decision-making processes for infrastructure management, the inclusion of user cost estimations in practice remains low (50 to 70% of agencies) (Hussain et al. 2004; Lee et al. 2018). More agencies appear to prefer to develop tools in-house rather than use tools resulting from extensive research. This illustrates an example of a research concept and software adaptation that struggles to realize wider agency

use, despite the evident value the paving industry has place on research methods. RealCost 2.5 continues to be available through FHWA's website, but it remained functionally unchanged. Beginning in 2017, the National Asphalt Paving Association (NAPA) has begun collaboration with Pavia Systems to integrate RealCost's LCCA methods as an extension of PaveXpress (discussed in Chapter 5).

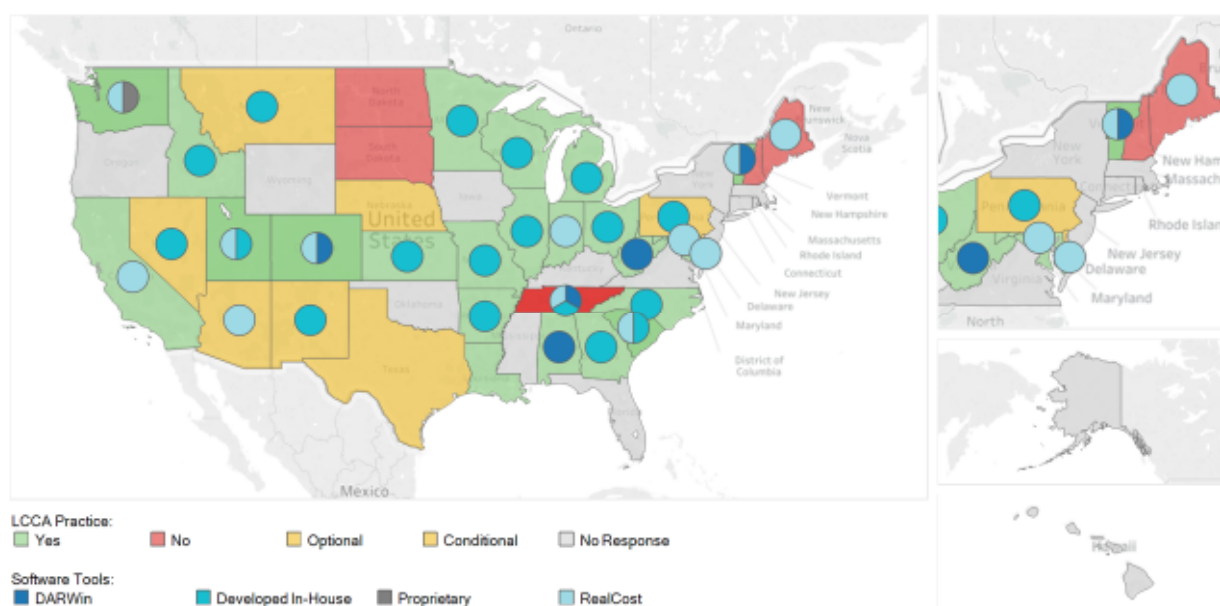


Figure 1.7. Prevalence of LCCA software practices in the United States (2009)

#### 1.4.4 Exhibit 3: Construction Productivity and Work-Zone Impacts

In 1998, the University of California at Berkeley (UC Berkeley) published a set of research papers that outlined a process for combining analyses related to construction productivity, work zone traffic impacts, and cost estimations in pavement construction (Lee et al. 2002, 2004, 2005a; b, 2006, 2007, 2008, 2011; Lee and Choi 2006; Lee and Ibbs 2005; Pyeon et al. 2012). This research was collectively intended to provide an analysis and assessment framework to facilitate decisions related to pavement constructability, design selection, closure strategy, and cost allocation. As such, the concepts embodied by the software are not collected in any standalone document but embodied in through a small library of publications.

The research team partnered with the State Transportation Departments of California, Texas, Minnesota, and Washington (CalTrans, TxDOT, MnDOT, and WSDOT respectively) to jointly develop CA4PRS (Construction Analysis for Pavement Rehabilitation Strategies) to mobilize the



However, the University of Washington's (UW) Civil Engineering senior-level undergraduate program incorporates CA4PRS use into a quarter-long course on infrastructure construction. Despite the relevance of its core concepts, it is unlikely CA4PRS use has grown given the lack of widespread adoption and discontinued product support. In 2016, Pavia Systems acquired the rights to CA4PRS to re-develop it as a web-app; no release date has been scheduled.

## 1.5 RESEARCH GOALS

### 1.5.1 *Purpose of Work*

The purpose of this work is to identify actions that may result in the development of more effective research-based software based on observed consumption trends for existing products. While recommendations exist for creating quality software in terms of product performance and usability, these do not address concerns specifically related to research quality. Consequently, this work also identifies software characteristics that indicate how well research knowledge is incorporated into software and consumed by its users. To address research questions and define value in the context of platform, development, and research, this body consists of three investigations with the following objectives:

1. Characterize technology consumption trends of transportation agencies in the context of pavement engineering and the greater construction industry
2. Determine emerging and consistent trends in user behavior in their consumption of two web-based services: a wiki-style knowledge repository, and a pavement design app
3. Document the development of a web and research-based service and generalize development practices for future research-based software

Ultimately, the study benchmarks how agencies currently attempt to democratize research knowledge and through software. To inform future development of research-based tools, this body of work will identify mechanisms driving research and software consumption habits in the paving industry. The resulting discussion synthesizes insights from the three investigations and applies them to the research-based software exhibits introduced in the previous chapter (Chapter 1.1). As well, the study examines several research extensions regarding IT-related skills beneficial to civil engineers, potential future development opportunities, implications to agency practices, and final recommendations how research-based software can effectively convey research concepts.

### 1.5.2 *Research Contribution*

This body of research synthesizes ten years of interactions between the paving industry and information technologies by benchmarking consumption trends. By doing so, the research establishes the gaps between the state of pavement research and its corresponding practice through software. The research then identifies how users consume research through web-based mediums compared to their intended use. The research also generalizes lessons learned from past and current development efforts to explain how researchers can effectively incorporate research concepts into software during the development phase. This is related in three ways:

1. by identifying software characteristics that specifically address how research is more effectively incorporated in software in terms of its contextual presentation and format;
2. by identifying a checklist of competencies software products should exhibit, which ensures that resulting products align with the consumption behaviors of its end users;
3. and by demonstrating how such characteristics and competencies can be applied to the development process for RXPave (see Chapter 5), and consequently other research-based development efforts

The resulting recommendations provide agencies with a list of software characteristics that allows them to more precisely articulate their development needs as well as a checklist of software competencies that can be used to assess research-based software. By adopting these criteria, agencies can progress towards the creation of analytical software that streamlines engineering workflows and improves the analytical capacity of its consumers.

The research provides a rational basis for pursuing research on research-based software in the context of pavement engineering. By identifying drivers and limitations to development efforts, the work also explains how researchers add value by improving the underlying research itself. Because development efforts are frequently collaborative across multiple agencies, this research may appeal to the interests of involved stakeholders representing the interest of private entities (e.g. developers), public agencies (e.g. DOTs), and academia (e.g. researchers).

## 1.6 BACKGROUND

This research includes concepts from data and computer sciences, construction and pavement engineering, as well as the development industry. To clarify their use in this work, this section summarizes their relevance to this research. This work adopts a general understanding that software are tools that operates on and extract value from data, and that data can have value beyond

the life of software. This research uses this data-centric perspective to provide a general characterization of software and development strategies to precede discussions of software, and research consumption. The concept is further elaborated in Appendix C (Figure 5.3 and Table 5.5)

### 1.6.1 *Research-Based and Internally Developed Tools*

DOT software catalogues contain an abundance of custom software tools developed in-house. This research focuses on such tools because they align with several DOT motivations for pursuing technical pavement-related tools that:

- extend beyond or address niche topics that fall outside the scope of vendor software
- require both IT and pavement construction domain knowledge
- are driven by a DOT's specific engineering needs rather than the software industry, such as performing complex calculations or mobilizing research methods into practice
- DOT's have greater oversight and influence over, especially product development

DOTs commonly use two routes to develop and deliver tools. First, tools developed in-house typically result in software templates or extensions. Second, developers deliver commissioned tools in one or more forms: on-premise or software as a service (SaaS), in which content is subscription-based or free with limited functionality.

### 1.6.2 *Software Types and Delivery Methods*

Five distinct software delivery methods have been identified in this research and are presented here disambiguate their use outside this work (Table 1.1). Though informal, definitions are intended to encompass the observed manners in which DOTs consume or implement software. It should also be noted that software products are sometimes offered in multiple delivery methods. For example, vendor software is frequently offered in SaaS and traditional on-premise versions to provide consumers greater flexibility in software ownership and deployment.

Table 1.1. Identification of Software Delivery Methods

<i>Delivery Method</i>	<i>Description / Examples</i>
<b>On-Premise Software</b>	Vendor products are directly installed or updated manually on a machine. On-premise software is purchased by seat, unlimited, or enterprise use, but updates must be purchased separately. Centralized IT support may be required for enterprise level installation. Software can be delivered on multiple platforms (e.g. mobile devices) and feature proprietary file type extensions, but functionally behave like SaaS.
	<i>Examples: Microstation, BlueBeam Revu or AutoDesk Revit</i>
<b>Software as a Service (SaaS)</b>	Software is delivered on a subscription basis and consequently users receive software updates as they roll out. Some web-services may be free to use with features such as storage costing extra. The software product may be available on multiple platforms, including web-based services. SaaS often utilizes cloud or web-services and may offer training or support as a modular subscription feature.
	<i>Examples: AASHTOWare, RSMMeans Online, Microsoft Office 365</i>
<b>Software Templates</b>	Templates are files that must be opened or executed by other software, but do not necessarily customize or change the way software operates. Templates are easily created and consequently widely used for prototyping.
	<i>Examples: Excel spreadsheet calculators, fillable PDF report forms</i>
<b>Software Extensions</b>	Extensions refer to custom analysis routines, macros, or functions that appended new functionality to a software's inherent capabilities. Development of software extensions typically requires greater software and coding proficiency than casual users.
	<i>Examples: Macros for AutoDesk Products, XLSTATS tools for Excel</i>
<b>Open Source</b>	Open source software is free and development files are publicly accessible for modification. Online communities for such software may offer libraries of templates, extensions, or add-ons contributed by users. In this case, services are not obligated or exchanged, and participation is voluntary. Consequently, product support may be limited and community based.
	<i>Examples: R-Studio, Q-GIS, Google Docs, Python function libraries</i>

### 1.6.3 Development and Distribution Pathways

To structure ensuing discussions of value, this research distinguishes factors that affect software development and software distribution / consumption. In this regard, the software and services examined in this research:

- Experience an initial development phase in which a concept is translated from research into a software product

- Experience a distribution phase in which agencies choose a distribution strategy for delivering software to their devices
- Require three basic components to survive: a purpose for being developed (user demand), a sustainable funding source, and expertise to translate a proof of concept into a polished product (researchers and developers)
- Are delivered and consumed in a form described in Table 1.1

Figure 1.9 visualizes these concepts to portray how data interactions with software can be impacted by factors that affect development or distribution.

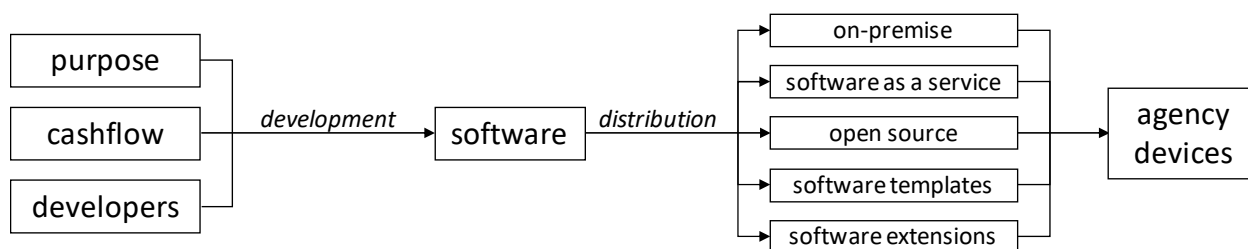


Figure 1.9. Development and Distribution Pathways

The discussion has several implications to software research in the paving industry:

- Software failures can be framed as a lack of one or more components, or poor alignment between development/distribution strategies
- Incorporating all three development components does not guarantee success but is generally a feature of successful software
- Developing software in-house is appealing when resources are limited are software and the software has a well-defined purpose or use case
- Stakeholders often provide one or more development components. For example, NCHRP may promote specific research objectives and fund software development that furthers them (i.e. purpose and cashflow)

#### 1.6.4 Common Adoption Strategies and IT Considerations

A review of state agency IT deployment efforts reveals five common strategies agencies use when considering IT investments, and their associated challenges:

- **Delay.** DOTs delay on IT investments because they lack a proper cost analysis framework, data to support it, or were unclear on assessment methods (Shah et al. 2017).
- **Give-and-Go (No Strategy).** IT investments are commonly qualified on subjective terms rather than through performance metrics (Andresen et al. 2002), or ultimately assumed successful by virtue of being deployed (Vaughan et al. 2013).
- **By Recommendation.** Case studies as guidelines to other DOTs that estimate ROI ranges for engineering productivity software (Shah et al. 2017).
- **Return on investment (ROI).** ROI calculation methods assume that both costs and benefits (or savings) are quantifiable over a time period and that such information is based on data collected at the point of evaluation (Marsh and Flanagan 2000). Economic benefits are often associated with time savings resulting improved workflow and time

distribution (Shah et al. 2017; Vaughan et al. 2013; Yamaura and Muench 2016), avoided transportation (Vaughan et al. 2013), savings resulting from non-responsive low bids due to clerical errors (Shah et al. 2017), and savings from avoided redundant data collection efforts (Yuan et al. 2016). Vaughan et al. (2013) found that most ROI estimation models for construction technology were conceptual, that few applied case studies exist, and that data collection was a primary barrier.

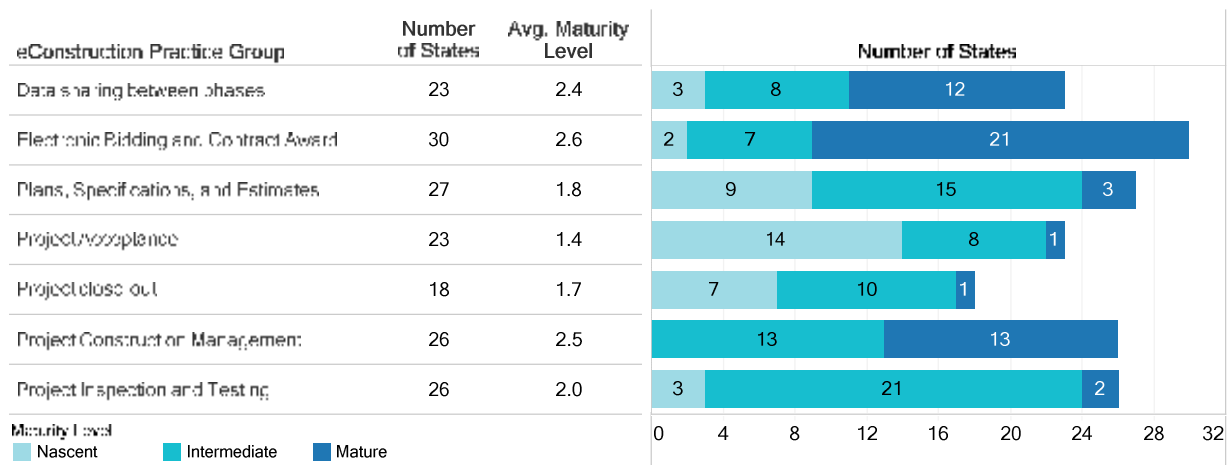
- **Technology Acceptance Model (TAM).** Ultimately, this model suggests that perceived usefulness and ease of use positively affect technology adoption (1989). Son et al. (2012) used TAM to conclude that both of perceptions impact user satisfaction, which in turn impacts the perceived performance of IT. Critics of qualitative methods (such as TAM) feel that because success and value are subjective, they fail to address the real economic aspects driving investments (Vaughan et al. 2013).

Overall, DOTs appear to approach IT with eagerness and caution because they want to ensure that investments have lasting value. The caution is justified by the challenges associated with predicting or measuring cost-benefit or selecting an appropriate performance metrics, especially when performance data to facilitate selections is challenging to acquire.

#### 1.6.5 *eConstruction and Trends Towards Software Reliance*

A common goal among state agencies is eConstruction, implying a paperless workflow enabled by software and services. This suggests that agencies are trending towards greater reliance on digital tools to perform both general and technical work tasks (Shah et al. 2017; FHWA 2016). In a study performed in 2015, the FHWA surveyed 32 state DOTs and assessed the maturity of eConstruction practices for six practice areas (Figure 1.10). On a scale of 1-3, level 3 maturity implies the capability to achieve eConstruction rather than an extent to which eConstruction is achieved.

The average state exhibits a combined maturity level of 11.3 (out of 21 maximum), meaning that the average DOT is between the nascent to intermediate maturity levels for achieving overall eConstruction goals. Maturity levels vary substantially across DOTs and specific practice areas. For example, DOTs are most mature in electronic bidding and project construction management, but no DOT is nascent in the area of project construction management. These trends imply that DOTs have room for growth in many practice areas, and that the interconnectivity among software tools is already of great interest.



The following state DOTs declined to respond and are excluded from results: AZ, DE, GA, HI, ID, IL, IN, ME, MD, MS, MT, NM, NY, OK, RI, SC, SD, WY. Additionally, Washington DC (DC) and Puerto Rico (PR) declined to respond.

Figure 1.10. Assessment of DOT Maturity in eConstruction Practices (Shah et al. 2017)

## Chapter 2. SOFTWARE AND SERVICE INTEGRATIONS: AN EMPIRICAL ASSESSMENT OF INFORMATION TECHNOLOGY USE IN STATE DEPARTMENTS OF TRANSPORTATION

### 2.1 PREFACE

The three investigations presented are written as stand-alone journal articles connected by the concept of research-based development in the paving industry (Chapter 2, Chapter 3, Chapter 4). Accordingly, each chapter is accompanied by a short narrative that describes the evolution of thought between investigations and in the context of the overall research.

The contents of this chapter (Chapter 2) were presented at a poster session and accepted as an extended abstract at the 2019 TRB Annual Conference, and the unabridged journal article is provided here in this work. Aside from aesthetic and consistency changes to format, the contexts are identical to that of the submitted article. Chapters Chapter 3 and Chapter 4 have not yet been submitted to peer-reviewed journals for publications.

### 2.2 INTRODUCTION

Transportation agencies require an unprecedented capacity to create, access, and process construction data to strategize and prioritize the maintenance of 8.5 million lane-miles of pavement infrastructure in the United States. State transportation departments (DOTs) are concerned that responsibilities must also be addressed with fewer financial and human resources (AASHTO 2016; Olsen et al. 2013). Amid these concerns, some consider the construction industry among the slowest to adopt and integrate such information technologies (ITs) compared to other engineering disciplines (Boddy et al. 2007; Rezgui et al. 2011). However, such perceptions may not fully acknowledge the specific pressures or needs that justify DOT hesitations with such investments.

The goal of this meta-analysis is to compare past and contemporary software consumption patterns that occurred in response to advancements in IT. DOTs have shown significant and growing interest in IT because their perceived benefits align with desires to improve worker productivity, capacity to collaborate, and derive additional value from construction data. Agencies

seek IT products that have organization-wide impacts on workflow but are unclear on effective selection strategies due to inherent risks and financial constraints and a rapidly evolving selection. As a result, there are few case studies in the paving or general construction industry from which other agencies can derive clear best practices for software adoptions (Janssen et al. 2016).

### 2.3 RESEARCH OBJECTIVES AND SCOPE OF WORK

This paper characterizes and assesses current IT implementation practices by DOTs in the United States, focusing on the gap between technological capabilities versus actual implementation. The study aims to clarify how agencies derive value from IT software investments and factors that currently drive such investments. The study identifies capabilities that agencies are most eager to enable through IT advancements, as well as the nature of barriers that prevent the realization of IT value. Using data analysis techniques to rationalize observations from technology surveys over the last decade, the study informs the relationship between perceptions regarding IT usability, functional value, and adoption success. Accordingly, this research contributes by identifying competency criteria to help DOT's prioritize technology adoptions.

### 2.4 BACKGROUND

#### 2.4.1 *Drivers and Barriers to Technology Adoption in DOTs*

The perceived benefits (and barriers) to IT implementation are well documented in research and industry (Table 2.1). In this study, IT tools refer to software or services that operate on or handle data throughout its useful life (e.g. collection, analysis). Mobile IT devices include laptop computers, handheld data collectors, tablets, smartphones, or wearable devices (Wang et al. 2016). Despite the strong interest in enabling IT benefits, multiple systemic barriers to IT adoption ultimately prevent agencies from making investments or realizing intended benefits.

Regarding challenges, a common barrier is the fragmented nature of data collection, integration, and post-processing that must occur to make data useable (Janssen et al. 2016; Rehman et al. 2016; Yang et al. 2017; Yuan et al. 2016). Exacerbating this is the lack of applied standards for structuring and managing data (AASHTO2016; Boddy et al. 2007; Chong et al. 2007) as well as poor or inconsistent data quality (Janssen et al. 2016; Son et al. 2012; Yang et al. 2017).

Table 2.1. Perceived Benefits and Barriers to IT Implementations by DOTs

	Total Count	(Yang et al. 2017)	(Wang et al. 2016)	(Chong et al. 2007)	(AASHTO 2016)	(Muench et al. 2010)	(Janssen et al. 2016)	(Son et al. 2012)	(Yuan et al. 2016)	(Boddy et al. 2007)	(Melville 2010)	(Rehman et al. 2016)	(Griffith 2014)	(Patel 2015)	(Vaughan et al. 2013)	(Shah et al. 2017)
<b>PERCEIVED BENEFITS</b>																
Process Automation / Integration	8		x		x	x	x	x	x	x		x				
Accessibility / Availability	7	x	x	x	x			x		x		x				
Mobility (Workforce)	6	x	x		x	x		x	x							
Knowledge MGMT / Transfer	6	x		x		x	x			x	x					
Process Improvement	6						x	x	x	x	x	x				
Efficiency / Productivity	5	x	x	x				x	x							
Streamlined Data Collection / Entry	5		x		x		x	x	x							
Value Creation	4	x		x		x						x				
Collaboration	4	x				x	x				x					
Information Dissemination	4	x						x			x	x				
Decision Support	3	x		x			x									
Data / Information Quality	3					x	x		x							
Project Administration	2	x					x									
Risk Reduction	1			x												
Economic Savings	1										x					
Environment	1										x					



Regarding IT development, Patel reports that 9 in 10 startup companies ultimately fail (Patel 2015). Failures were primarily attributed to the lack of market need for products (42%), ‘running out of cash’ (29%), ignoring customer needs (14%), and lacking a business model to sustain development (17%) (Griffith 2014). Seeking lasting returns on investments, agencies are rightfully skeptical towards IT products whose development and support have large chances of being discontinued. Muench et al. as well as DOT employees expressed this concern when characterizing the value of web-based tools (AAASHTO 2016; Muench et al. 2010). Such statistics further discourage agencies who perceive IT investments to have prohibitive resource costs (Wang et al. 2016). Research contracts in the construction field are generally finite and lack funding to maintain content. Muench et al. concluded that success depends on secured funding beyond initial development (2010).

Regarding existing IT, users suggested existing tools were insufficient at fostering collaboration (Boddy et al. 2007; Muench et al. 2010; Yang et al. 2017) and placed inadequate focus on usability or the user experience (AASHTO 2016; Muench et al. 2010; Son et al. 2012). Many agencies feel unprepared to handle disruptions when migrating, replacing, or integrating legacy tools into newer IT systems (AASHTO 2016; Wang et al. 2016). Agencies are particularly concerned that migrating data from legacy tools will involve resource-intensive manual entry without clear value (Son et al. 2012; Wang et al. 2016; Yuan et al. 2016). Regarding guidance, agencies perceive a shortage of proper implementation strategies or decision-support tools to realize successful technology adoptions (AASHTO 2016; Yang et al. 2017).

Other technical issues include: insufficient allocation of resources to knowledge transfer to foster organizational growth (Wang et al. 2016), concerns regarding data security and privacy (AASHTO 2016; Wang et al. 2016), ubiquity of cellular coverage for mobile IT (Vaughan et al. 2013; Wang et al. 2016), lack of community engagement for knowledge generation (Chong et al. 2007; Muench et al. 2010) or stakeholder participation in deployment (Chong et al. 2007).

#### 2.4.2 *Timeline of Technology Used by the Pavement Industry*

Although the pavement industry has access to a wide array of IT-enabled tools, the types and capabilities they support evolve quickly. The timeline in Figure 2.1 illustrates various technologies (and supporting technologies) used by the industry. Each technology is partitioned to depict the durations of growing, peak, and declining use periods. Although dates are not intended to be

precise, they provide a snapshot of which technologies were simultaneously available and their respective maturity levels at a given time.

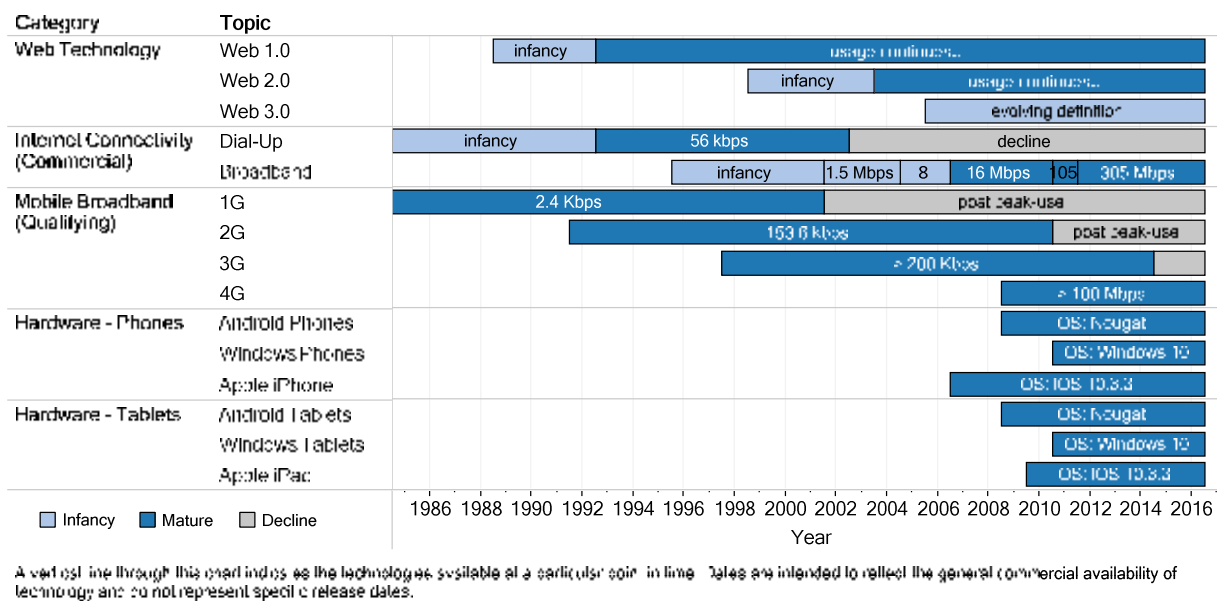


Figure 2.1. Timeline of Technology used in the Paving Industry

The growing interest of DOT’s in IT parallels the development timeline of core concepts driving the evolution of services offered on the world-wide-web via the internet (web services). Discussions of functionality enabled by changes in web versions (Web 1.0, 2.0, and 3.0) is consequently relevant to software consumed by DOTs. While web versions do not replace each other but are used to distinguish design concepts driving the original services.

Reproduced in Figure 2.2, Santos distinguishes the differences between web versions in terms of the capabilities available to different ‘actors’ (large organizations, individuals, and agents / devices) to consume or produce content as well as the overarching virtues driving each generation (2015). Web 1.0 refers to the ability to access static content online almost exclusively produced by large organizations. For Web 1.0 services, individuals and small business entities could access and consume but not produce information. The subsequent Web 2.0 milestone collectively refers to new capacities offered: content can be both consumed and produced by individuals, resulting in a greater capacity to collaborate, generate community-driven data, and produce more flexible representations of information (Muench et al. 2010). Mobile agents are first enabled in the Web 3.0 generation, implying that agents or devices are now capable of consuming, processing, and producing content (the ‘capacity of action and knowledge’). This definition suggests that devices can apply programmed intelligence and apply context to act autonomously on incoming data.

Generation	Virtue Democratized	Portals (Large Orgs.)		Individuals (Small Companies)		Agents (Devices)	
Web 1.0	access to information	● P		○ C			
Web 2.0	the ability to produce content	● P	○ C	● P	○ C		
Web 3.0	the capacity to apply context (act on knowledge)	● P	○ C	● P	○ C	● P	○ C

Legend: ● Produce ○ Consume

Figure 2.2. Generations of the World Wide Web (Santos et al. 2015)

Overall, IT solutions that support Web 2.0 services have been available for effectively 10 years. Mobile devices (phones and tablets) became commercially available during the peak of 3G mobile broadband and Web 2.0 era, shortly after Web 3.0 conceptualizations emerged. Consequently, broadband-enabled tablets and phones were the first generation of mobile hardware to be capable of supporting Web 3.0 services. As 4G connectivity overtook 3G broadband, access to data-heavy web services became increasingly possible due to substantially faster data connection speeds.

Web generations influence the capabilities of available technologies and how users can consume and produce web content. The desire for IT services exhibiting Web 2.0 (or later) capabilities is established in research case studies. For example, the pavement industry has sought IT-enabled solutions that facilitate the generation of pavement life cycle inventories and assessments or environmental product declaration systems that can be accessed and shared more effectively (Melville 2010; Santero et al. 2011; Santos et al. 2015). Appendix E elaborates more on the perceived distinctions between Web generations.

### 2.4.3 *Perceptions of Value in Information Technology Adoptions*

Academia and industry employ both quantitative and qualitative methods to support IT investment decisions based on empirical studies, but no consensus exists on best strategies. In general, IT investments are often qualified on subjective terms rather than through performance metrics (Andresen et al. 2002): for example, some organizations assume that continued use of an IT adoption qualifies as one metric for success (Vaughan et al. 2013). Though most DOTs have begun some IT implementations, the FHWA finds that agencies delay because they lack a proper cost analysis framework or are unclear how to begin assessments (Shah et al. 2017).

In the pavement industry, economic IT benefits are often associated with time savings resulting from improved workflow and the value of freed-up activities (Shah et al. 2017; Vaughan et al. 2013; Yamaura et al. 2015). Other quantifiable benefits include the value of avoided transportation (Vaughan et al. 2013), savings resulting from non-responsive low bids due to clerical errors (Shah et al. 2017), and savings from avoiding redundant data collection (Yuan et al. 2016). Return on investment (ROI) is a common economic performance metric used to justify the value of investments. Such methods heavily rely on data being actively collected throughout the project (Marsh and Flanagan 2000). Vaughan et al. (2013) found that most ROI estimation models for construction technology were conceptual and that few applied studies use data spanning the entire construction phase. Researchers also suggest that project scale affects the comparability of ROI results because larger projects can justify IT investments more easily, even though some initial investment costs are avoided in future projects (Vaughan et al. 2013).

Other researchers suggest that IT still generates qualitative value, despite subjective perceptions. Bowden et. al showed that adoption levels of mobile IT can substantially improve workflow processes (Bowden et al. 2005). Davis' Technology Acceptance Model (TAM) suggests that both perceived usefulness and ease of use also affect technology adoption rates (1989). Son et al. used the TAM to conclude that perceived usefulness is more likely to impact user satisfaction than perceived ease of use, and that user satisfaction impacts perceived performance of IT (2012). Others perceive value in terms of knowledge management and transfer, which are considered essential to continued education and transforming innovations into practice (Chong et al. 2007; Muench et al. 2010). Rehman et al. have suggested that IT helps reduce the complexity of construction big data and reduce time spent managing it (2016). However, critics of qualitative methods believe they lack objectivity and practicality in their failure to address economic drivers (Vaughan et al. 2013).

Overall, literature suggests that DOTs approach IT with caution to ensure that technology investments create lasting value. This caution is justified by the challenges associated with characterizing cost-benefit and selecting appropriate performance metrics, particularly in lieu of implementation best practices or comprehensive data sets that could inform product selection.

## 2.5 METHODS AND DATA SOURCES

The research is divided into two component efforts that explore different aspects of IT integrations using a mixture of primary data sources (Table 2.2).

Table 2.2. Primary Data Sources and Relevance to Research Methods

	Source Type	References	Relevance
<b>Exploration 1</b>	Surveys	AASHTO Annual IT Surveys (AASHTO 2013, 2014, 2015, 2017; AASHTO2016)	Surveys IT personnel from state DOTs specifically in terms organizational capabilities enabled by IT adoptions as well as future integration plans
		JBKnowledge Construction Technology Integration Reports (JBKnowledge 2012, 2013, 2014, 2015, 2016)	Captures how public and private stakeholders address information technology
	Reports	FHWA Report HIF-17028 (Shah et al. 2017)	Details the state maturity levels of DOTs regarding paperless construction practices in 13 states
	Journal Articles	Various Sources	Research related to agency policies on how STA employees use mobile IT devices (2016) in practice as well as their perceptions
<b>Exploration 2</b>	Websites	DOT Websites	Indicates software resources available within the agency, documented support, or policies regarding software usage
		NCHRP Publication Database (2011-2016)	Review of projects resulting in the creation of a software tool or became the underlying concept for a software tool produced outside project scope
	Journal Articles	Various Sources	Research that specifically discuss STA adoption of IT software and across multiple states

### 2.5.1 Exploration 1: Synthesis of IT Surveys

This exploration examines survey data (Table 2.3) to gauge how perceptions and attitudes towards IT and software/service usage have evolved in the last five years (AASHTO 2013, 2014, 2015, 2017; AASHTO2016; JBKnowledge 2012, 2013, 2014, 2015, 2016; Shah et al. 2017; Wang et al. 2016). Additionally, this section aims to identify readiness of DOTs to use IT software and services, highlighting the drivers and conditions that affect DOT capacity in different areas of

construction practice. Surveys analyzed in this study covered a broad range of topics including the state of practice of IT technology usage, implementation efforts, and organizational policies that govern their use or deployment.

Table 2.3. IT Surveys Examined in Research Effort

Scope	Reference	Published	Respondents	Survey Topics Included [Count of Relevant References]				
				Policy and Procedure	IT Hardware	IT Resources	Implementation Efforts	Software End-Use
				[7]	[9]	[10]	[10]	[10]
<b>Industry Wide Responses</b>	Construction Technology Integration Reports (JBKnowledge 2012, 2013, 2014, 2015, 2016)	2012	452	<b>X</b>			<b>X</b>	<b>X</b>
		2013	706		<b>X</b>	<b>X</b>	<b>X</b>	<b>X</b>
		2014	1028		<b>X</b>	<b>X</b>	<b>X</b>	<b>X</b>
		2015	2044		<b>X</b>	<b>X</b>	<b>X</b>	<b>X</b>
		2016	2604		<b>X</b>	<b>X</b>	<b>X</b>	<b>X</b>
<b>State Agencies Only</b>	*AASHTO Annual IT Surveys (AASHTO 2013, 2014, 2015, 2017; AASHTO2016)	2013	26 states	<b>X</b>	<b>X</b>	<b>X</b>	<b>X</b>	<b>X</b>
		2014	23 states	<b>X</b>	<b>X</b>	<b>X</b>	<b>X</b>	<b>X</b>
		2015	30 states	<b>X</b>	<b>X</b>	<b>X</b>		<b>X</b>
		2016	30 states	<b>X</b>	<b>X</b>	<b>X</b>		<b>X</b>
		2017	28 states	<b>X</b>	<b>X</b>	<b>X</b>	<b>X</b>	
	*FHWA Report HIF-17028 (Shah et al. 2017)	2017	32 states				<b>X</b>	<b>X</b>
	*Wang et al. (Wang et al. 2016)	2016	42 states	<b>X</b>		<b>X</b>	<b>X</b>	
<p><b>*Note:</b> AASHTO surveys exclude responses from DOTs outside the United States.  Wang et al. includes 100 respondents representing a total of 42 states  Shah et al. includes respondents representing 32 states.</p>								

The demographics of surveys include both industry-wide responses as well as state DOT-specific scopes, allowing some contrasts to be drawn. Results are presented by number of states where possible but otherwise presented as a percentage of responses.

### 2.5.2 *Exploration 2: Development and Distribution of IT Software and Services*

The software/service catalogues of DOTs typically feature a mixture of software/service types and hardware platforms, but it is unclear how DOTs assess their value in practice. The goal of this task is to examine these catalogues (and related literature) to identify how DOTs select appropriate tools and assess development of technical software/services because there is little (if any) literature discussing the utility and consequences of DOT's creating such tools. Moreover, observations focus on two groups of specialized tools because they represent niche functional needs of DOTs that are unlikely to disappear. First, internally developed ('in-house') software and services that provide technical functionality seemingly outside the scope of vendor products; second, software/services based directly on specialized research.

## 2.6 RESULTS AND OBSERVATIONS

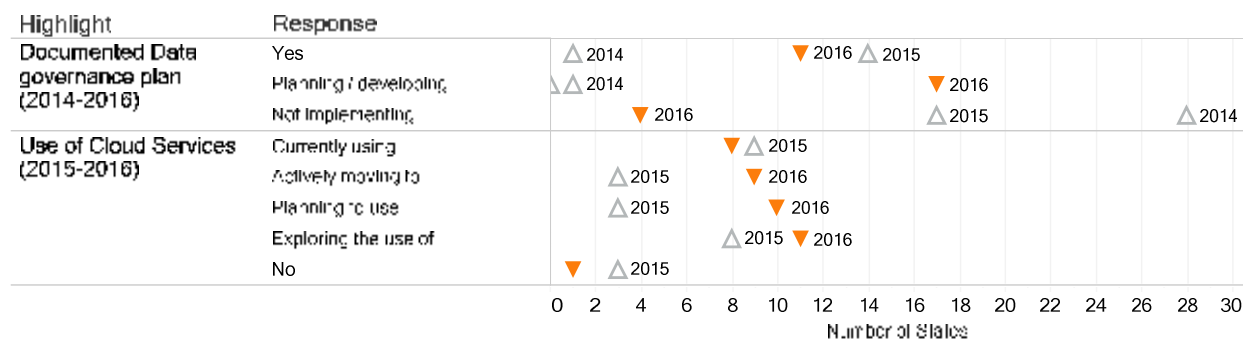
### 2.6.1 *Exploration 1 Results: Synthesis of Surveys*

Survey results are visualized in Figure 2.3 to Figure 2.6 and separated into 4 topics: Maturity and Policy, Devices and Platform, IT infrastructure, and Dedicated IT Resources. The observations drawn from surveys focus on revealing three primary distinctions: between DOT responses and the greater pavement industry, changes in responses or perceptions over time, and deployment strategy versus realized benefits.

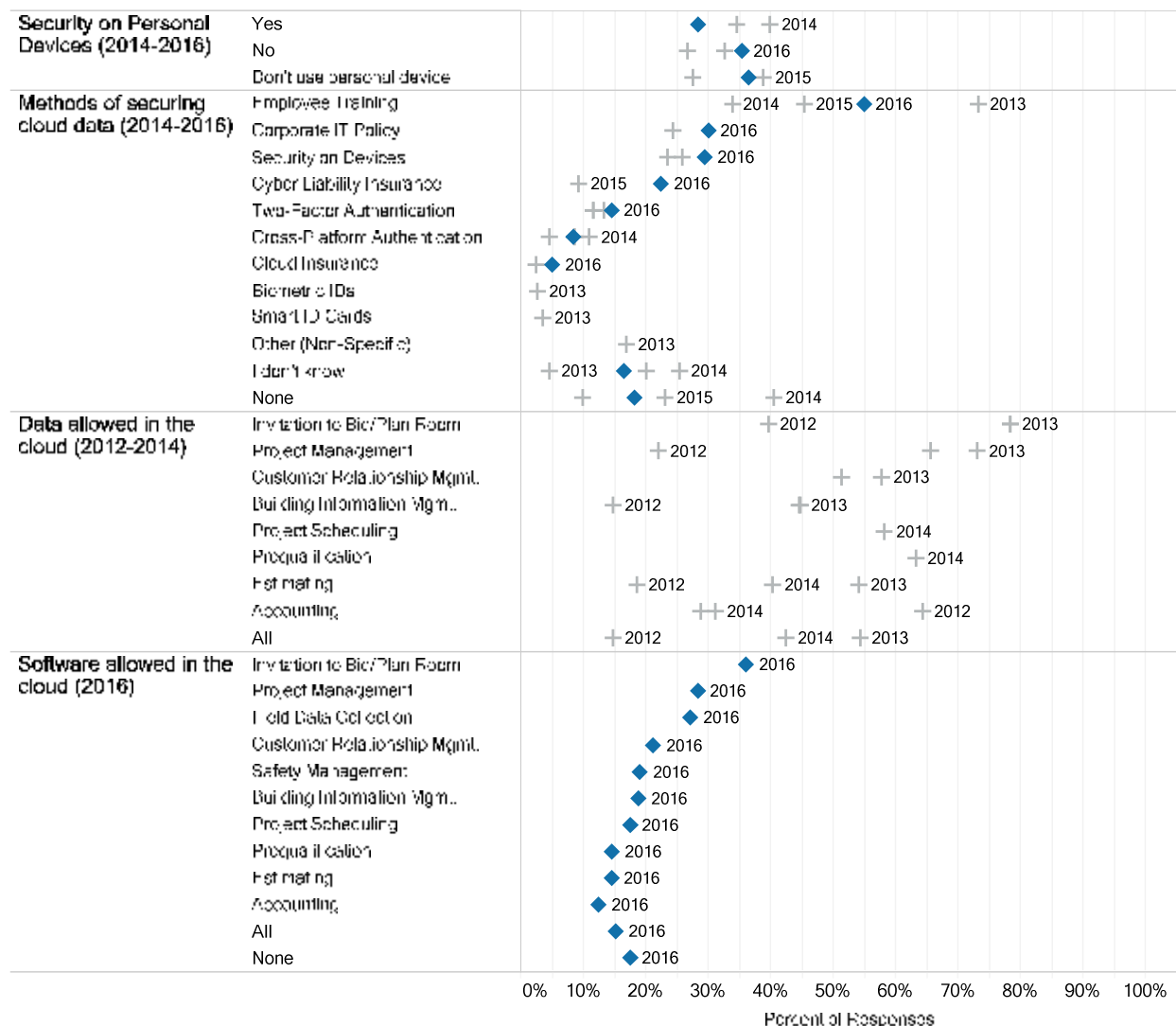
#### **Data Governance**

28 of 31 DOTs surveyed between 2014 and 2016 indicate the use or active development of a data management plan (Figure 2.3). Conversely, DOTs lacking such is decreasing but remains non-zero. Although the surveys are unclear if "yes" implies pilot projects or system-level implementation plans, the most common response from DOTs indicated current or active plans for adoption.

### Topic 1: Policy and Maturity



Legend: ▼ DOT Response Only (Most recent) ▲ Older Data



Legend: ◆ Industry Only (Most recent) + Older Data

Description: Data labels indicate the year responses were collected, as opposed to the publication year. Triangles indicate responses from DOTs only while diamonds indicate industry-wide responses (potentially including DOT responses). Filled, colored shapes indicate the most recent available data while greyed-out shapes indicate older response data.

Figure 2.3. Survey Synthesis: Policy and Maturity

### **Use of Cloud Services and Security**

Between 2015 and 2016, the number of states currently using or active moving to cloud services increased from 12 to 17; the number of states that do not use cloud services dropped from 3 to 1. Most states reporting use of cloud services generally included ‘low level’ uses (e.g. email access and word processing) (Wang et al. 2016). Similarly, Industry-wide survey responses shows increased acceptance towards the use of cloud data between 2012-2014, and similar levels of integration for cloud software or services in 2016 as DOTs (10-30%).

Between 2014-2016, industry responses indicating a lack of cloud security in any form decreased from 41% to 18% (as well, the number of responses more than doubles in this period). Results indicate that specific employee training was most common (55%) and that security measures of all forms have increased in the pavement industry, excepting cross-platform authentication. Although DOT responses provided no quantitative information regarding security practices, data security was indicated as a qualitative concern in 25 comments in all five surveys.

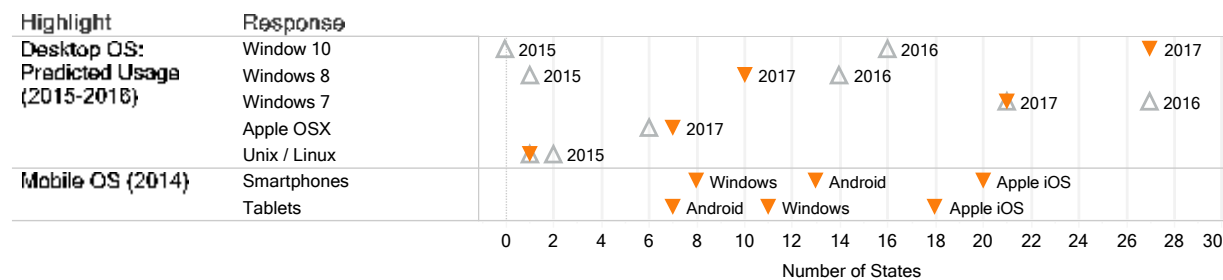
### **Importance of Mobile Capabilities**

Industry-wide surveys indicated an increasing belief in the importance of using mobile devices (59% to 79% in 2016). Similarly, responses indicating the unimportance of mobile capabilities declined from 40 to 20% in the same period (Figure 2.4).

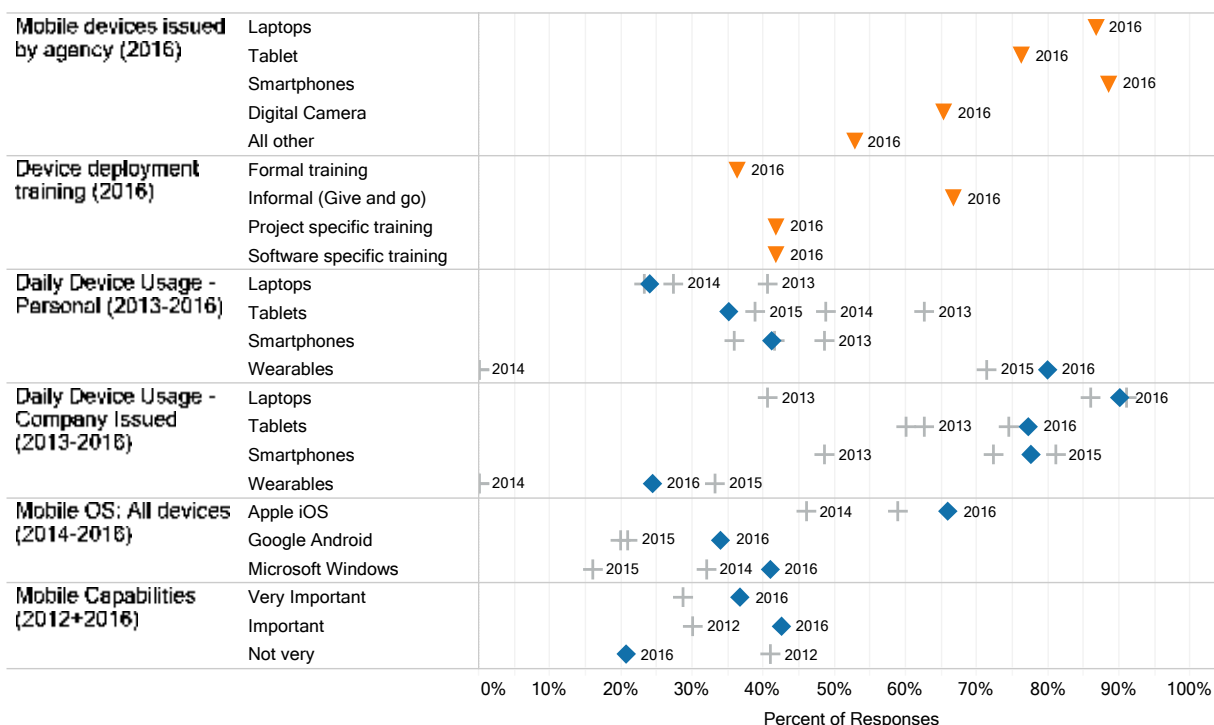
### **Device Deployment and Use**

In 2016, both DOTs and the greater pavement industry reported issuing devices (smartphones, tablets, and laptops) at increasing rates (over 75%). Except for wearable devices, industry responses indicated declining use of personal devices at work. About 65% of DOTs receive no training of any form for their devices (so-called a ‘give-and-go’ tactic) compared 35-42% indicating device training of any form. Regardless of ownership, daily device usage among laptops, tablets, and smartphones by the industry increased between 2013-2016. Excluding wearables (e.g. smartwatches), the industry reported that daily usage rates were highest smartphones and tablets (40% and 35%), followed by laptops.

## Topic 2: Devices and Platform



Legend: ▼ DOT Response Only (Most recent) ▲ Older Data



Legend: ◆ Industry Only (Most recent) ▼ DOT Response Only (Most recent) + Older data

**Description:** (Desktop OS Predicted Use) Labels indicate the year of predicted use; data year is 2015. (Mobile OS) Labels indicate operating system; data year is 2014. (All others) Data labels indicate year of responses. Filled, colored shapes indicate the most recent available data while greyed-out shapes indicate older response data. Shapes indicate scope of survey responders.

Figure 2.4. Survey Synthesis: Devices and Platforms

### Operating System and Platforms

Both state agencies and industry professionals prefer a mixture of devices and platforms for their servers, desktop and laptops, and mobile devices. Desktops and servers are dominated by Microsoft platforms, while smartphones and tablets by Apple platforms. Android or Windows OS makes up approximately one third of issued mobile devices each. Overall, the distribution of mobile OS usage in state agencies is similar to the construction industry in general.

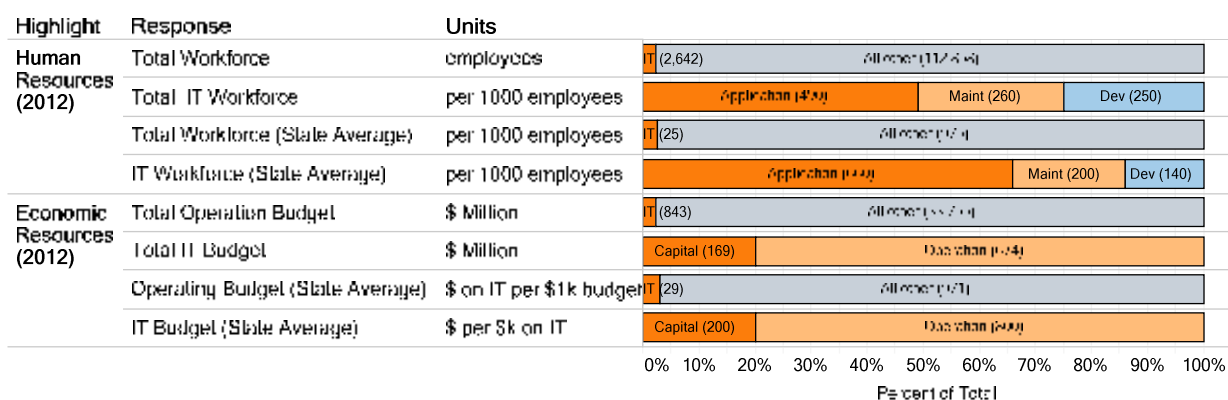
Topic 3: Dedicated IT Resources

**Human Resources**

The collective DOT IT workforce is primarily dedicated to application support (49%-66%), with maintenance and development comprising the balance. Although proportions vary between states, the least human resources are consistently dedicated towards development (Figure 2.5).

**Economic Resources**

Among DOTs, operating costs occupied 80% (\$667 million) of the aggregated IT budget, with a similar allocation shown between states (about 67% on average). In all but 3 states, operating costs were greater than capital costs: states invested an average 2.4% of their total budget towards operation and 0.5% towards capital costs (ranges of 0.5-7.3% and 0.08-9.3% respectively).



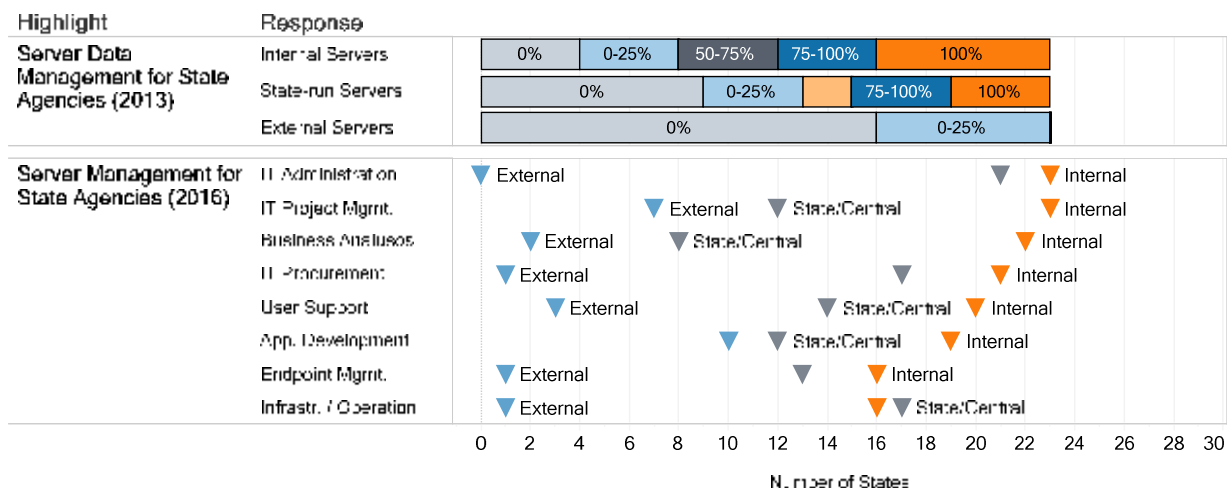
Description: Human and economic resource allocations for 24 state DOTs in 2012. To normalize data across DOTs, values are shown in base units (employees or ISS), and averages on a per employee basis or per budget dollar basis. For example, DOTs spent an average of \$29 per \$1000 of operating budget in 2012. DOTs also have an average of 25 IT employees per 1000 employees.

Figure 2.5. Survey Synthesis: Dedicated IT Resources

Topic 4: Supporting IT Infrastructure

DOTs indicate a stronger preference for using internal servers over both centralized state-run or external servers (Figure 2.6). The 2013 data shows the number of DOTs that host data internally, externally, or via state-run servers and the extent for each (e.g. 4 DOTs indicate hosting 75-100% of data internally). Notably, 11 DOTs report exclusive use of internal or state-run servers, 12 prefer a combination of internal or state-run, and none reported exclusive use of external servers.

A similar question regarding DOT hosting preferences was posed in 2016 for eight categories of oversight. With 26 states responding, most preferred internal servers for all categories of oversight except infrastructure and operation. When states do use external servers, they are primarily intended for application development or IT project management.



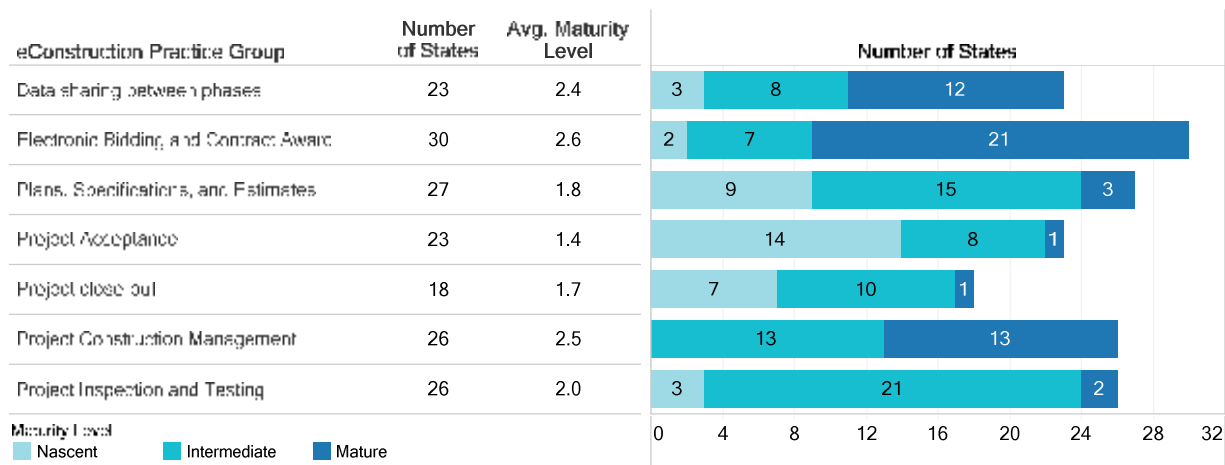
Descriptions: (Top) Self reported breakdown of DOT server data management. For example, 6 states reported hosting 100% of their data on internal servers; the same number of DOTs reported hosting 0-25% of their data on external servers. (Middle) Number of DOTs who use internally, externally, or centrally hosted servers for different IT practices.

Figure 2.6. Survey Synthesis: Supporting IT Infrastructure

### Topic 5: Maturity of eConstruction Practices

In a 2017 study, the FHWA surveyed individuals representing 32 DOTs and assessed the maturity of their eConstruction practices in six practice areas as well as data sharing capabilities among these practices. Maturity was ranked on a scale of 1-3 based on the extent to which DOTs utilize software or services to achieve a paperless workflow system for pavements, a primary goal of eConstruction and an appealing capability to DOTs. The authors defined level 3 maturity as the capability to achieve eConstruction goals rather than an extent to which eConstruction is achieved. Study results were re-visualized by maturity levels for each eConstruction practice (Figure 2.7).

DOTs appear most mature in the areas of EB&CA, PCM, and data sharing among phases (averages greater than 2). No DOT is nascent in PCM practices. In contrast, DOTs generally appear between nascent and intermediate levels (averages less than 2) of maturity for the remaining practices. When organized by state, the average state has a combined maturity level of 11.3 out of 21 maximum (range of 2 to 19), indicating that a given state is likely to be between nascent and intermediate maturity levels for achieving eConstruction overall.



The following state DOTs declined to respond and are excluded from results: AZ, DE, GA, HI, ID, IL, IN, ME, MD, MS, MT, NM, NY, OK, RI, SC, SD, WY. Additionally, Washington DC (DC) and Puerto Rico (PR) declined to respond.

Figure 2.7. Assessment of DOT Maturity in eConstruction Practices

## 2.6.2 Exploration 2 Results: Software Development and Distribution Pathways

### Identification of Common Software and Service Delivery Methods

Five distinct software delivery methods are identified in Table 2.4 based on how users implement or adopt products into their existing software catalogue. Though informal, these definitions include all observed manners in which software is consumed and implemented by DOTs. We subsequently focus observations on internally developed and research-based tools (as opposed to vendor products) based on several observations:

- DOTs have greater control and influence over their development and a research goal is to provide actionable recommendations to DOTs specifically
- Such tools are driven directly by specific DOTs needs rather than the software industry
- They extend beyond capabilities of vendor software and require both IT and construction domain knowledge

Table 2.4. Software and Service Delivery Methods

Delivery Method	Description / Examples
<b>On-Premise</b>	<p>Products purchased from vendors but must be installed manually on a target device off-line (as opposed to remotely through servers). On-premise software is purchased by seat or enterprise use, but updates may require separate purchase or installation. Centralized IT support may be required for enterprise level installation. On-premise software may also feature SaaS versions for convenience.</p> <p><i>Examples: Any vendor software requiring physical installation.</i></p>
<b>Software as a Service (SaaS)</b>	<p>Software is delivered on a subscription basis and subsequently users receive updates as they roll out. Like on-premise software, the software product may be available on multiple or specific platforms. Mobile devices rely heavily on SaaS for delivery of software and services, frequently utilizing cloud or web-app services. A limited version of the software may be offered for free, with additional features requiring purchase (e.g. training, cloud features, or technical support).</p> <p><i>Examples: BlueBeam Revu, RSMeans Online, Microsoft Office 365</i></p>
<b>Open Source</b>	<p>Open source software is free and development files are publicly accessible for modification. Open source software may also offer libraries of templates, extensions, or add-ons developed by its base community. This is distinct from SaaS and on-premise because services are not obligated or exchanged: participation is voluntary and support is community driven (albeit frequently limited)</p> <p><i>Examples: R Studio, Google Docs, programming development libraries</i></p>
<b>Software Templates</b>	<p>Templates are files that must be opened or executed via a specific software but do not modify the way software operates. These commonly include spreadsheet calculators or pre-generated files that users alter to meet custom needs. Templates are often be generated by research efforts, community or state developed, or third-party vendors.</p> <p><i>Examples: Excel spreadsheets, fillable PDF forms, Access databases</i></p>
<b>Software Extensions</b>	<p>Extensions refer to custom routines, macros, or functions that are appended to a base software package. Distinct from a template which is simply opened in software, an extension changes the inherent capabilities of the software. They can be developed internally by agencies, third-parties, or directly by the base-software developers.</p> <p><i>Examples: GIS analysis macros, XLSTATs probability toolbox for Excel</i></p>

### Internally Developed Tools

Software templates and extensions exist in abundance in DOT software catalogues and are typically not inventoried. In general, capabilities added, or functions performed by these tools are extremely customized and not usually offered in vendor software.

Based on survey results, some DOTs also indicated collaboration with contractors or academic institutions to develop products. Some result from internal development or research projects (e.g. CA4PRS, RealCost, WESLEA), while others are purchasable add-ons offered directly by a developer. For example, in FHWA's report on best practices on e-Construction, all 13 DOTs surveyed indicated use of multiple tools developed in-house to facilitate construction and data management practices. The majority of these tools are software extensions, templates, or add-ons built in Microsoft Excel or Access and generally are used for engineering analysis or decision support purposes.

### Research-based Development

Figure 2.8 categorizes results by NCHRP-defined fields of research and indicates that 25 of 167 (15%) of NCHRP research projects completed between 2011 and 2016 expressly resulted in the creation of a software tool or service (any kind, including databases). These 25 projects resulted in 26 software tools or services:

- 19 projects resulted in editable Microsoft Excel spreadsheet templates or macro-enabled extensions. Templates may have specific version compatibility requirements.
- 3 resulted three web-based tools. The web-based tools included a training website, a decision-support method, and a strategy selection tool for asset management.
- 3 resulted in databases or database templates, including updated methods for pavement design software.
- 1 resulted in a stand-alone software application for Windows.

Overall, it is rare for NCHRP projects to result in full software products or services. When produced, the most common platform is an Excel spreadsheet (76% of projects resulting in tools). Generally, tools provide proof-of-concepts for new research methods, revise or improve upon existing analysis method from previous research projects, or provide support for decision-making. Despite their accessibility, the extent to which DOTs (or researchers) have used these resources it is unclear. Although some NCHRP projects immediately result in extensions or templates, some are later be redeveloped into full software products. For example, NCHRP research completed prior to 2011 was later integrated into AASHTO's DarwinME (a.k.a. AASHTOWare Project).

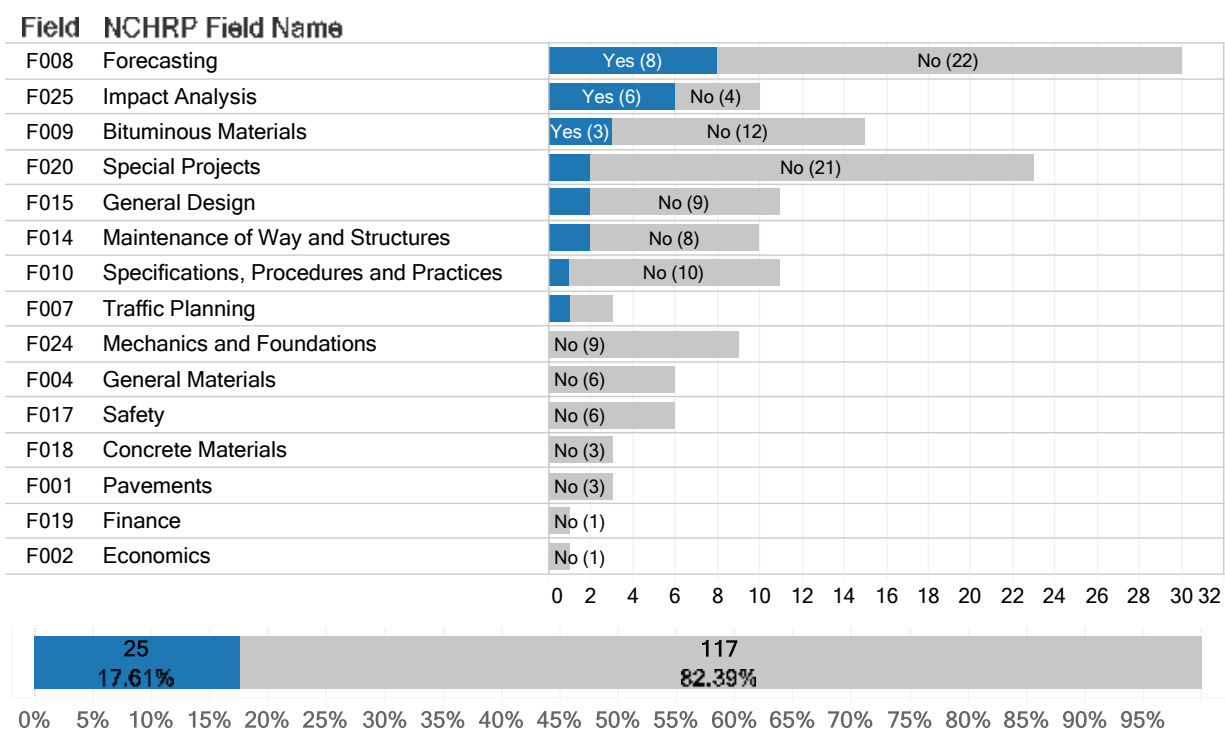


Figure 2.8. NCHRP Projects Resulting in Software Tools (2011-2016)

## 2.7 DISCUSSION

*Migration to mobile platforms is trending but device and software training are uncommon.*

Both DOTs and the construction industry are increasingly issuing mobile devices to employees resulting in the use decline of personal devices (Figure 2.4). However, 28 DOTs indicate distributing mobile devices without any formal training (so-called a ‘give-and-go’ tactic). Only 15-18 states indicate any formal, project, or software-specific training. Although responses from the construction industry indicate that employee training is the most common mode of training for using cloud-based services securely, DOT levels are likely equal or lower given their tendency towards give-and-go tactics for issued devices.

*DOTs prefer a mixture of devices and operating system platforms*

DOTs and the general construction industry issue a variety of devices to employees, but the preferred operating system for each depends on the platform (Figure 2.4). The industry’s daily usage of laptops, tablets, and smartphones has also consistently risen over time. For servers,

desktops, and laptops however, DOTs strongly prefer Microsoft platforms; for smartphones and tablets, Apple platforms followed by Google.

*DOTs acknowledge the importance of data governance and IT management*

The industry is reacting to changes and advancements in IT that provoke new considerations previously absent from discussions of technology integrations, such as remote accessibility and data security. 28 DOTs indicate the use or active development of a data manage plan while only 4 DOTs indicate lacking such policies (Figure 2.3). This compares to rates found in a nation-wide survey across 16 market sectors that found 46% of respondents have no formal data governance strategy and 40% without a dedicated budget (CIO Magazine n.d.; Erwin, Inc. n.d.). States also exhibit wide variation in terms of their individual maturity levels across seven eConstruction practices identified by the FHWA (Figure 2.7).

The number and variety of hardware types and device platforms issued to employees in the general construction industry may be influencing the need for such data policies. As well, DOTs may be cautious about adoptions if they currently lack the proper IT infrastructure, policies, or training programs necessary to effectively manage their devices across multiple hardware platforms.

*DOTs prefer internal (rather than external) management of IT hardware, services and data.*

DOTs predominantly host their data or cloud services on internal servers or state/centralized servers, preferring to use external servers for less than 25% of agency data and primarily for development staging purposes (Figure 2.6). This appears to stand in contrast to national and global trends towards IT outsourcing (Lacity et al. 2017; Rajaeian et al. 2017), the market for which has continuously grown over the last five years (Overby 2013). In general, businesses outsource 42-72% of their IT functions and this practice is expected to continue increasing (Deloitte 2016). Although the proportion of human and economic resources dedicated to IT varies between states, DOTs in general allocate the smallest portion of their IT budget towards capital growth and IT workforce towards services development (Table 2.1).

DOTs may be exhibiting hesitation towards adopting external IT solutions due to organizational constraints. Software products and services increasingly rely on web-based or

cloud-based services for delivery. While such services require additional considerations for hosting and maintenance, they also require less internal development and staffing requirement.

*DOTs have greater influence and control over internally developed and research-based tools.*

Through their abundance of internally developed tools however, DOTs may be indirectly expressing a desire to customize or calibrate software to meet specific needs. DOTs internally develop software tools primarily to facilitate data interactions (e.g. analysis for decision-support), supporting the findings of Yang et. al. (2017). Research topics are influenced by DOT interests, as they vote to allocate research funding (e.g. NCHRP research funds). Given the extent of internal development and array of devices issued by DOTs, software may be a salient medium to communicate research results.

Vendor software is not typically designed to handle nuances or technical analysis, let alone address specific needs of an agency. The inability to customize software may result in a loss of perceived software utility as well as the results it produces, which in turn can reduce the likelihood of technology acceptance and continued usage (Son et al. 2012). The continued use of internally developed tools means that they still provide value, even if they remain disconnected from or incompatible with newer IT investment capabilities.

## 2.8 CONCLUSIONS

*DOTs increasingly issue mobile devices but may not always have purposeful reasons for doing so.*

The pavement industry is clearly trending towards integrating mobile devices in workflows, but this stands in contrast to the low rates of device, software, or service training. Despite emerging options for securing data, the industry also lacks best practices regarding device security training. Other explanations may be that device or software training is rarely perceived as necessary, or that DOTs may also be trending towards digital, more decentralized, just-in-time learning or training.

*DOTs believe they will benefit from upgrading their IT, despite unclear best practices or guidance.*

DOTs vary greatly in their quickness to react to emerging IT but continue to pursue paperless workflows through enterprise software systems (eConstruction). Mobile IT has only been effectively available for about 10 years and the growth of web technologies was largely enabled by 4G broadband connectivity (Figure 2.1). Consequently, DOTs who continually pursue

emerging IT are more likely to receive both passive (e.g. improved broadband speeds) and active benefits (e.g. more capable workforce).

*DOTs may be unable to keep up with the pace of needed development cycles.* DOTs still prefer to manage IT data and services internally and are shifting towards greater reliance on mobile technologies. Meanwhile, IT is trending towards web-based development cycles. Consequently, DOTs may find their internal resources and capabilities decreasingly adequate to support development activities in addition to other needs.

*Research rarely results in software, but agencies frequently attempt to develop tools in-house that mobilize research concepts.*

This should concern DOTs because human and financial IT resources typically do not focus on IT internal development and capital growth. The abundance of existing software templates/extensions in DOT catalogues implies that they are seeking modular functionality that is largely absent from available vendor software. Agencies internally develop these tools to mobilize proof-of-concepts into practice, avoid purchasing more expensive alternative, or in lieu of waiting for software updates. However, tools developed in such manner tend to remain unintegrated from software or data management systems and are inaccessible by other agencies who may benefit from their use.

## 2.9 RECOMMENDATIONS

*DOTs should embrace advancements in mobile IT but avoid give-and-go tactics in general*

As give-and-go tactics are most common, DOTs may be missing opportunities to leverage mobile technologies with greater purpose or perform case studies to verify technology benefits. Mobile IT relies heavily on web technology to deliver services, so it is attractive when software and services are offered for multiple platforms or are platform independent.

*Web-based services address compatibility issues through platform independence and offer an alternative medium to software extensions and templates.*

DOT preferences for hardware platform depends on the device and consequently, compatibility issues, data migration, and obsolescence are natural consequences over time. Web technologies and services featuring Web 2.0 concepts are a potential solution to compatibility issues because

such tools are relatively platform independent via the internet. As a medium, the web aligns well with motivations for developing software templates or extensions because they are typically small enough in scope to translate into simple web services. However, DOTs must address resources requirements for hosting and on-going maintenance.

*DOTs should continue to pursue and exploring solutions from IT advancements*

By doing so, DOTs are less likely to encounter issues related to compatibility and obsolescence. However, many agencies possess legacy software and data that requires migration or preservation prior to investing in enterprise data integration tools and migrating to newer platforms. Accordingly, this study also recommends that DOTs avoid on-premise software and services in future adoptions, the predominant distribution channel of legacy software systems.

*DOTs should consider outsourcing development of software or some IT services*

By outsourcing some IT services, agencies can redistribute internal resources to address issues emerging from software and service integrations or support new activities, such as web services development and software training. However, DOTs should be aware that outsourcing services implies that agencies must first address implications to existing IT infrastructure.

As well, agencies should be aware that IT implementations may require expertise beyond traditional job roles in DOTs. Development increasingly focus on the experience of end-users in construction, but implementations are typically managed by the IT workforce (Muench et al. 2010). Consequently, the development of services may benefit from combining domain knowledge in the construction, development, and IT.

*Refocus efforts regarding internal development and research.*

To ensure that efforts spent on internal development and research are maximized, this research recommends that DOTs seek alternative development pathways to extensions and templates where possible. This may include pursuing research projects that directly mobilize concepts or research results through IT-enabled software or services. DOTs see these efforts as valuable, but tools developed in-house may not fully utilize the potential of IT in terms of mobile devices or the capabilities of Web 2.0 or later, nor receive the exposure to industry they deserve.

## Chapter 3. THE CONSUMPTION OF RESEARCH: KNOWLEDGE TRANSFER THROUGH SOFTWARE AND SERVICE MEDIUMS

### 3.1 PREFACE: SOFTWARE CONSUMPTION BEHAVIORS

Chapter 1 introduces how transportation agencies commonly address financial constraints and expertise requirements by outsourcing some services to consultants. This strategy appears to be driven by needs to reduce FTEs or acquire expertise absent in-house. Additionally, high employee attrition by both retiring and the younger workforce (~10 years of service) has caused agencies to seek how they can best capture the knowledge and expertise of its workforce. This apparent contention between outsourcing expertise and fostering this expertise in-house is influenced by perceived technology benefits and expectations of an engineer's technical skills.

Chapter 2 characterizes how transportation agencies are trying to evaluate IT integrations and software adoptions to bolster its workforce's overall ability to leverage research. AASHTOWare and Pavia Systems are two examples of organizations who specialize in transforming pavement research into interactive digital services, i.e. software and services. However, their development efforts are often complicated by factors such as the complexity of underlying research, developer capabilities, income, training requirements, or data requirements.

The subsequent chapter attempts to advance these discussions by investigating how users are consuming pavement research knowledge through web-based services (web-apps).

Ultimately, the investigation aims to associate trends in consumer behavior with development practices for research-based software. By inferring the nature of consumption, the overarching research becomes better positioned to derive development practices that can both address the critical concerns of researchers as well as agency goals to efficiently train its workforce.

### 3.2 INTRODUCTION

Workforce training and retention of expertise are a growing concern for state agencies who predict that current employee attrition rates will result in a smaller and less-experienced workforce in the next decade (Taylor et al. 2013). For agencies like WSDOT, IT and software products are potential

strategies for addressing these concerns (WSDOT, 2016). As well, agencies often desire specialized software that embody methods from pavement research but frequently have greater training and knowledge requirements.

However, software and service products rarely result from research directly and vendor products do not inherently offer these specialized capabilities. Nonetheless, there are examples of research-based software used by the paving industry that are notable because their underlying research remains relevant even in 2019. For example: AASHTOware's PavementME embodies decades of evolving pavement design research; UC Berkeley's CA4PRS is a decade-long effort combining classic civil engineering concepts to create performance metrics for construction strategies (e.g. user costs, overall construction productivity); FHWA's RealCost is decision-support tool that calculates life-cycle costs for pavement project alternatives. The underlying concepts for each have also seen multiple attempts at development into a software or service. This demonstrates that agencies have continued interest in preserving the research and leveraging them in software form. However, guidelines or development best practices for research-based software also scarce, particularly those addressing the paving industry specifically.

This research examines how construction research knowledge is translated into web-apps to determine how development efforts can learn from observed trends in consumption behavior. To accomplish this, the current work investigates Google Analytics (GA) data available for two research-based web-services developed by Pavia Systems: Pavement Interactive (PI) and PaveXpress Design (PX). PI is a unique, wiki-style repository of curated pavement research that may inform similar efforts to build knowledge repositories. PX is intended as a user-friendly pavement design app for empirical design methods (AASHTO93 and 98), the most commonly practiced methods by DOTs (Pierce and McGovern 2014). The author finds this topic particularly salient because research-based software for pavement engineering is uncommon, as are data sets that inform their use performance.

This investigation uses benchmarks for web-services and data visualization techniques to reveal consumption trends regarding the benefits and limitations to consuming research through software mediums. It begins with an overview of user demographics (e.g. location, affiliation), and delves into increasing detail regarding channels for site acquisition (e.g. hardware, browser) and finally how users navigate through the app (e.g. page hits, bounce rates). Observations regarding consumption behavior are used to infer development practices that may result in more

effective transferal of pavement research knowledge through software. In doing so, the research establishes the gap between the state of research methods and their practice through software.

### 3.3 RESEARCH GOALS AND STATEMENT OF PURPOSE

The purpose of this effort is to determine how researchers can develop software that allows the pavement industry's workforce to effectively leverage pavement research in practice. The availability of Google Analytics data for PI and PX provides an opportunity to inform the limited research on development best practices for such software. Whereas research on pavement software typically focuses on the merits of the research concept, the current work instead focuses user preferences for consuming research through digital mediums, as well as factors contributing user reception of software interfaces. Accordingly, the research aims to identify:

- trends that characterizes how users consume research information through web-apps,
- software features and development practices that are well-received in terms of user reception and behavior,
- and ways researchers can impact how knowledge is consumed by the pavement industry through software during the development phase.

PI and PX are examples of development efforts to improve construction practices by harnessing research knowledge and information technology. Consequently, the findings of this research can be generalized to future development efforts. Using a combination of common metrics to benchmark web-service performance and data visualization techniques, the results demonstrate how users want to consume research knowledge available. Ultimately, the findings are intended for transportation agencies who seek guidance for selecting appropriate software to support the capabilities of agency workforces.

### 3.4 BACKGROUND

Literature suggests that employees perform better when knowledge sharing is greater among departments within an organization, but that data silos can prevent information and knowledge exchange among them (Poleacovschi Cristina and Javernick-Will Amy 2016). This is particularly true for state transportation agencies and organizations which are driven by large volumes of data (Gandomi and Haider 2015; Woldeesenbet et al. 2016). However, it is unclear how such observations result in actionable strategies when developing research-based software embodying pavement research. To provide context for discussion, the following sections briefly explain the

nature of DOT involvement in research-based development and best practices available for web-based development. Collectively, these sections benchmark the available knowledge base guiding this research

Industries (including DOTs) commonly describe knowledge sharing use terms such as data, information, knowledge, and wisdom. A disambiguation for using such terminology in this research is presented in Appendix D.

### 3.4.1 *State Agency use of Research-Based Software*

State Transportation Agencies (STAs) have demonstrated interest in mobilizing research concepts into software to starting in the late 1990s and early 2000s. As well, use of personal computers with internet access for agency work became increasingly prevalent during this time.

Agencies have also valued pavement software that mobilize research concepts that make actionable central tenets of pavement design such as maximizing pavement performance, optimizing constructability, and value engineering. Although such efforts often span decades of interrelated projects funded through national and state agencies (e.g. NCHRP, TRB, SHRP2, FHWA, NAPA, local DOTs), rarely has such research resulted in software tools.

DOTs have indicated developing software tools in-house or collaborating with others (private developers, vendors, universities) to develop customized software. In 2016, the FHWA found that states were increasingly pursuing paperless workflows (eConstruction), signifying growing DOT reliance on software and services (2016). However, it is difficult to quantify tools in use by DOTs because surveys generally focus on prominent enterprise vendor products rather than more technical tools such as research-based software. Nevertheless, use of in-house tools by DOTs is substantial and will likely continue: these tools provide technical functions that are seldom offered directly in vendor software. Moreover, most existing research-based tools are software extensions and templates (e.g. Microsoft Excel macros) and generally behave more like prototypes or proofs of concepts rather than practice-ready products.

In practice, such software capabilities are valued by the paving community for their predictive capacity and are thought to generate greater predictive capabilities for pavement design and asset management. Over time however, such software is threatened with obsolescence if it cannot incorporate advances in technology, research, or standards in a timely manner. Accordingly, this

research seeks to understand the drivers of this kind of development, and subsequently, how development practices can address observed trends in consumption behavior.

### 3.4.2 *Development Best Practices in Web 2.0*

Muench et. al. used Web 2.0 to describe the state of web use and competencies for companies that deliver Web 2.0 products or content (2010). A website build using Web 2.0 conventions refers to the idea that content (data) is both consumed and produced by users. This is in contrast sites built in the Web 1.0 era, during which concepts like collaboration, community-driven knowledge, and flexible representations of data and information were not yet possible (Muench et al. 2010). A more detailed description of Web Generations can be found in Appendix E (Figure 5.4).

Muench et. al. specifically identified seven criteria for assessing the value of knowledge management that specifically serves the paving industry. Furthermore, the authors include three key conclusions that inform sustainable web-service development practices. These criteria are adopted in this research because summarize development best practices for web-based tools intended for the paving industry. The criteria are paraphrased in Table 3.1. Although definitions of Web 2.0 may have evolved, the boundaries between Web 2.0 and emergent Web 3.0 features are not well defined or commonly accepted. With such assessment framework however, this research can expand upon the ideas presented.

Table 3.1. Essential Ideas for Web 2.0 (Muench et al. 2010)

<b>Concept</b>	<b>Interpretation</b>
<b>Unique quality content</b>	useful content attracts traffic and community participation
<b>Service and not product</b>	services do not suffer from the same accessibility issues as products which require manual installation and become outdate.
<b>Users as codevelopers</b>	users appreciate engagement for new features and provide valuable feedback
<b>Harness collective intelligence</b>	collective knowledge facilitates growth and helps prioritize service improvements
<b>Serve the individual user rather than the larger organization</b>	organize content in a manner that prioritizes the needs of individuals (end users), but still considers and aligns with the needs of the organization
<b>Software usable on multiple devices</b>	services should be accessible on all web-enabled devices such as smartphones, tablets, (excludes desktop and laptop computers)
<b>Simple applications and development models</b>	simplicity encourages repeat usage (acceptance), whereas over complexity tends to encourage the opposite

### 3.4.3 *Pavement Interactive and PaveXpress*

Pavement Interactive (PI) and PaveXpress (PX) are two web-based tools developed by Pavia Systems and whose content is primarily based on findings from established research. Going live in September 2006, PI was an experiment that explored the role of technology in engineering publication harnessing concepts of Web 2.0 (Muench et al. 2010). The tool curates over 20 years of research findings over a collection of 520. No content has been added since 2005, however.

In contrast, PX is a web-based application (web service) that exists on two separate sites that appear seamless to the average user: one hosts the essential documentation (including training and background resources) and the other hosts the application and saved user projects. Going live in October 2014, PX's goal was to bring empirical pavement design to a web-based platform. Previous efforts to digitize pavement design largely existed in the form of software templates or extensions (e.g. Microsoft Excel or Access-based files), or on-premise software (offline). Today, the research methods (AASHTO93/98) remain relevant research topics in the civil engineering undergraduate curriculums across the country (National Asphalt Paving Association n.d.).

Now 2019, this research revisits the findings of Muench et. al. (2010) to determine how consumption trends have evolved for PI and benchmark those for PX. Given the relative uniqueness of both services, investigation of GA site-traffic data provides a research opportunity to reveal emerging consumption habits (and how precisely), as well as the associated implications to knowledge transfer through digital mediums.

## 3.5 DATA DESCRIPTION AND ANALYSIS METHODS

### 3.5.1 *Approach to Investigation Efforts*

The analysis of available Google Analytics data is into three primary investigations that are organized to mimic the pathways through which users interact with the service (Figure 3.1). These themes focus on:

1. Demographic information that characterizes users by location or affiliation;
2. Pathways taken by users to acquire the services (PI and PX);
3. Trends in user interactions that inform how users 'consume' the service.

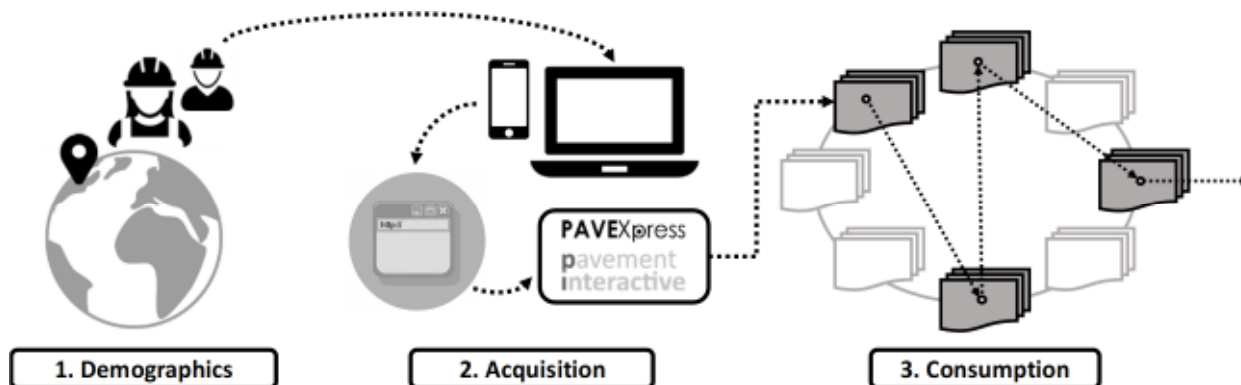


Figure 3.1. Organization of Investigations by Theme

Some investigations include sub-investigations (8 in total) distinguishable by intent and the primary dimensions used to extract GA data. These investigations are:

#### Investigation Theme 1: Demographics

1.1. Location: Identify demographic distribution of users to understand differences in intended and actual audience

1.2. Affiliation: If available, identify user affiliations (e.g. educational, commercial, private, government, military) to understand context of use

#### Investigation Theme 2: Acquisition

Determine the common hardware platforms users access services to understand distribution of device preferences and how users find / navigate to the services

#### Investigation Theme 3: Consumption

3.1. Overall Performance: provide summary statistics that include overall performance benchmarks to qualify each tool's performance and other generalizations

3.2. Content Popularity: Identify most and least popular site content (by pageviews) to understand what and how users want to consume information

3.3. Collaboration: Identify trends in behavior that distinguish types of users

3.4. User Types and Depth of Interaction: Identify trends regarding how users end a session to inform how developers can improve user retention / return use

3.5. Interaction Pathways: Identify trends regarding how users progress through a session to assess whether users find desired content

### 3.5.2 *Data Description and Extents*

Three GA data sets available for PI and PX. PX yields two because the service itself has a separate address from the so-called marketing site, which includes general information and knowledge resources. The availability of data for each site differs substantially in date range and the type of data requested from GA. Incidental to the timing of data collection, Google changed its data retention policies effective May 25, 2018 in which users must select a data retention period, else risk losing older data (Google, Inc. 2018). While requests for pre-aggregated data are unaffected, Pavia defaulted to a 26-month retention period, causing some older data to be permanently deleted. As extractions were ongoing in the midst of data retention policy changes, this partially informs the different date ranges available for each investigation (Table 3.2).

The standard version of GA (as opposed to GA 360) limits data extractions to 5,000 rows of data per extraction. This means that extraction of large data sets (e.g. time series data) must be piecewise through multiple extractions, or pre-aggregated to reduce volume (but consequently require additional post-processing to disaggregate for analysis). For practical reasons, this research pre-aggregates data to reduce volume, with the maximum investigation extraction size of 50,000 rows (10 extraction partitions). Moreover, the data extraction process for each investigation requires the identification of one or more primary or secondary aggregation dimensions to address extraction constraints (Table 3.2). Definitions for metrics extracted from GA are defined in Table 3.3) Finally, data is sorted prior to ensure that extractions are 90% complete in terms of the primary dimensions of interest. If data is pre-aggregated, the calculated metrics are necessary because direct extraction of such measures from GA will not result in accurate statistics without proper re-aggregation (e.g. avoiding averages of averages).

Table 3.2. Google Analytics Data Extract Ranges by Investigation

#	Primary Aggregation Dimensions	PI	PX (App)	OX (Site)
1.1	Year / Month / Day (PX only) City, Country	08/16/2016 – 08/31/2018	09/02/2014 – 08/15/2018	09/02/2014 – 08/15/2018
1.2	Year / Month / Day Report, User	n/a	09/02/2014 – 08/31/2018	n/a
2	Channel, Source Device Type + OS (Landing Page)	08/01/2016 – 07/31/2018	09/02/2014 – 08/15/2018	09/02/2014 – 08/15/2018
3.1	Year / Month / Day	08/01/2016 – 07/31/2018	09/02/2014 – 08/15/2018	09/02/2014 – 08/15/2018
3.2	Year / Month Page Name Content Type	01/01/2009 – 05/31/2018	09/02/2014 – 08/15/2018	09/02/2014 – 08/15/2018
3.3	Year / Month / Day Report, User Email Primary / Secondary Domain	01/01/2010 – 12/31/2017	09/02/2014 – 08/15/2018	09/02/2014 – 08/15/2018
3.4	Year / Month / Day Page Depth User Type	01/01/2009 – 12/31/2017	n/a	n/a
3.5	Interaction Page Name / Type	01/01/2009 – 12/31/2017	n/a	n/a

Table 3.3. Definitions for Google Analytics Benchmarks

<b>Benchmark Metric</b>	<b>Description</b>
<b>Extracted Metrics</b>	
Sessions (Visits)	Total number of visits to the site (includes multiple visits by user)
Users (New Visits)	Unique users visiting the website. Also indicates new visits.
New Users	Number of new visitors in time period
Returning Users	Number of returning visitors in time period (difference between Users and New Users)
Pageviews	Total pages viewed on the site across all sessions
Entrances	The number of sessions beginning on a given page
Exits	The number of sessions terminating on a given page
Bounces	The number of sessions that start and terminate on a given page, without any further interaction
<b>Calculated Metrics</b>	
Total Time Spent (Duration)	Total amount of time spent across all sessions by visitors. If extractions are pre-aggregated to reduce volume, this value is calculated but otherwise can be directly extracted
Avg. Num. Sessions per User	Average number of visits to site by unique visitor
Avg. Time per Page (Avg. Duration)	The total time spent on a page divided by the difference between Pageviews and Exits
Avg. Time per Session (Visit)	The ratio between the total duration of session to the number of sessions
Avg. Pageviews per Session (Visit)	The average number of pageviews per session, not necessarily unique pages
% New Users	Percent of users in time period who are new
% Return Rate	Percentage of unique visitors who return to site for at least one additional session
Avg. Bounce Rate (% Bounce)	The ratio of total bounces to entrances, i.e. percent of visits that enter and leave the site from the entrance page. Serves as a measure of user tendency to view multiple pages in which may imply either users were disinterested in exploring further or needed content was found on the entrance page.

### 3.5.3 *Data Availability: Extraction and Postprocessing Details*

The data extraction and post-processing requirements for each investigation's data set required additional considerations that may limit how results can be interpreted. Consequently, the availability of data for each investigation is explained as follows:

#### Investigation 1.1. Location

GA uses “n/a” to indicate that a country or city is unidentifiable. For analyses based on City, results exclude records in which the City and/or Country is n/a; for analyses based only on Country, results include records in which the City is “n/a” but the Country is known.

#### Investigation 1.2. Affiliation

Affiliation data is only available for the PX service because users are required to register an email address to use the service. Because GA no longer provides data associated with user IP addresses, email address domain and subdomains are used to it was possible to partially identify and aggregate PaveXpress users by affiliation.

#### Investigation 2. Acquisition

In GA, “Desktops” may actually indicate a laptop and “Mobile” represents only mobile smartphones (not tablets).

#### Investigation 3.2. Content Popularity

For PI, pages are separated into categories (Content, Navigation, or Unusable) and sub-categories of page groups. This distinguishes pages which contain substantive content associated with research, pages necessary for navigation but lacking content, and pages with data that cannot be included or interpreted for the analysis (respectively). For PX (site), content pages include all page groups except Home and App.

#### Investigation 3.3. Collaboration

Primary and secondary user domains and types were extracted from registered users of PX via email address. The primary domain and domain type include the suffixes featured by the email (e.g. .edu is an educational institution), whereas the secondary domain and type identifies the specific organization or group (e.g. @uw.edu indicates a UW user)

#### Investigation 3.4. User Types and Depth of Interaction

The daily timeseries extracted from GA is aggregated on page depth (unique pages viewed in a session, beginning at depth of 1), with each point including benchmark metrics (bounces, duration,

etc.). Pavia has not configured GA to provide customized analytics indicating how Page Depth is interpreted for apps like PX service, in which most sections of the interface exists on just a few pages. Page depth here is interpreted as increasing when users navigates to a different page within the site or app.

### Investigation 3.5. Interaction Pathways

GA's standard thresholds provides data describing the first five interactions for 621,400 sessions randomly sampled between 2009 and 2017 for PI. In this work, the 0th interaction is considered the landing page. Pages are also classified into four types: Search, indicating use of a search function; 404 indicating a 'page not found' error; Drop, indicating a user exits a session; and Content, indicating a page or article with informational content.

## 3.6 RESULTS AND OBSERVATIONS

### 3.6.1 *Observations for Investigation 1: Demographics*

#### Investigation 1.1. Location

For PI, United States was again the largest source of traffic (32.5%). Collectively, the top five countries represent 63.7% of traffic by sessions (Figure 3.2). The top five traffic contributors by city contribute only 13% of traffic. In contrast to PX, none are in the US.

70-77% of all PX sessions came from the United States, with Lebanon, India, and Canada contributing the next most traffic (1.3 to 2.5%) (Figure 3.3). In terms of sessions by city, 9 of the top 10 contributions came from the United States (representing 8 states), with Beirut, Lebanon as the only foreign state.

Rank	by Country	F	by City
1	USA (597,139 or 32.5%)		Bengaluru, India (38,377 or 2.1%)
2	India (332,242 or 18.1%)		Hyderabad, India (31,220 or 1.7%)
3	Canada (93,920 or 5.1%)		Kuala Lumpur, Malaysia (28,978 or 1.6%)
4	Philippines (77,092 or 4.2%)		Chennai, India (26,993 or 1.5%)
5	Malaysia (69,009 or 3.8%)		Quezon City, Philippines (21,673 or 1.2%)

Figure 3.2. Top 5 Contributions to Pavement Interactive Traffic by Number of Sessions

Rank	by City Site			by Country Site		
	App	Site	Both	App	Site	Both
1	Seattle, WA, USA (3,300 or 13.2%)	Seattle, WA, USA (5,148 or 9.2%)	Seattle, WA, USA (8,457 or 10.4%)	United States (10,308 or 77.4%)	United States (36,331 or 69.5%)	United States (58,429 or 72.0%)
2	East Lansing, MI, USA (1,250 or 5.0%)	East Lansing, MI, USA (1,143 or 2.0%)	East Lansing, MI, USA (2,432 or 3.0%)	Lebanon (625 or 2.5%)	India (1,305 or 2.5%)	India (1,037 or 2.0%)
3	Shoreline, WA, USA (457 or 1.8%)	Shoreline, WA, USA (881 or 1.6%)	Shoreline, WA, USA (1,338 or 1.6%)	Canada (337 or 1.3%)	Canada (1,090 or 2.0%)	Canada (1,130 or 1.8%)
4	Beirut, Lebanon (472 or 1.8%)	New York, NY, USA (655 or 1.2%)	Beirut, Lebanon (1,027 or 1.3%)	Mexico (297 or 1.2%)	Lebanon (807 or 1.4%)	Lebanon (1,132 or 1.8%)
5	Clemson, SC, USA (406 or 1.6%)	Beirut, Lebanon (585 or 1.0%)	Clemson, SC, USA (986 or 1.2%)	Dominican Republic (295 or 1.2%)	United Kingdom (700 or 1.2%)	United Kingdom (920 or 1.1%)

Figure 3.3. Top 5 Contributions to PaveXpress traffic by Number of Sessions

### Investigation 1.2. Affiliation (PaveXpress Service only)

Two basic metrics (Users and Associated Projects) are used to rank the popularity of User Categories and Sub-Domains indicated by a user's email address (i.e. the primary and secondary user domains) (Figure 3.4). Most users features commercial email domains (.com), followed by educational institutions (.edu), and International domains (e.g. .nz, .can). Collectively, these 3 categories account for 95.7% of all projects within the last four years. Beyond these, rankings differ slightly depending on the metric. Government organization and educational institutions contributed the most unique sub-domains (59% of identifiable sub-domains).

The top four sub-domains (ranked by Users) were Commercial addresses (@hotmail.com, @gmail.com, @yahoo.com) and contributed to 74.5% of all users (60.0% of projects). Notably, USA domains (email terminating in .us) have the highest ratio of associated projects per users (4.6), followed by educational institutions (3.9). For comparison, Pavia employees who test and provide support to the application contribute 15 users (<0.2%) and are associated with 301 different projects (1.6%), a ratio of 20.1 associated projects per user.

User Category	Sub-Domains	Users	Associated Projects	% of Users	% of Projects	Relevant Totals	
Commercial	30	6,808	14,099	77.2%	73.1%		<b>9 User Categories</b> Categories of domain types (e.g., Education, Government)
Education	123	892	3,522	10.1%	18.3%		
International	85	349	823	4.0%	4.3%		
Organization	12	225	437	2.6%	2.3%		
Government	128	220	478	2.5%	2.5%		
Generic	5	166	294	1.9%	1.5%		
USA Domain	40	143	659	1.6%	3.4%		
Military	2	12	18	0.1%	0.1%		
						<b>267 Domain Names</b> Based on email's primary domain ending suffix (e.g., .com, .net)	
User Category	Sub-domains	Users	Associated Projects	% of Users	% of Projects	<b>426 User Sub-Domains</b> Secondary domain category, if available (e.g., specific instance of education or government agency)	
Commercial	Hotmail	2783	3215	31.6%	16.7%		
Commercial	n/a	1865	3819	21.2%	19.8%		
Commercial	Gmail	1479	3652	16.8%	18.9%		
Commercial	Yahoo	437	909	5.0%	4.7%		
Organization	n/a	188	379	2.1%	2.0%		
Generic	Net	156	284	1.8%	1.5%		
Education	University of Washington	94	360	1.1%	1.9%		
Education	Clemson University	92	320	1.0%	1.7%		
Education	University of Missouri	64	190	0.7%	1.0%		
International	Canada	57	88	0.6%	0.5%		
							<b>2188 User Domains</b> Based on full email domain (e.g., @clemson.edu and @g.clemson.edu are distinct)

Figure 3.4. Affiliation of Pavexpress App Users

### 3.6.2 Observations for Investigation 2: Acquisition

Acquisition of user sessions was aggregated for each data set in terms of channel (5 types), device type (3 types), and in terms of operating system (5 types) (Figure 3.5, Figure 3.6, and Figure 3.7). Because each data set includes a different number of data days, sessions are calculated as a percent of total sessions (Table 3.4). PX receives substantially more traffic than PX (both site and app), and the PX app received less than half the traffic of the site.

Table 3.4. Total Sessions and Average Session Acquisition Rates (All Contexts)

Context	Begin	End	Days	Sessions	Avg. Sessions / Mo
<b>Pavement Interactive</b>	8/1/2016	7/31/2018	729	1,872,887	78144
<b>Pavexpress (App)</b>	9/2/2014	8/15/2018	1443	25,073	529
<b>Pavexpress (Site)</b>	9/2/2014	8/15/2018	1443	55,000	1159

Results indicate that most PI sessions were acquired via organic searches (e.g. via Google or Bing's search engine). Most users directly accessed the PX app through the marketing site (direct), some sessions resulted from referrals (10%). Sessions for the marketing site were evenly split between organic searches, referrals, and direct for the PX site.

Users overwhelmingly use PCs (desktops or laptops) to access all three products. Though more sessions were acquired from smartphones compared to tablets, both contribute significantly less than desktops. While 29% of PI sessions were acquired from mobile devices (smartphones and tablets), this value was only 4.9% for the PX app and 11.2% for the PX marketing site.

For PCs, 63-78% of sessions for each product were acquired from Microsoft-based computers, with Apple following (4.8% for PI, 17-18% for PX). For mobile devices (smartphones and tablets), users appeared to prefer Google Android-based devices for PI (21% of sessions), but Apple devices for using the PX app or site (6.1% of sessions).

#### Number of Sessions by Acquisition Channel

	Organic Search	Direct	Referral	Social
All Sessions	86.4% (158,572K)	9.5% (17,442K)	3.4% (6,302K)	0.7% (1,228K)

#### Channel vs Device Type

	desktop	mobile	tablet
Organic Search	63.1% (115,726K)	21.3% (39,054K)	2.1% (3,792K)
Direct	3.9% (7,113K)	5.3% (9,797K)	0.3% (531K)
Referral	1.4% (2,561K)	1.9% (3,574K)	0.1% (168K)
Social	0.3% (562K)	0.4% (651K)	0.0% (14K)

#### Device Type vs Operating System

	Microsoft	Google	Apple	Linux	BlackBerry
desktop	63.1% (115,742K)	0.2% (387K)	4.8% (8,756K)	0.6% (1,077K)	
mobile	0.4% (770K)	21.0% (38,472K)	7.4% (13,625K)		0.1% (210K)
tablet	0.3% (597K)	0.8% (1,384K)	1.4% (2,522K)		0.0% (2K)

Figure 3.5. Pavement Interactive: Session Acquisition by Channel

Number of Sessions by Channel

	Organic Search	Direct	Social	Referral
All Sessions:	0.5% (0.17K)	88.7% (22.23K)	0.3% (0.01K)	10.8% (2.70K)

Channel vs Device Type

	desktop	mobile	tablet
Organic Search	0.5% (0.17K)	0.3% (0.00K)	
Direct	84.1% (21.05K)	2.7% (0.08K)	1.0% (0.17K)
Social	0.3% (0.00K)	0.3% (0.00K)	
Referral	10.7% (2.63K)		0.3% (0.01K)

Device Type vs. Operating System

	Microsoft	Google	Apple	Linux	BlackBerry
desktop	77.0% (19.52K)	0.3% (0.01K)	17.0% (4.27K)	0.4% (0.11K)	
mobile	1.1% (0.27K)	0.8% (0.20K)	0.8% (0.21K)		0.3% (0.00K)
tablet	0.5% (0.13K)	0.1% (0.07K)	1.2% (0.31K)		

Figure 3.6. PaveXpress App: Session Acquisition by Channel

Number of Sessions by Channel

	Organic Search	Direct	Social	Referral	Email
All Sessions:	38.7% (21.27K)	31.0% (17.07K)	0.9% (0.48K)	28.8% (15.85K)	0.6% (0.37K)

Channel vs Device Type

	desktop	mobile	tablet
Organic Search	33.8% (15.57K)	4.0% (2.18K)	0.3% (0.52K)
Direct	27.2% (14.09K)	2.0% (1.01K)	0.3% (0.17K)
Social	0.4% (0.23K)	0.4% (0.22K)	0.1% (0.03K)
Referral	25.0% (14.80K)	1.2% (0.65K)	0.7% (0.37K)
Email	0.5% (0.26K)	0.1% (0.06K)	0.3% (0.01K)

Device Type vs. Operating System

	Microsoft	Google	Apple	Linux	BlackBerry
desktop	69.8% (35.70K)	0.1% (0.05K)	18.1% (9.58K)	0.8% (0.43K)	
mobile	0.3% (0.51K)	3.3% (1.80K)	4.1% (2.72K)		0.3% (0.02K)
tablet	0.4% (0.23K)	0.4% (0.21K)	1.7% (0.95K)		0.3% (0.00K)

Figure 3.7. PaveXpress Site: Session Acquisition by Channel

### 3.6.3 Observations for Investigation 3: Consumption

#### Investigation 3.1. Overall Performance Benchmarks

Consumption is examined using common web-site performance benchmarks to produce site wide summary statistics for PI and PX (both site and app) (Table 3.5, with data ranges described in Table 3.2). Analysis reveals that some metrics increased:

- All three sets showed more traffic per year: PI averaged 605K additional sessions per year over 9 years (5.9 million users total) while PX averaged 18.8K additional sessions per year over 4 years (81.1 thousand users total).
- Users (new and returning), pageviews, and total duration increased for both PI and PX
- Average Session remained relatively consistent for each site, with each having slightly different overall average durations: PI averaged 2.43 min/session, with a range of 2.3 to 3.3 min, while PX averaged 4.8 minutes with a range of 4.3 to 9.6 min.

Other benchmark metrics changed minimally:

- New Users comprise the bulk of traffic (68% for PI versus 80% for PX) and rates remained relatively consistent for all data years (+/- 2% for PI versus +/- 5% for PX).
- For both PI and PX, average sessions per use was only slightly above 1
- On average PI users generally viewed 2-4 pages per session; for PX this is 1-2 pages

Only one benchmark was split between PI and PX. For PX, bounce rates averaged 68% over 4 years, with a range of 65-70%. On the other hand, average Bounce Rates for PI fluctuated between 44 and 72% for the first five years of data collected, but sharply drop to less than 15% in subsequent years. Given that typical ranges for sites are 20-70%, with under 25% considered highly unlikely, the rates implied by the data for 2014-2018 have questionable accuracy.

Table 3.5. Pavement Interactive: Overall Performance Benchmarks (2009-2018)

	Grand Total	2009	2017	2015	2016	2014	2018	2010	2012	2011	2013
Sessions (Visits)	5,939.9K	198.3K	837.0K	924.1K	991.6K	695.2K	494.4K	293.4K	492.8K	480.6K	532.6K
Users (New Visits)	5,155.2K	172.8K	734.8K	783.0K	866.6K	588.3K	435.3K	258.6K	431.4K	419.1K	465.3K
New Users	4,012.4K	139.2K	561.4K	599.4K	657.2K	459.2K	328.1K	210.4K	350.4K	343.0K	364.0K
Pageviews	19,603K	791K	3,093K	3,352K	3,539K	2,451K	1,653K	941K	1,421K	1,210K	1,151K
Total Duration	240.9K hr	12.8K hr	31.6K hr	36.0K hr	38.4K hr	27.9K hr	17.1K hr	15.5K hr	19.1K hr	19.6K hr	22.9K hr
Avg. Duration	2.43 min	3.86 min	2.27 min	2.34 min	2.32 min	2.41 min	2.07 min	3.17 min	2.32 min	2.45 min	2.58 min
Avg. Sessions / User	1.15	1.15	1.14	1.18	1.15	1.18	1.14	1.14	1.15	1.15	1.15
Pageviews / Session	i.i. 3.3	4.0	3.7	3.6	3.6	3.5	3.3	3.2	2.9	2.5	2.2
Avg. Bounce Rate	34.36%	56.55%	4.11%	4.14%	3.60%	12.41%	4.46%	59.80%	44.42%	64.74%	71.86%
% New Users	68.4%	70.2%	67.0%	65.0%	66.2%	66.1%	66.2%	71.3%	71.1%	71.3%	68.4%

Note: 2009 was incomplete at the time of data extraction (See Table 7 for date ranges)

Table 3.6. PaveXpress: Overall Performance Benchmarks (2014-2018)

	Grand Total	PaveXpress (App)					PaveXpress (Site)				
		2014	2015	2016	2017	2018	2014	2015	2016	2017	2018
Sessions (Visits)	81,147	825	3,828	5,560	8,985	5,836	2,723	12,821	12,366	17,429	10,774
Users (New Visits)	64,668	670	3,007	4,371	6,586	4,438	2,319	11,272	10,156	13,203	8,646
New Users	45,601	515	1,886	2,628	4,097	2,421	1,859	9,142	7,434	9,706	5,913
Pageviews	169.5K	1.7K	6.4K	10.1K	32.7K	12.8K	5.2K	19.4K	21.6K	37.6K	22.0K
Total Duration	386,490	4,348	16,375	26,436	86,408	36,797	9,970	32,248	44,311	79,753	49,843
Avg. Duration	4.8 min	5.3 min	4.3 min	4.8 min	9.6 min	6.3 min	3.7 min	2.5 min	3.6 min	4.6 min	4.6 min
Avg. Sessions / User	1.25	1.23	1.27	1.27	1.36	1.32	1.17	1.14	1.22	1.32	1.25
Pageviews / Session	2.1	2.1	1.7	1.8	3.6	2.2	1.9	1.5	1.7	2.2	2.0
Avg. Bounce Rate	67.8%	69.9%	73.1%	71.3%	56.5%	66.2%	66.8%	72.9%	69.1%	65.8%	63.3%
% New Users	79.7%	81.2%	78.6%	78.6%	73.3%	76.0%	85.2%	87.9%	82.1%	75.8%	80.2%

Note: 2014 and 2018 are incomplete data years as the time of data extraction (See Table 1 for date ranges)

### Investigation 3.2. Content Popularity by Page Name, Content Category

Most pageviews for PI focused on articles and research content (Article or Category page groups, 87% of all pageviews and 94% of all time spent (Table 3.7). Pages categorized in this groups account for the bulk of distinct pages, unique pageviews, and total duration. Average time per page is highest among pages in the Content category, but generally under 1 minute. All other page groups (unidentifiable and navigation page types) each contributed less than 6.7% of total page views and less than 4.2 percent of all time spent. The calculated bounce rates are atypically low; if valid, they mean that users generally have more interactions before exiting.

18 distinct content pages comprise the Top 10 Content pages for complete years between 2010 and 2018 (Table 3.8). The Top 10 content pages of all time contribute 5.9 million pageviews (about one third of all pageviews between 2010 and 2017) and average between 2-5-minute session durations (compared to 1.2 minutes for all sessions).

Exploration of the PX marketing site is minimal: while the PX home page has about 90,000 pageviews, all other site content has a combined total of 520 pageviews in a 4-year span (Table 3.9). Most of the 520 pageviews focused on pages with more substantive and technical content: Training lessons, Background information, and App-related resources (less than 1% of all pageviews, and total time spent on site).

Examining the same data by individual pages reveals that most popular informational content are the Introduction features (Tutorials and Overview) (Table 3.10), with a smaller number

progressing to further material. As bounce rates are very high (considered 70% or more), most average times per page are less accurate and unmeaningful to interpret.

Table 3.7. Pavement Interactive: Content Popularity by Page Groups (2010-2017)

Category	Page Group	Distinct Pages	Pageviews	Unique Pageviews	Total Duration	Avg Time on Page	% Bounce Rate	Relevant Totals
Content	Article	538	5,477,479	2,363,765	3,777,993	1.02 min	3.1%	621 (68.9%) (Content Pages)
	Category	55	1,035,251	351,695	442,276	0.49 min	3.3%	
	App	28	106,175	37,696	62,376	0.72 min	1.4%	
Navigation	Search	2	228,829	96,862	79,262	0.37 min	1.6%	121 (19.8%) (Navigation Pages)
	Home	8	154,122	66,377	57,134	0.43 min	2.7%	
	Index	89	89,787	41,363	55,200	0.89 min	9.4%	
	Usergroup	22	10,801	4,621	3,911	0.44 min	3.3%	
Unusable	404 Error	4	139,795	111,911	51,470	0.45 min	3.3%	101 (11.3%) (Unusable Pages)
	Unknown	77	25,516	17,479	21,480	1.84 min	50.5%	
	Other	20	513	233	730	1.77 min	46.4%	
Totals		843	7,268,268	3,092,002	4,551,833	0.87 min	3.5%	

### Investigation 3.3. Collaboration (PaveXpress App only)

Most projects (96.5%) are only associated with a single user, and 95.6% of users are associated with 5 or fewer projects (Figure 3.8). 75% of users are only associated with a single project, yielding a sample-wide average of 2 associated projects per user. If all session data is used (including zero-duration sessions), users from each primary domain generally spend the same amount of time per page (4-5 min) and have similar typical bounce rates (55-65%) but vary in their overall session length. Users in the Education primary domain have the longest average session (8.6 min), followed by Commercial and Generic (.net) users (6.7 and 6 min, respectively).

### Investigation 3.4. User Types and Depth of Interaction

Plotting page depth versus average session duration (aggregated daily, then on visitor type and page depth) yields six figures shown in (Figure 3.9), which visualizes the results for new and returning users for each data context. When data points that include a total duration of zero are excluded, the results are slightly different (Figure 3.10). Associated data for both figures is shown in Table 3.11. The amount of zero-duration sessions differs between data sets: for PI, less than 10% of sessions are zero-duration for both returning and new users. For PX site and app, this amount is about 71-73% of sessions for new visitors and 56-60% for returning.

Table 3.8. Pavement Interactive: Top Pages by Pageviews (2010-2018)

Rank	All Time	2010	2011	2012	2013	2014	2015	2016	2017	2018
1	Normal Distribution (731.6K / 1.0 min)	Normal Distribution (90.7K / 1.1 min)	Normal Distribution (199.3K / 1.4 min)	Normal Distribution (173.2K / 1.1 min)	Normal Distribution (30.1K / 2.7 min)	Normal Distribution (69.9K / 0.5 min)	Normal Distribution (80.4K / 0.5 min)	Coarse Agg. Superpave Design (84.9K / 1.2 min)	Coarse Agg. Superpave Design (90.4K / 1.2 min)	Coarse Agg. Superpave Design (67.7K / 1.2 min)
2	Coarse Agg. Superpave Design (433.5K / 1.3 min)	ESAL (17.1K / 3.6 min)	ESAL (21.6K / 3.9 min)	Coarse Agg. Superpave Design (26.6K / 1.8 min)	Coarse Agg. Superpave Design (24.3K / 5.0 min)	Coarse Agg. Superpave Design (60.6K / 1.3 min)	Coarse Agg. Superpave Design (78.9K / 1.2 min)	ESAL (71.6K / 1.2 min)	ESAL (56.8K / 1.2 min)	ESAL (38.0K / 1.3 min)
3	1993 AASHTO il le xhile Design (307.1K / 1.3 min)	Gradation and Size (11.4K / 3.6 min)	Gradation and Size (15.5K / 3.5 min)	Los Angeles Abrasion (20.6K / 1.9 min)	1993 AASHTO il le xhile Design (19.1K / 1.9 min)	ESAL (57.2K / 1.1 min)	1993 AASHTO il le xhile Design (67.7K / 1.1 min)	Marshall Mix Design (67.9K / 1.2 min)	Marshall Mix Design (52.5K / 1.1 min)	Asphalt Surface Treatments (37.8K / 0.9 min)
4	ESAL (302.4K / 1.3 min)	HMA Pavement (9.8K / 2.6 min)	Coarse Agg. Superpave Design (14.4K / 4.2 min)	Gradation and Size (19.9K / 2.2 min)	Los Angeles Abrasion (20.2K / 5.6 min)	1993 AASHTO il le xhile Design (53.3K / 1.3 min)	ESAL (63.6K / 1.2 min)	1993 AASHTO il le xhile Design (66.6K / 1.2 min)	ESAL (48.0K / 1.1 min)	Marshall Mix Design (37.5K / 1.1 min)
5	Marshall Mix Design (276.7K / 1.3 min)	Asphalt (8.8K / 2.2 min)	Superpave Mix Design (12.4K / 3.2 min)	1993 AASHTO il le xhile Design (19.1K / 1.9 min)	Gradation and Size (17.6K / 4.5 min)	Los Angeles Abrasion (40.8K / 1.4 min)	Gradation and Size (60.6K / 1.1 min)	Asphalt Surface Treatments (62.3K / 1.0 min)	1993 AASHTO il le xhile Design (47.0K / 1.0 min)	Los Angeles Abrasion (37.4K / 1.0 min)
6	Gradation and Size (264.2K / 1.3 min)	Superpave Mix Design (8.3K / 3.1 min)	Los Angeles Abrasion (11.8K / 4.1 min)	Pavement (18.2K / 0.5 min)	Pavement (15.5K / 0.8 min)	Gradation and Size (37.9K / 1.2 min)	Marshall Mix Design (58.8K / 1.3 min)	Gradation and Size (59.6K / 1.1 min)	Asphalt Surface Treatments (47.0K / 1.0 min)	ESAL (31.4K / 0.9 min)
7	Los Angeles Abrasion (253.9K / 1.3 min)	Los Angeles Abrasion (7.7K / 3.9 min)	Asphalt (11.5K / 2.1 min)	Testing (16.3K / 0.5 min)	ESAL (15.2K / 5.0 min)	Superpave Mix Design (35.4K / 1.4 min)	Superpave Mix Design (51.2K / 1.3 min)	Normal Distribution (56.9K / 0.4 min)	Los Angeles Abrasion (43.2K / 1.1 min)	Superpave Mix Design (30.4K / 1.2 min)
8	Superpave Mix Design (245.1K / 1.4 min)	1993 AASHTO il le xhile Design (7.5K / 2.2 min)	HMA Pavement (11.2K / 3.1 min)	HMA Pavement (15.0K / 1.7 min)	Superpave Mix Design (14.5K / 4.2 min)	Marshall Mix Design (33.3K / 1.3 min)	Asphalt Surface Treatments (47.3K / 1.1 min)	Superpave Mix Design (56.4K / 1.2 min)	Superpave Mix Design (42.8K / 1.2 min)	1993 AASHTO il le xhile Design (29.4K / 0.9 min)
9	Asphalt Surface Treatments (216.3K / 1.0 min)	California Bearing Ratio (7.0K / 2.5 min)	Marshall Mix Design (10.9K / 3.4 min)	Materials (14.9K / 0.5 min)	Testing (14.1K / 0.8 min)	California Bearing Ratio (28.3K / 1.0 min)	Los Angeles Abrasion (45.0K / 1.2 min)	Los Angeles Abrasion (46.6K / 1.1 min)	Pavement (40.0K / 0.3 min)	Gradation and Size (29.3K / 1.1 min)
10	Pavement (196.6K / 0.4 min)	Marshall Mix Design (6.9K / 3.3 min)	1993 AASHTO il le xhile Design (10.5K / 2.3 min)	Marshall Mix Design (14.7K / 1.9 min)	California Bearing Ratio (14.0K / 3.9 min)	Theoretical Max. Superpave Design (27.4K / 1.3 min)	Pavement Types (40.4K / 0.7 min)	Theoretical Max. Superpave Design (41.5K / 1.2 min)	Gradation and Size (39.4K / 1.1 min)	California Bearing Ratio (26.8K / 0.8 min)

Legend:

■ Rank 1-5 Overall
■ Rank 6-10 Overall
■ Rank 11-15 Overall
■ Rank 16+

Note: Text in red indicates pages that were not available in the year shown.

Table 3.9. PaveXpress Site: Top Page Groups by Pageviews (2014-2018)

Page Group	Unique Pages	Users	Pageviews	Total Time on Page	Avg. Time on Page	Bounces	% Bounce Rate
Home	2	51,507	104,176	215,641	4.4 min	37,102	67.2%
Training Lessons	10	128	183	354	2.4 min	10	55.6%
Background	6	116	177	58	0.4 min	6	66.7%
App	21	54	67	111	2.0 min	0	0.0%
ePublications	1	47	57	72	2.6 min	18	90.0%
Help & FAQ	3	27	31	22	0.9 min	0	0.0%
Grand Total	43	51,879	104,691	216,258	4.4 min	37,136	67.2%

Table 3.10. PaveXpress Site: Top Pages by Pageview (2014-2018)

Page Name	Page Group	Pageviews	% Bounce Rate	Avg. Time per Page
PaveXpress Design Home	Home	89,535	67.1%	4.5 min
Index	Home	14,641	69.0%	4.1 min
PaveXpress Tutorials (Introduction)	Background	137	66.7%	0.3 min
PaveXpress Overview (Introduction)	Training Lessons	60	50.0%	0.5 min
ePublications	ePublications	57	90.0%	2.6 min
PaveXpress Overview (Part 1)	Training Lessons	33	0.0%	1.1 min
New Pavement Designs with 1993 and 1998 AASHTO	Training Lessons	29	50.0%	1.6 min
PaveXpress FAQ	Help & FAQ	23		1.2 min
Resources	Background	16		0.3 min
PaveXpress Overview (Part 2)	Training Lessons	15		4.1 min
AASHTO Equations	Background	15		1.3 min
Intro to Mechanistic Empirical Design w/ Perroad	Training Lessons	12	100.0%	6.3 min

Domain Type	Pageviews	Visits	Bounce Rate	Total Duration	Avg. Time Per Page	Avg. Time in Session	Relevant Totals
Commercial	43,658	17,047	64.3%	114.226 min	4.3 min	6.7 min	8816 Unique Users
Education	12,372	4,256	59.4%	36.756 min	4.5 min	8.6 min	
International	1,820	878	65.9%	4,416 min	4.6 min	5.0 min	19275 Projects Created
Organization	2,458	1,196	65.7%	5,905 min	4.6 min	4.9 min	
Government	1,041	509	63.5%	2,972 min	5.7 min	5.8 min	40183 Sessions
Generic	908	396	63.1%	2,392 min	4.5 min	6.0 min	
USA Domain	1,242	669	66.8%	3,128 min	5.2 min	4.7 min	63813 Pageviews
Military	31	14	57.1%	35 min	2.1 min	2.5 min	

#	# Projects Associated with a User	# Users Associated with a Project
1	6,816 Users(75.05%) <i>(Running Total = 75.0% of Users)</i>	18,598 Projects(96.49%) <i>(Running Total = 96.5% of Projects)</i>
2	935 Users(10.61%) <i>(Running Total = 85.7% of Users)</i>	398 Projects(2.06%) <i>(Running Total = 98.6% of Projects)</i>
3	352 Users(3.99%) <i>(Running Total = 89.6% of Users)</i>	251 Projects(1.30%) <i>(Running Total = 99.9% of Projects)</i>
4	255 Users(2.89%) <i>(Running Total = 92.5% of Users)</i>	2 Projects(0.01%) <i>(Running Total = 99.9% of Projects)</i>
5	166 Users(1.88%) <i>(Running Total = 94.4% of Users)</i>	1 Projects(0.01%) <i>(Running Total = 99.9% of Projects)</i>
6	105 Users(1.19%) <i>(Running Total = 95.6% of Users)</i>	9 Projects(0.05%) <i>(Running Total = 99.9% of Projects)</i>
7	78 Users(0.86%) <i>(Running Total = 96.5% of Users)</i>	12 Projects(0.06%) <i>(Running Total = 100.0% of Projects)</i>
8	42 Users(0.48%) <i>(Running Total = 96.9% of Users)</i>	3 Projects(0.02%) <i>(Running Total = 100.0% of Projects)</i>
9	33 Users(0.37%) <i>(Running Total = 97.3% of Users)</i>	0 Projects(0.00%) <i>(Running Total = 100.0% of Projects)</i>
10	30 Users(0.34%) <i>(Running Total = 97.7% of Users)</i>	1 Projects(0.01%) <i>(Running Total = 100.0% of Projects)</i>

Figure 3.8. PaveXpress Associated Projects and Users (App only)

Collectively, the figures imply that returning users: view more pages per session; have longer average session duration; and have lower bounce rates regardless of the inclusion/exclusion of zero-duration sessions. This is evident by the calculated averages for duration and page depth and the amount of data required to represent 95% of the data.

When zero-duration visits are excluded, bounce rates effectively become zero (all contexts), and average session durations increase substantially for PX site and app. For these cases, average more than tripled for new visitors, and more than doubled for returning visitors.

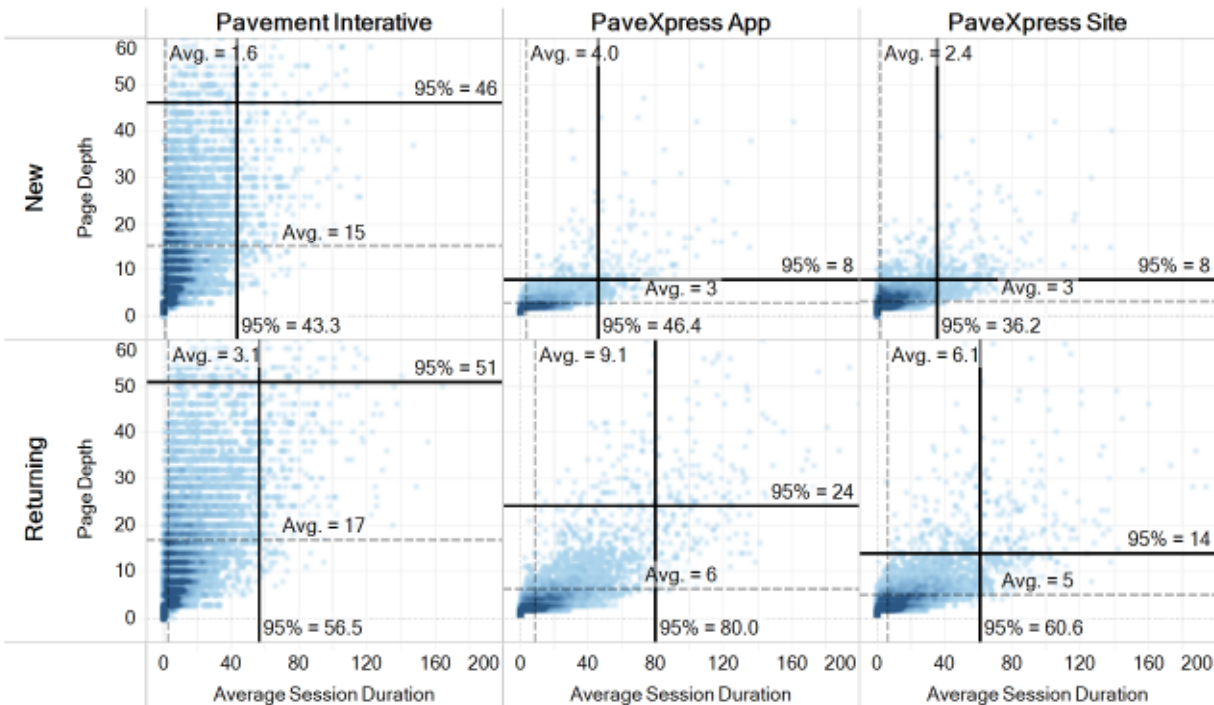


Figure 3.9. Page Depth vs. Average Session Duration (2014-2018, All Data)

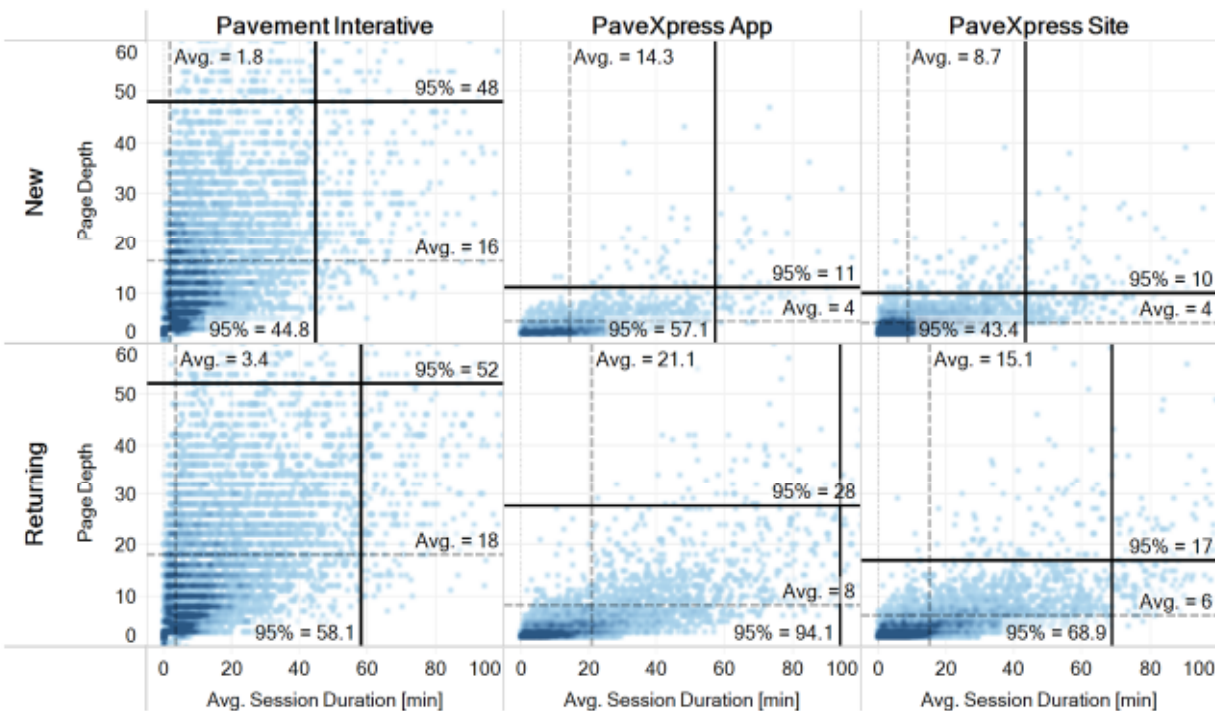


Figure 3.10. Page Depth vs. Avg. Session Duration (2014-2018, Non-Zero Durations)

Table 3.11. Performance Metrics by User Type (All Contexts)

<a href="#">All Data Included</a>	Pavement Interactive		Context / User Type PaveXpress App		PaveXpress Site	
	New	Returning	New	Returning	New	Returning
Users	980,972	439,825	11,669	11,789	34,161	19,050
Sessions	980,977	487,014	11,669	13,663	34,161	22,214
Pageviews	2,974,809	2,023,554	20,267	44,037	54,226	52,663
Total Duration	1,568,191	1,533,668	47,118	124,678	81,482	136,486
Average Session Duration	1.6 min	3.1 min	4.0 min	9.1 min	2.4 min	6.1 min
Bounce Rate	9.6%	8.7%	71.6%	56.7%	72.4%	59.3%

<a href="#">Only Records with Non-Zero Duration</a>	Pavement Interactive		PaveXpress App		PaveXpress Site	
	New	Returning	New	Returning	New	Returning
Users	888,074	402,648	3,303	5,550	9,377	8,449
Sessions	888,079	445,562	3,303	5,910	9,377	9,030
Pageviews	2,881,908	1,982,665	11,889	36,284	29,443	39,469
Total Duration	1,568,191	1,533,668	47,118	124,678	81,482	136,486
Average Session Duration	1.8 min	3.4 min	14.3 min	21.1 min	8.7 min	15.1 min
Bounce Rate	0.1%	0.3%	0.0%	0.0%	0.0%	0.0%

Context	New		Returning	
Pavement Interactive	90.53% (888.1K)		91.49% (445.6K)	
PaveXpress App	28.31% (891.4K)	71.69% (101.3K)	43.26% (451.5K)	56.74% (49.2K)
PaveXpress Site	27.45% (900.8K)	72.55% (126.0K)	40.65% (460.5K)	59.35% (82.4K)

Legend: ■ Non-Zero Duration Sessions ■ Zero Duration Sessions

### Investigation 3.5. Interaction Pathways (Pavement Interactive only)

An examination of user behavior flows reveals that 83.6% of sessions drop after arriving (landing page), and 95.5% of all sessions have dropped off by the fifth interaction (Figure 3.11). 13% of sessions immediately land on Content pages, with the remaining 3.4% landing on search-result pages or a missing page (404-error). As sessions progress, 50-65% of sessions continue through Content pages while 24-39% of sessions drop each interaction.

Figure 3.12 adds detail to Figure 3.11 by further classifying interactions by previous/next page type (incoming/outgoing type). This additional resolution shows that most sessions encountering 404-errors return to content pages, and about half of searches result in subsequent Content views.

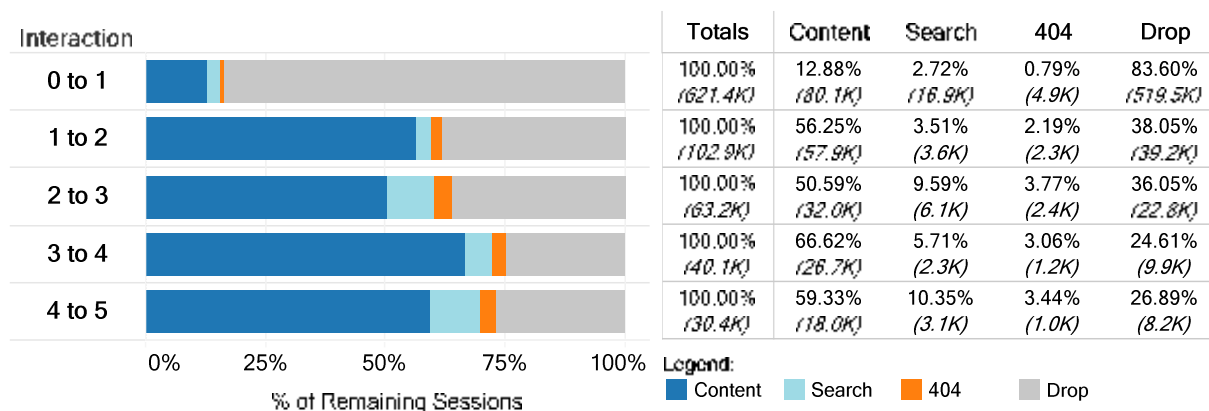


Figure 3.11. Pavement Interactive: Behavior Flows (Summary)

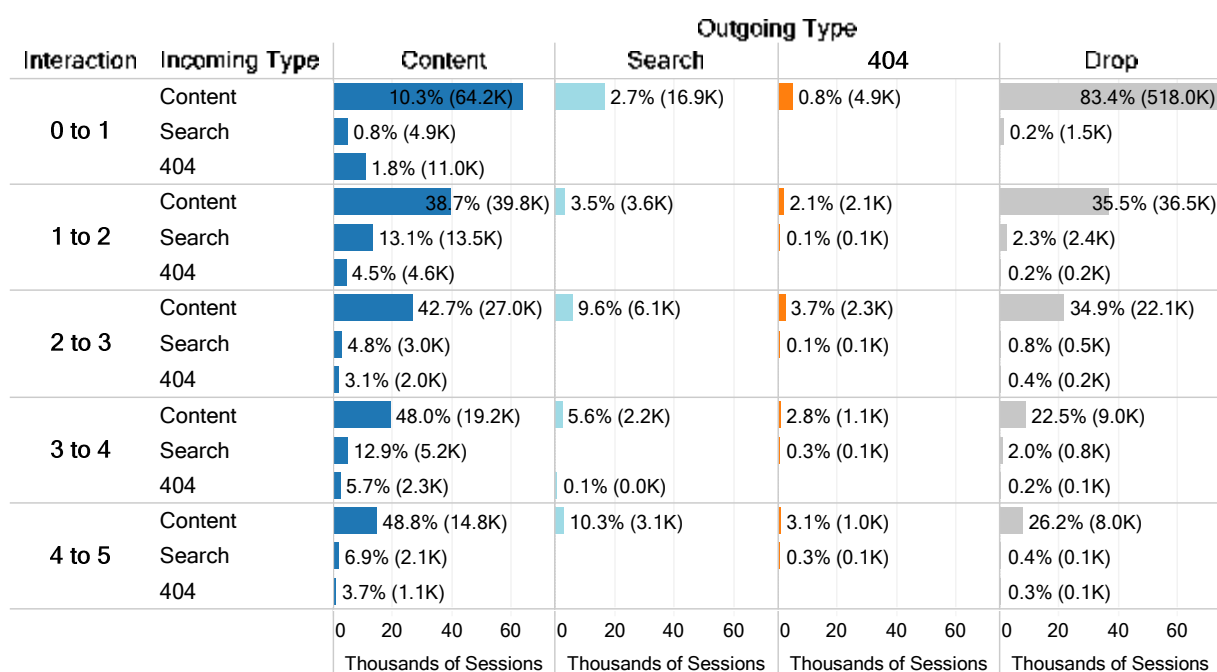


Figure 3.12. Pavement Interactive: Behavior Flows (Detailed)

## 3.7 DISCUSSION

### 3.7.1 *Limits to Data Interpretations*

The accuracy of statistics presented depends on limitations inherent to the standard version of GA (as opposed to GA 360) and the degree to which custom metric tracking is added for each website. Pavia Systems uses default settings for all analytics so results must be interpreted with caveats.

First, the standard version of GA limits data extraction sizes and defaults data retention to 26 months before deletion. This would require multiple, routine extractions to avoid data loss

beyond this timeframe. Moreover, extracting data using pre-aggregation to reduce data size can be challenging because one must choose appropriate aggregation dimensions in advance.

Second, GA by default may falsely assign a duration of zero to sessions to bounces (entrances and exits from the same page). Hence, bounce rates may not accurately reflect actual performance or result in accurate session duration calculations. For example, most user interactions in the PX app will occur in sections of the same page, but such activity may register as a bounce, conflating real bounces with valid sessions. Consequently, metrics regarding time calculations or bounce rates may have questionable accuracy, as false zero-duration records tend to yield lower central measures of tendency.

Finally, calculating statistical measures is less meaningful for population-wide data (especially if pre-aggregated) because such metrics tend to average-out metrics that could distinguish behavioral differences among user types into single, unrepresentative metrics. As such, research findings should be interpreted as an investigation into the kinds of useful information can be possibly divulged even from default GA web-analytics.

### 3.7.2 *Inferences from Investigation Results*

*Use of PI and PX has grown substantially in the last 10 years and International traffic now outpaces domestic (USA) traffic and exhibits different preferences for technology.*

Compared to a pilot study in 2010, most sessions (70%) originate from outside the USA in 2018. Growth in international traffic would be expected for either PI or PX, as global access to the internet rose by 70% between 2010 and 2016 (1.9 to 1.6 billion, with countries outside of Europe and North America contributing the most substantially (Murphy and Roser 2015). This value is 30% for PX, with no prior benchmark for comparison. While use of mobile devices with broadband access have become increasingly common, the majority use laptops and desktops to access PX and PI (94% and 70% of sessions respectively).

Countries vary in their preferences for device platform and type compared to the USA. The differences in mobile device use between PX and PI could be attributed to more complicated interactions with the PX app (e.g. entering inputs compared to browsing PI. Users may not perceive a distinct advantage in accessing PI or PX on mobile devices and merely do so out of curiosity.

Additionally, government Government agencies and academic institutions appear increasingly interested in web-based services like PaveXpress. At least 250 different government

agencies or academic institutions government were identified, the most unique email sub-domains counted for any domain type. The breadth of institutions represented by PaveXpress' userbase underscores the need to craft content that addresses an increasingly diverse audience.

Overall, the results suggest that international viewers are comfortable with consuming PI content, despite content primarily focusing on pavement practices in the USA. Content on PI has substantial domestic and international exposure, which should interest agencies who seek ways to expand the exposure of their research knowledge. As the userbase has evolved beyond the originally intended audience (domestic users), the results highlight the importance of developing services that address multi-platform compatibility.

*Users continue to see Pavement Interactive as a referential resource for knowledge on-demand.*

Overall user consumption habits have not changed much relative to compared to the findings of Muench, et al. (2010) nearly 10 years later.

First, users still commonly find PI and PX through organic searches, suggesting that access is unintentional, or that users simply find the PI or PX content through organic searches (86% used search engines). Due to the service's architecture, it is likely that users access to the PX app is its marketing site (89% are direct hits). Additionally, some users may find the PX app from PI, even though most users still find the PX marketing site first through organic searches. Although the search feature in PI is used, this amount is small compared to those who use search engines to find the same content.

Second, average durations have not changed substantially and remain around 2 minutes or less, including the top ranked pages for traffic. This may suggest that average users may do not spend adequate time to read an entire article but rather are scanning for specific information, akin to the findings of Muench et al. (2010). From this perspective, users may be consuming research knowledge as-needed (aka on-demand learning, just-in-time-learning) and in less linear or structured manners. Thus, PI may be facilitating knowledge transfer by refining or simplifying research content into a format is easily digestible in only a few minutes. It may also be that web-bots (automated scripts) artificially dilute session data with numerous short session times.

Finally, bounce rates calculated for PI overall have questionable accuracy. Average bounce rates of 40-60% are typical for content sites, and rates below 10% and above 80-90% are considered outliers (Kadavy and CXL n.d.; Kusinitz n.d.; Peyton n.d.). Given that PI is relatively

unique in its focus on pavement research, such performance criteria may not be exactly relevant. Default data extracted from GA may inaccurately reduce session durations and result in lower-than-expected calculated average durations, particularly when bounce rates are high. This could imply that users spend more time than can be detected. Calculated metrics may also be less meaningful because they do not focus on specifically defined group of users. Higher accuracy may potentially be achieved by defining meaningful cut-off criteria for data to reduce the weight of unmeaningful data points in results. Strategically defining appropriate primary dimensions for aggregation may also help filter unmeaningful data from analysis.

*Users commonly appear to learn PaveXpress through their use experience and rarely access the available standalone training materials.*

The fundamental difference between PI and PX is that PX content addresses knowledge transfer in terms of application (“know-how”) in addition to just factual knowledge (“know-what”). PI largely focuses on the later. As some of PX’s traffic is likely received directly from PI, their treatment of PI as a referential tool for demanding knowledge may translate into their consumption of PaveXpress.

However, users rarely access training materials available (less than 1% of site Pageviews), despite these pages including the substantial content for training and research knowledge. Like PI, average session durations span only several minutes and suggests users rarely consume this content not in their entirety. In lieu of this, users may be trying to learn PX simply by using it, believing that any gaps in understanding can be searched. Alternatively, most users may find that consuming the training materials is unnecessary to successfully use PX, either because users are already proficient or because adequate in-app support is present.

Regardless, such findings raise questions of how the format and presentation of knowledge content optimally aligns with user consumption habits and addresses goals of knowledge transfer within agencies. The process of developing training materials for services is challenging because expertise is needed to strategically select relevant research that specifically informs users how to use (or not use) the service, in addition to identifying any pre-requisite knowledge outside the application scope. While a linearly structured format may be optimal for academic environments, this may not be true for practitioners. Thus, in assessing the adoption of research-based digital tools, agencies may also want to consider:

- The resources needed to generate content (services and documentation): do use levels justify the resources spent to create and maintain them?
- The appropriate depth for knowledge and training content to encompass the breadth of expected audience skill levels: can one format fit both experts and non-experts?
- The format or presentation of research knowledge or training materials acknowledges consumer behavior in the context of the service: is research knowledge translated into actionable advice that users can find and quickly consume to progress, or must users seek this elsewhere?

*It is unclear whether users complete PaveXpress projects*

The time needed to complete a PX project is unclear, making it difficult to determine whether bounce rates or average duration are good a proxy for this. While medians suggest reasonable timeframes to complete a simulation, it is unclear which metric is more trustworthy. The real ‘average’ is likely somewhere in between calculated averages when sessions under one second are excluded or excluded: for PI this is 1.6 to 3.1 minutes, 4.0 to 9.1 minutes for the PX app, and 2.4 to 6.1 minutes for the PX site. Thus, it is unclear how frequently users complete a project not how the results are used in their workflows (if at all). Several interpretations may be:

- users believe PaveXpress can supply valuable results but struggle to complete simulations for various reasons, such as lack of required inputs
- users create project to test the app, validating the service against their engineering expertise, expectations, or computations performed elsewhere
- users are trying to understand considerations and data requirements to perform pavement design, but do not need to complete a project

In either case, a cursory use of PX may have benefits by exposing users to data requirements, reveals a user’s knowledge gaps, or reveal previously unknown complexities in pavement design.

### 3.8 CONCLUSION AND RECOMMENDATIONS

Through an investigation of strategically extracted Google Analytics data, this research reveals trends regarding the consumption of research knowledge through two web-based tools. While user demographics for PI and PX have shifted to include a greater international audience, results for PI reinforce the findings of Muench et al. (2010) regarding user habit nearly a decade later. Users continue to treat PI as a reference tool, as sessions typically approach PI organically through search engines and seek specific pieces of information (rather than consuming page content in their entirety). Investigations also present evidence of knowledge transfer: 30% of users return and engage in longer sessions, view more pages, and bounce less. Thus, the services provide referential information to consumers at minimum.

In addition to the explicit aspects of knowledge (know-what), apps such as PX must also train users to apply research knowledge (know-how). Given the presence of both academic and government users of PX, the content must address a wide breadth of skill levels. However, very few users ever approach the available training and knowledge content (~2% of users). Such behavior could mean that users prefer an unstructured approach and seek information as-needed, rather than through dedicated structured training sessions or standalone linear training manuals. The format of educational content may not always be well received. Thus, limitations exist.

Attention should be placed on the alignment between how research is formatted versus how users are attempting to consume the product. Based on observations for PI and PX, users may be expressing a desire for a less-structured learning environment in which knowledge is presented only on-demand. Consequently, agencies must consider whether traditionally structured training is effective for transferring research information or knowledge, particularly if viewership cannot justify resources required to generate such content. By contrast, entertainment software (e.g. video games and mobile app games) frequently lack instruction manuals and rely on so-called experiential learning (Buchanan 2010; Carroll 2014; Davidson 2011; Davis 2009; Fahey 2016; Fletcher 2010; Kapp 2012; Lynch 2016; Malykhina n.d.; Samuel 2013; Suddaby 2012).

This research does not suggest that user manuals or training sessions are unnecessary or not useful. Rather, this research suggests learning and technological preferences are evolving such that traditional teaching methods are less compatible with consumer behavior. Users appear more likely to simply start using an application and so, this research proposes that agencies attempt to incorporate research knowledge and training into the use experience of the app. Many examples of software or web-apps are recognized for their ability to attract users with little to no instruction or training include: Waze and Google Maps (real-time navigation web service and apps), Fandango (a movie ticket showtime aggregator and point-of-sale application), Intuit's TurboTax (a federal income tax filing service) (Jamieson 2015; Shah 2018; Weiners n.d.). Even if structured training is mandatory, having similar but refined knowledge content available in-app may improve user exposure to otherwise rarely seen research content. While development may be tedious, such features may be valuable because content would receive greater exposure.

The extent to which the use experience of a web-based service is adequate for transferring the necessary research knowledge for application purposes is unclear and likely topic specific. Future research could clarify this by identifying criteria that would indicate where users are most likely

to struggle with concepts, and thus identify where training is particularly necessary. Depending on the complexity or nuance involved, research content may require varying levels of documentation detail to be taught effectively. However, even with default GA configurations, meta-data regarding website traffic and use provides enough resolution to imply that the actual use of PI and PX has evolved beyond its originally intended purposes. As such, this research recommends placing greater focus on determining how development practices can more effectively format research content for consumption through software mediums.

Finally, further research addressing software characteristics that demonstrate competency may also help identify the necessary tasks or considerations involved in translating research concepts into practice-ready software or information repositories. Overall, the findings of this research should inform the efforts required to produce such content compared to way it is being consumed and how agencies can leverage information technology to better align with apparent consumption habits.

## Chapter 4. EVALUATION OF RXPAVE: COMPETENCY CRITERIA FOR RESEARCH-BASED SOFTWARE

### 4.1 PREFACE: INCORPORATING VALUE INTO THE DEVELOPMENT PROCESS

The first investigation (Chapter 2) establishes the state of practice for technology consumption among transportation agencies, revealing gaps between research and use in practice via software. The second investigation (Chapter 3) reveals how users consume research through digital mediums such as web-apps and digital services like Pavement Interactive. Collectively the efforts reveal challenges when translating research into software but emphasize how research drives the development effort

This study takes a closer examination at the development process of a new web-based tool (RxPave) and investigates how development choices can impact and extend the value of its underlying research. Using a mixture of qualitative and quantitative data from RxPave's development, this research attempts to more specifically define how the development of research-based software creates value in three contexts: platform, development, and research knowledge (introduced in Chapter 1).

### 4.2 INTRODUCTION

RxPave is a web-based service intended to assist the Washington State Transportation Improvement Board (TIB) in the selection of rehabilitation options for low-volume roads funded by the Small City Grant Programs, specifically the preservation and arterials programs (SCPP and SCAP). Small cities are defined as having a population under 5000 and low-volume roads experience under 1 Million ESALs (Equivalent Single-Axle Loads) over a 40-year service life. Compared to large cities with higher geographic concentrations, the physical region encompassed by TIB's small-city clients is substantially larger and is distributed throughout most of the state. TIB provides funding for these cities and towns because they typically lack the financial resources to fund transportation improvement, and affected population size (TIB n.d.). Consequently, TIB

has sought to streamline their process for prioritizing road maintenance for these small cities and their collective low-volume roads throughout the state.

The development of RxPave translates a decision-support method resulting from previous UW-TIB research between 2013 and 2015 into a web-based application (web-app). This prior research updated TIB's existing SCPP program, which helped small cities scope preservation grants for which they were applying. TIB sought to limit preservation options to those most applicable to low-volume roads and assist applications in selecting the appropriate preservation strategy for their perceived pavement type and conditions. TIB ultimately adopted an abridged version of the research process as a paper-based model, and the details of this method were delivered in the form of a static digital report. Consequently, this research has received limited exposure outside of TIB.

In 2018, TIB commissioned RxPave as a standalone application and a component that assists in the small cities grant application process. RxPave also updates the application process to more closely match the original research model, while adding revisions and additional logic to guide users towards meaningful results. The project is jointly funded by TIB (\$25,000) and the State Transportation Innovation Council (STIC) (\$100,000) and sponsored by the Washington State Department of Transportation (WSDOT). The University of Washington (UW) is the performing entity for research, with Pavia Systems, Inc. and TriSight Engineering as subcontracted developers. Due to the young age of the underlying research, relevant knowledge will be primarily consumed through a web-based medium as just-in-time information. Consequently, agencies may be interested in understanding how the development of RxPave can reveal competencies for future research-based development efforts.

This study explores the idea that software development can both inform and extend the value of the research effort which it was based. More specifically, this examination focuses on how RxPave's development fosters opportunities to create or extend value in three ways (Table 4.1).

The development of RxPave can improve pavement practice in two manners: first, research on low-volume roads is scarce because most cities lack the resources to fund innovation projects or absorb the inherent risks of emergent technology, and because national organizations are typically concentrated on highways in research. Second, it is unlikely for research efforts such as this to be funded by TIB without the assistance of STIC funding, and consequently, the research is a rare opportunity to bring the value of innovation to TIB, those 150,000 lane-miles and 500,000

residents it serves. As such, this study investigates how RxPave can create further opportunities for future integrations, extended applications beyond Washington state, or be used as a modular analysis component for pavement asset management.

Table 4.1. Three Contexts of Value for Research-Based Software

<b>Value</b>	<b>Description</b>
<b>Platform</b>	Value generated by developing and consuming (using) a software/service on a specific technology platform (e.g. Windows laptops, Apple tablets): passive platform capabilities that enhance functionality access to knowledge resources and community improves communication between users and developers improves consumer analytical or work capacity of improves use of time (efficiency, workflow, reduced clerical work)
<b>Development</b>	Value generated from development choices or design of the software, and transferred to its consumers (end-users) by using the app: incorporation of software development best practices alignment between a software's features, performance, and the goals or objectives of its consumers format and presentation of knowledge content through in-app features or training documentation / knowledge resources
<b>Research</b>	Value generated by informing underlying research, improving the learnability and applicability of research, or addressing the gap between research and practice: reveals limitations of application or necessary revisions for research methods to be effectively practicable provides new opportunities for further research to extract further use from data or research reveals patterns in consumption behavior and extent of use identifies new or appropriate contexts for presenting knowledge

This study investigates several data sets regarding RxPave's development and documentation: Project data for 120 past projects funded by TIB's SCPP to validate RxPave's functionality and alignment with research and TIB goals, and Application documentation and meta-data from development that highlights actions taken to mitigate concerns regarding barriers to development or product delivery. Collectively, these assessments of RxPave define what constitutes as value in the context of research-based software as well as reveal the qualities that research-based software must possess to produce value beyond economic estimations. In turn, identifying key characteristics of the development process and the app itself reveals a set of competency criteria that can be used to provide a structured assessment of research-based software and services and inform best practices for translating research into practice-ready tools for the paving industry.

### 4.3 RESEARCH GOALS AND STATEMENT OF PURPOSE

The development of RxPave represents a growing desire among transportation agencies to transform a research process into an accessible, digital service. However, the niche of software based on pavement research are generally created as proof-of-concepts or prototypes, and rarely as practice-ready tools. Consequently, they are generally not concerned with compliance with best practices for software development, and documentation of the development process is rarely addressed by research. Although compliance with software quality standards is generally not a research goal or rarely considered in research-based development, incorporating them may result more effective software tools that which exhibit certain characteristics. To address how such concepts can be applied to research-based development in pavement engineering, this research includes three goals:

- Deliver RxPave under a development model that reflects best practices and lessons learned from previous investigative efforts and literature
- Provide rationale (or caveats) for supporting future efforts on research-based development or re-examination of published research-based on documentation of RxPave's development
- Identify and document evidence of value generated by research-based software (including development and use) through a structured and organized evaluation

The goals are achieved by linking observations regarding RxPave's development to quality criteria defined in standards and literature, as well as identifying value added by specific actions performed during or decisions regarding RxPave's development. This process subsequently allows us to define competencies of research-based software by associating sets of quality criteria to intended project outcomes. Ultimately, the intended research outcome is a checklist of competencies which the paving and pavement industry may employ as a specifications list or evaluation criteria when for future integration efforts.

### 4.4 BACKGROUND

#### 4.4.1 *Low-Volume Roads and Small Cities in Washington State*

Low-volume roads in are defined as those which experience traffic volumes of less than 400 vehicles daily on average taken on a yearly basis. Based on this definition, there are approximately 150,000 lane miles of low-volume roads in the state (75% of the state's low volume roads). Of these small cities, classified in in Washington State as having under 5,000 population, own about

~3,000 lane-miles. According to the 2016 US Census Bureau and these criteria, this implies that the 163 cities served by TIB are home to approximately 550,000 (10% of the state’s population) and eligible for grant funding under TIB’s small cities preservation program (SCPP). Figure 4.1 visualizes the distribution of 120 SCPP project segments funded during the 2015-2017 fiscal years.

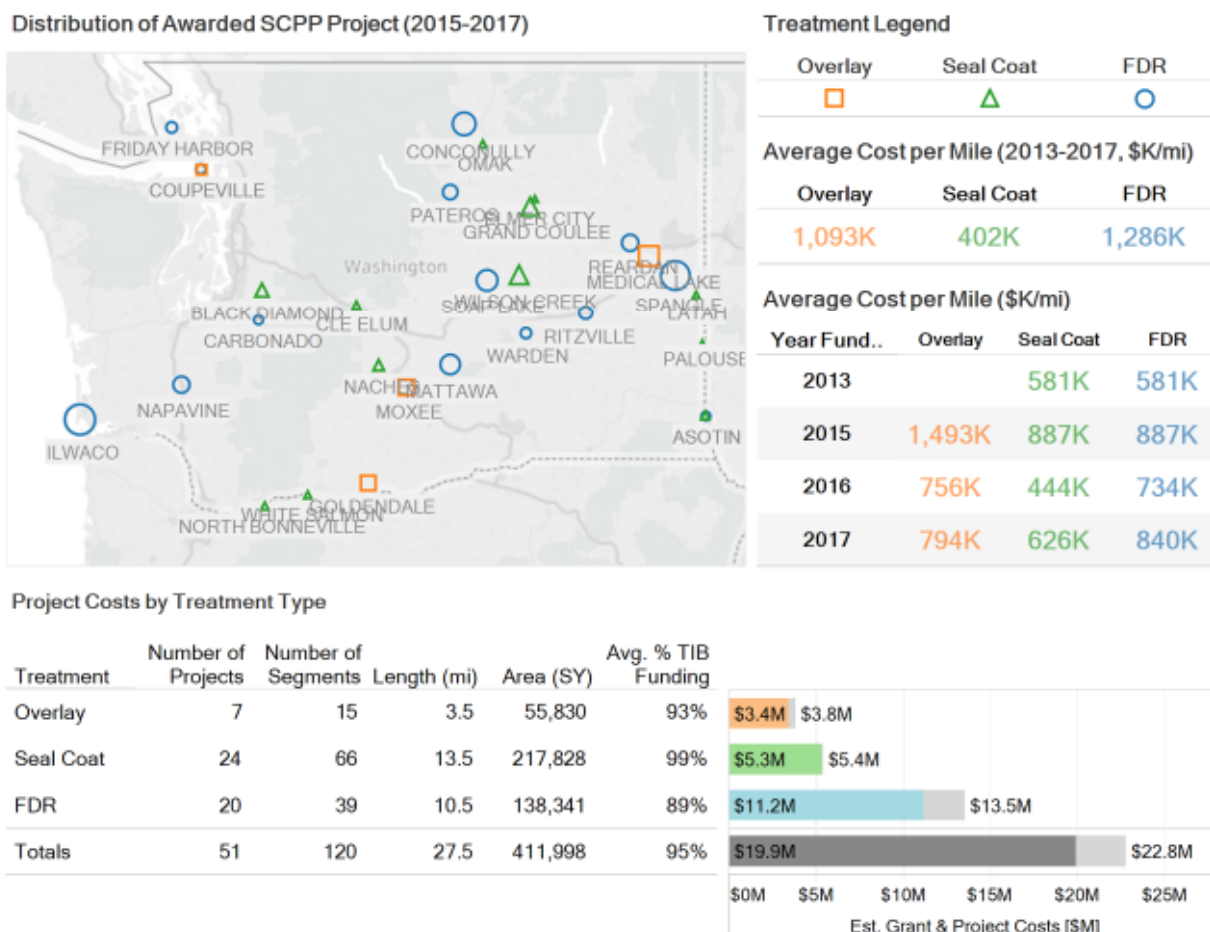


Figure 4.1. Distribution of Awarded SCPP Projects between 2015 and 2017 FY

#### 4.4.2 Maintenance of Low-Volume Roads for Small Cities in WA

Prior to TIB’s formation in 1988, small cities are often unable to afford the care of their roads from taxes alone because the income to pay for the maintenance and upgrades of road infrastructure is raised through gas taxes and property taxes. However, the price of pavement tends to remain constant in terms of order of magnitude and small cities lacked the population to generate adequate funds. Additionally, many of these low-volume roads are smaller in capacity (i.e. 2 lane highways) and statistically further from major materials distribution points. These factors may create more challenging construction conditions that increase logistical costs of construction activities (e.g.

material hauling, required fleet sizes for construction activities). Furthermore, small cities tend to have limited staffing to address pavement repair and frequently lack adequate training to make the proper assessments for selecting maintenance strategies. Collectively, these issues warrant investigation because they frequently result in incorrect selections, poor service performance, and wasted money or material resources. Moreover, resolving issues regarding rehabilitation scoping issues may have greater implications to the state's treatment of this issue, let alone the country's portfolio of low-volume roads.

#### 4.4.3 *Funding through TIB's Small Cities Preservation Program (SCPP)*

TIB is an independent state agency created by the Washington Legislature to prioritize state-level investment in local transportation projects. To do this, TIB uses a fixed 3.04-cents of the state-wide gas tax (49.4 cents as of 2016) to fund grant programs that serve cities, urban counties, and transportation benefit districts in Washington State. The TIB categorizes its grant funding into two programs based on city population: the small cities program (under 5000 population) includes four funds for different project types, and the urban program (populations of 5000 or more) similarly includes three funds. In particular, the small cities preservation program (SCPP) provides funding for pavement preservation and is a non-competitive program: funds are provided based on condition ratings, economies of scale, and assessed valuation of cities. This valuation determines the required funding match that must come from the cities. In 2012, TIB grant programs resulted in \$104 million awarded to 168 projects. In 2018, TIB estimates this amount to be ~\$97 million in funding per year, assuming \$32 million annual income per cent earned from the Gas Tax.

Considering these economic challenges, TIB is interested in streamlining the process of scoping and prioritizing rehabilitation projects through the development of RxPave. RxPave is intended to be a tool used by applicants for funding under the small cities preservation programs (SCPP). By replacing a currently paper-based process with a streamlined web-service, the TIB intends to streamline their application process and review rate as well as expend their limited fund for pavement rehabilitation more efficiently.

#### 4.4.4 *Basis for RxPave: 2013-2015 Research with UW*

The concepts and scoping model mobilized in RxPave are based on a set of research projects also performed by the University of Washington between 2013 and 2015. These research projects

collectively addressed and updated TIB's SCPP and resulted in a scoping tool that allows TIB to prioritize and select funding for rehabilitation projects through a manual process that is currently used by TIB. Specifically, the method requires an applicant to provide a pavement and material profile, estimations of traffic data, and an assessment of a pavement's current conditions. Based on these parameters, the procedure subsequently disqualifies or ranks different paving options based and recommends the any options for further consideration.

Between 2008 and 2014, Pavia systems developed web-based application for SHRP 23 that functionally provides the same rehabilitation guidance as RxPave intends but for high volume roads (above 10 million equivalent single axle loads or ESALs). Given model similarities, the performing parties decided to retrofit and update the existing architecture of RePave for RxPave's development and create new documentation based on the source research. This strategy reduces the cost of development by approximately 60% and substantially shortens the development time because the architecture is already a functional proof of concept. Consequently, this research focuses on the process of translating it for development purposes.

#### 4.4.5 *Motivation for the Development of RxPave*

TIB and stakeholders were primarily motivated by three factors:

**Resource Efficiency:** Ensuring roads received appropriate treatments and by extension, improve the quality and consistency of distress evaluations driving decisions. This is of particular interest to FHWA and WSDOT who are project stakeholders.

**Process Efficiency:** Implementing implement a service (RxPave) that digitizes part of TIB's paper-based grant application process while also allowing agencies outside of Washington to use the service to identify viable strategies for maintaining their low-volume roads.

**Access and Exposure:** Increasing exposure to the research behind RxPave and present the research in a manner that is usable by non-experts and integrated into the interface itself. Intended users include pavement researchers, students, developers in construction, and other agencies tasked with maintaining low-volume roads.

#### 4.4.6 *Standards for Evaluating Software Quality*

Researchers have identified countless characteristics that can be used to describe the quality of resulting software or service, including data quality, software/service quality as a product, and

quality as perceived by users. ISO standards are frequently used to evaluate software quality are intended to be comprehensive, but modifiable so that users may define alternative but equivalent evaluation criteria that fulfill use requirements. To rationalize evidence of RxPave's development and features generating value, this research uses the baseline ISO 25010 quality characteristics or identifies new qualities based on observations (ISO 1991, ISO 2011).

First issued in 1991, ISO 9216 defined a set of six primary quality characteristics (and their numerous subcharacteristics) to evaluate software and address human bias in development. After several revisions and updates, the standard was replaced by ISO/IEC 25010 in 2011 and rebranded into a set of standards, Software Product Quality Requirements and Evaluation (SQuaRE). Effectively, the new standard reclassified quality into a data, use, and product quality models, each with their own set of characteristics and subcharacteristics. Because DOTs include their own data management and quality plans, the SQuaRE data quality model is incorporated into this investigation, aside from considerations to model data requirements. ISO 25010 includes 8 primary characteristics and 31 subcharacteristics for the Product Quality model, and 5 primary characteristics with 11 subcharacteristics for the Quality in Use model (definitions for primary characteristics in Figure 2). In general, Product Quality characteristics are more objective in that they define features a software might demonstrate, whereas Quality in Use characteristics are more subjective, based on user perception. For either models, ISO 25010 does not provide guidance for realizing such characteristics, nor define extents to which characteristics are realized.

#### 4.5 AVAILABLE DATA AND DESCRIPTIONS

The data resulting from the development of RxPave includes both qualitative and quantitative information regarding different stages of the development process. These data sets include:

##### 4.5.1 *Historical SCPP Application Data (2015-2017 FY)*

Since the completion of the underlying research in 2015, the TIB has incorporated a paper-based, abridged version of the research methods, resulting in data from SCPP applicants. This data set includes project information from 120 projects funded between FY 2015 and FY2017 and are used to partially validate the RxPave model in development.

#### 4.5.2 *Data from App Documentation*

This broadly includes any documents used to coordinate the development of RxPave, including official documentation, contract and development requirements, app features, training materials including in-app features, or guidance for result interpretation. Though qualitative in nature, observations can be drawn from this data collection and associated with benefits identified in standards and research.

#### 4.5.3 *Personal Communication with TIB*

Engineers from TIB were actively involved in creating development and usability criteria for RxPave, as well as co-authors of the underlying research (Lew et al. 2015; Muench and Lew 2015a; b; Muench and Yamaura 2015a; b; c) . Discrepancies were resolved with TIB during model validation steps to verify that RxPave's outputs aligned with TIB's expectations.

### 4.6 METHODS

#### 4.6.1 *Overview of Procedure*

The investigation focusses on relating categories of value (platform, development, and research) to development and use characteristics demonstrated by RxPave and subsequently defining sets of characteristics as competencies for research-based software overall. Visualized in Figure 4.2 and described below, these steps include:

- Draw observations from data sets linking specific features or characteristic of RxPave to the creation of platform, development, or research
- Associate observations with characteristics of software quality defined in ISO 25010. If an observation cannot be linked to existing ISO characteristics, a new characteristic or sub-characteristic will be defined or justified from literature
- Analyze characteristics exhibited by RxPave and define competencies that result from possessing such sets of characteristics
- Relate competencies to value categories, resulting in a checklist with which research-based software can be evaluated by transportation agencies and non-experts

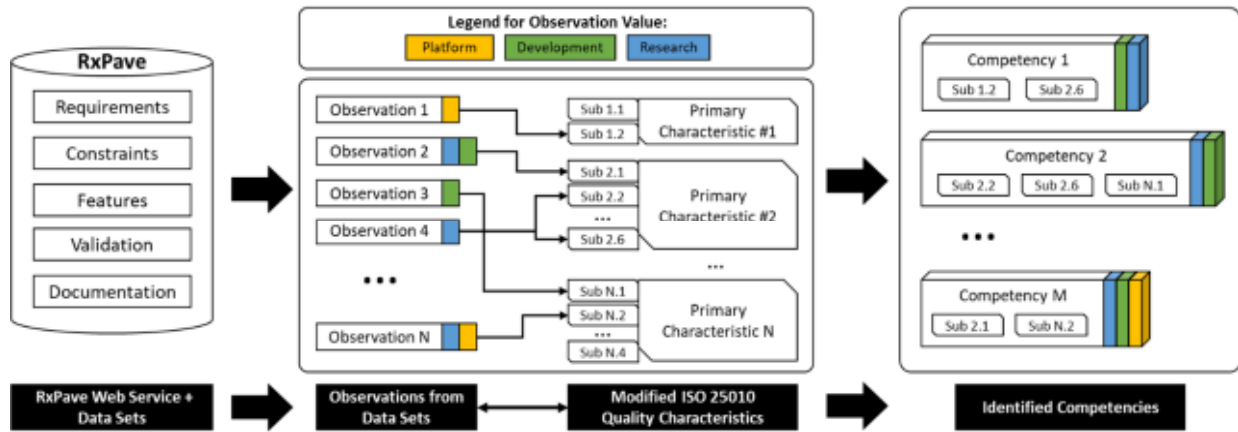


Figure 4.2. Visualization of RxPave Analysis Strategy

#### 4.6.2 Basis for Defining Additional Characteristics

ISO 25010 intends to provide a comprehensive but generalized baseline set of software qualities. However, this research is not seeking compliance; ISO terms are used here to provide a structured language to structure observations and are consequently less formally applied. Meanwhile the research must also address:

- stakeholder concerns for development; and
- characteristics that address the goals of pavement researchers (e.g. conveying research knowing, preserving research fidelity);
- how to communicate research concepts in a language easily understood by the paving research community and transportation agencies.

### 4.7 RXPAVE DEVELOPMENT

#### 4.7.1 RxPave Use Objectives

The objective of RxPave to provide expertise to small cities with limited knowledge resources in the selection of pavement rehabilitation strategies for low volume roads are limited. RxPave's procedure determines whether four paving rehabilitation options are viable using a decision tree for each option. RxPave requires a mix of qualitative and quantitative inputs, including:

- basic project information and location identifiers, including optional notes
- observed presence and levels of distress for 8 different pavement distress types
- existing pavement type, operating conditions, and features (e.g. surface or subsurface features that may conflict with treatments)
- questions designed to reveal whether additional construction considerations are needed

#### 4.7.2 *Development Criteria and Expectations*

The performing and funding entities for RxPave defined a set of project development and delivery criteria that include requirements, feature requests, and perceived development best practices (Table 4.2). TIB provided 3 primary criteria for development (C1-C3), leaving more technical specifications to the performing parties to determine. The performing entities added additional criteria based on best-practices for knowledge transfer in web-based environments (Muench et al. 2010) (C4-C10), and based on research interests (C11-C15).

Table 4.2. Product Development and Delivery Criteria for RxPave

ID#	RxPave Development and Delivery Criteria	Driver
C1	Streamline a paper-based process into a digital service, meanwhile minimizing disruptions and resource requirements to sustain use of the resulting service	TIB
C2	Provide a structured environment to carry out an analysis consistently across end-users	TIB
C3	Provide expertise to a non-expert audience where knowledge resources are limited, including app use and interpretation of results	TIB
C4	<b>(Web 2.0 Essentials)</b> Unique, quality content	UW / Pavia
C5	<b>(Web 2.0 Essentials)</b> Service, not product	UW / Pavia
C6	<b>(Web 2.0 Essentials)</b> Users as codevelopers	UW / Pavia
C7	<b>(Web 2.0 Essentials)</b> Harness collective intelligence	UW / Pavia
C8	<b>(Web 2.0 Essentials)</b> Serve the individual user rather the larger organization	UW / Pavia
C9	<b>(Web 2.0 Essentials)</b> Software usable by multiple devices	UW / Pavia
C10	<b>(Web 2.0 Essentials)</b> Strive for simplicity in application and development models	UW / Pavia
C11	Increase accessibility and exposure of RxPave's underlying research by generalizing its use beyond TIB's purposes	UW
C12	Provide adequate detail in documentation and in-app support such that users could reproduce results manually, given all necessary inputs	UW
C13	Provide users with rationale for steps taken in RxPave, e.g. results of intermediate calculations or reasoning behind the rejection of certain treatment strategies	UW
C14	Identify discrepancies in process or interpretations between existing practices and proposed RxPave methods	UW
C15	Identify and distinguish sources of error resulting from user inputs and include a means for users to correct them	UW

### 4.7.3 Responses

The development and delivery criteria are addressed by responses, referred to here as groups of implemented actions during the development of RxPave. Effectively, the development criteria are treated as the rationale motivating responses. Seven identified responses collectively address all development criteria, and each response addresses multiple criteria (Table 4.3)

Table 4.3. Responses to Development Criteria

ID#	Response Description
<b>R1</b>	Platform Choice: Developed as free, web-based service. Users must create accounts to use RxPave, but documentation and resources are available to all.
<b>R2</b>	Translation of Research: Methods were adjusted from a set of smaller decision trees to a single equivalent evaluation that is more computationally efficient. Disqualifying and conditional criteria we translated into equivalent numerical scores that facilitate future checkpoint calculations or inform the trigger/warning system (see Chapter 4.7.4) <ul style="list-style-type: none"> <li>▪ All checkpoint evaluations are performed to include all possible reasons for disqualifying certain rehabilitation strategies</li> <li>▪ Added variables to address data year to check data consistency</li> <li>▪ Allow users to leave certain inputs blank, to be filled in later</li> </ul> Fixed criteria error from original research for one decision tree
<b>R3</b>	Data Verification: Incorporated a trigger/warning system to inform the user of potential input errors, with the ability to: <ul style="list-style-type: none"> <li>▪ Distinguish types of different of input errors from user</li> <li>▪ Display warning messages in real time or in results / reporting</li> <li>▪ Help users troubleshoot error sources and make appropriate corrections</li> </ul> Additional details can be found in Chapter 4.7.5
<b>R4</b>	Interactive Report: Features a report system that provides information to support decisions on viable rehabilitation strategies. Report does not render a final selection but equips users with rationale to support their final decisions. Key features include: <ul style="list-style-type: none"> <li>▪ Summary and detailed views of results, including intermediate calculations</li> <li>▪ Provides rationale for both recommended and disqualified treatment strategies</li> <li>▪ Indicates possible outcomes if optional information is missing</li> <li>▪ Summarizes any unaddressed warnings triggered by current inputs</li> </ul> Includes a summary of input data so results can be reproduced elsewhere
<b>R5</b>	Interface Features: Features were incorporated into to facilitate workflow efficiency: <ul style="list-style-type: none"> <li>▪ Save, reload, and share projects</li> <li>▪ Duplication of segments or projects to reduce redundant data entry</li> <li>▪ Compare results between segments or projects, showing only key results</li> </ul> Contact form provides users a channel to report issues or ask questions
<b>R6</b>	Validation Testing: After performing validation testing and subsequent discussion with TIB, performing parties determined that issues revealed could be addressed by: <ul style="list-style-type: none"> <li>▪ Using RxPave’s severity definitions, reflecting actual, unadjusted conditions</li> <li>▪ Updating pavement condition (PCR) criteria to match the RxPave’s research</li> </ul>

	Prepare additional guidance (in-app and documentation) that encourages consistent recognition of pavements distresses and severities
<b>R7</b>	Documentation: Create or provide access to documentation that addresses stakeholder interests as well as the end-users overall. The documentation uses non-technical language understandable by non-experts while providing adequate technical depth for expert users. Additional documentation details are described in (Table 4.5)

#### 4.7.4 Trigger and Warning Guidance System

Four categories of data entry issues were identified, distinguished by how the service should respond. These warnings are triggered by input combinations meeting certain conditions, many of which are extracted from the source research. These responses are described in Table 4.4:

Table 4.4. Warning System and Programmed Responses in RxPave

Warning Type	RxPave Response When Triggered:
<b>Data Validation</b>	Text warning(s) that certain inputs are invalid due to improper formatting or outside a range of options. Affected inputs must be revised to produce results.
	<i>Example: User enters a value outside an expected numerical range, such as a 0-100 scale</i>
<b>Data Consistency</b>	Text warnings that input values are computationally valid but are unexpected or inconsistent with expectations. Warnings can be ignored at the user's discretion but would likely produce inaccurate results.
	<i>Example: A given pavement condition suggests no rehabilitation is necessary.</i>
<b>Disqualifier</b>	A specific application outcome is flagged for disqualification. Warnings with rationale for disqualification is provided within the report results.
	<i>Example: Presence and severity of an entered distress disqualifies a rehabilitation option.</i>
<b>Conditional / Qualifier</b>	Warnings that certain outcomes are only valid if additional conditions are satisfied, but evaluation of such conditions is outside the scope of the service. Considerations are indicated in the report, and users may determine whether further investigation is needed.
	<i>Example: A treatment outcome is only valid if the subbase condition is sufficiently high, but otherwise requires prior repairs to be viable.</i>

#### 4.7.5 *Validation Testing*

The RxPave model was validated using data from 52 previously funded SPCPP projects. This testing was done to see how well RxPave's recommendations would align with actual strategies adopted by the TIB. Although TIB's historical project data includes fewer inputs that RxPave would expect, enough data is available to simulate all projects in RxPave with additional assumptions. Validation testing revealed several issues that were ultimately resolved in subsequent discussion with TIB. Identified issues are:

**Issue 1:** RxPave uses a different scoring system than TIB's current scoring methods when performing a visual distress survey. TIB currently uses a numerical scale to indicate distress severity but adjusts these values to incorporate engineering judgement and expertise, e.g. the surveyor may inflate, deflate, or eliminate a distress observation to affect certain outcomes. Consequently, historical data scores could not be interpreted consistently across different survey performers, and any attempt assign a consistent mapping to RxPave scores will be imperfect.

**Issue 2:** The validation tests found that RxPave could not yield matching recommendations for 11 (9%) historical projects, revealing a set of small discrepancies:

- In all but one of these cases, RxPave disqualified the actual strategy used by TIB because it did not interpret TIB's severity scores as sufficiently high to justify the treatment
- In five cases, certain treatments were disqualified because PCR range definitions for TIB differed slightly from research recommendations
- In three cases, no recommendations were possible because combinations of inputs disqualified all treatments.

#### 4.7.6 *Documentation and Knowledge Transfer*

Documentation for RxPave exists entirely in the form of an interactive website and in-app support; there is no traditional stand-alone user manual. RxPave's documentation relates information relevant to different stakeholders and general audiences in a language that must be understood by non-experts such as funding entities, researchers, and engineers. As a research-based tool, the documentation must also address research knowledge and training requirements, in addition to providing typical software use guidance.

To address these criteria, supporting documents are created with different levels of technical detail. Additionally, a great deal of technical information contained in these support documents is presented to users through in-app support features, such as tooltips and triggered warnings. Table

4.5 summarizes supporting documentation created for RxPave. A more detailed version of this table can be found in Appendix F (Table 5.6).

Table 4.5. Summary of Documentation Efforts

<b>Overview and Marketing</b>	The overview is an executive summary that relates the intent and scope of the development effort, provides context for use, and relates intended perceived benefits. Intended for funding entities and first-time visitors.
<b>Development Background</b>	Contents provide context for development and research efforts, effectively summarizing the state of practice in relationship to the state of the art. Intended for funding entities and academic researchers.
<b>Knowledge Transfer (Training and Guidance)</b>	Software use training and guidance is addressed through in-app support and recommended resources that describe relevant background knowledge and research concepts. Intended for researchers, skeptics, and general audiences (non-expert users).
<b>Frequently Asked Questions</b>	A log of anticipated or frequently asked questions regarding RxPave use, development, or interpretation. Section also provides users with a means to contact the TIB for additional questions. Intended for general audiences.

## 4.8 ANALYSIS AND OBSERVATIONS

Observations intend to identify connections between development criterium, responses that collectively meet the criteria, the perceived values produced by incorporating the responses into development, and ISO subcharacteristic(s) associated each response. The perceived valued produced by responses are described in Table 4.6, and results are aggregated in Figure 4.3, which provides the following information for each response: a summary of primary characteristics addressed by responses (based on ISO Quality in Product (QP) and Quality in Use (QU) model definitions); development criteria addressed; and ISO Subcharacteristics addressed.

### 4.8.1 *Evaluation of Responses*

#### *Values and Development Criteria Addressed by Responses*

7 responses were needed to address the 16 development criteria and yielded 36 observations where potential value is identified in one or more category (platform, development, or research).

Research value is the most addressed category (15 observations), followed by development (14 observations). Key observations include:

- On average, each response addresses 6-7 criteria. Except R6, Responses address all 3 value categories (R6 does not directly contribute to creating Platform value)
- In terms of Development value, R2, R5 and R7 are perceived to address value the most in terms of number of addressed criteria and resulting value observations for each. For Platform value, this is R1 and R7; for Research, this is R2, R6, and R7
- Responses addressed Criteria 8 most frequently (serving individual rather than organization), followed by Criteria 1, 3, and 10

### *ISO Characteristics Associated with Responses*

Responses are also analyzed in terms of which ISO subcharacteristics they express. In terms of associated primary characteristics, 25/42 possible subcharacteristics were associated with responses (19 QP, 6 QU), and 17/42 remaining unaddressed (12 QP and 5 QU) (Table 4.8). Key observations are:

- Median and mode number of associated responses per subcharacteristics is 2-3 each
- All primary characteristics have at least one subcharacteristic addressed by responses, except Freedom from Risk (QU model) for which no subcharacteristics were addressed
- Three primary characteristics had all subcharacteristics addressed by aggregated responses: Functional Suitability, Usability, and Compatibility (all in QP model)
- Product Usability (QP) and Satisfaction in Use (QU) are addressed by all 7 responses, with product functionality as the next highest with 4 Responses.

Table 23. Subcharacteristics Not Addressed by Development Responses

Quality Model	Primary Characteristics	Count	Subcharacteristics Not Addressed
Product Quality (QP)	Performance Efficiency	1/3	<b>Capacity</b>
	Reliability	2/4	<b>Fault tolerance</b>
			<b>Recoverability</b>
	Security	3/5	<b>Confidentiality</b>
			<b>Integrity</b>
			<b>Non-repudiation</b>
	Maintainability	3/5	<b>Modifiability</b>
			<b>Modularity</b>
<b>Testability</b>			
Portability	2/3	<b>Adaptability</b>	
		<b>Replaceability</b>	
Quality in Use (QU)	Satisfaction	1/4	<b>Comfort</b>
	Freedom from Risk	3/3	<b>Economic Risk Mitigation</b>
			<b>Environmental Risk Mitigation</b>
			<b>Health &amp; Safety Risk Mitigation</b>
Context Coverage	1/2	<b>Context completeness</b>	

The 36 value observations presented in Table 4.6 are also linked to ISO quality characteristics to determine how development efforts can result in software demonstrating specific qualities (Figure 4.4). This table sorts subcharacteristics by the number of value observations the subcharacteristics could affect, and results are expressed as a fraction of total value observations identified for each value category (platform, development, research). Key observations include:

- The top 10 subcharacteristics most frequently addressed by Response belong to 3 primary characteristics: Usability (QP), Satisfaction (QU), and Efficiency (QU). Responses R2 and R7 are associated with the implementation of most of their subcharacteristics.
- In terms of QP subcharacteristics, Responses most frequently address Usability, followed by Functional Suitability, and finally compatibility.
- The 10 least addressed subcharacteristics are addressed by 2 or fewer Responses or Value Observations. 8 of these subcharacteristics are addressed R1 (Platform choice), and 5 are solely addressed by R1: Security, Installability, Resource Utilization, Interoperability, and Co-Existence subcharacteristics

ISO Model	Primary Characteristic	Associated Responses	Criteria	Total	R1	R2	R3	R4	R5	R6	R7	
			Total	81	10	22	7	8	10	6	18	
Quality in Product	usability	7 / 7	1	8	4	2	×	×	2	×	×	
	functionality	4 / 7	2	2	1	1	×	×	×	×	×	
	performance efficiency	3 / 7	3	11	×	2	3	2	×	×	4	
	reliability	3 / 7	4	5	1	2	×	×	1	×	1	
	maintainability	3 / 7	5	2	1	×	1	×	×	×	×	
	compatability	2 / 7	6	2	×	×	×	×	1	1	×	
	portability	2 / 7	7	0	1	1	×	1	2	1	×	
	security	1 / 7	8	12	×	3	1	1	1	1	5	
	Quality in Use	satisfaction	7 / 7	9	2	1	×	×	1	×	×	×
		efficiency	4 / 7	10	8	×	3	×	1	×	×	4
effectiveness		3 / 7	11	4	1	2	×	×	1	×	×	
context coverage		12	7	×	2	×	1	×	×	×	4	
		13	4	×	2	1	1	×	×	×	×	
14	2	×	1	×	×	×	1	×	×			
15	6	×	1	1	×	×	2	2	×			

ISO Model	Primary Characteristic	Subcharacteristic	Total	R7	R5	R4	R3	R2	R1	R6
			ll.	6	1	1	1	1	1	1
Quality in Product	usability	appropriateness recognizability	5	1		1	1	1		1
		learnability	4	1		1	1		1	
		operability	4	1	1		1	1		
		user error protection	5	1		1	1	1		1
		user interface aesthetics	4	1	1	1	1			
		functionality	functional appropriateness	2				1	1	
	functional completeness		2			1		1		
	functional correctness		3			1		1		1
	performance efficiency	resource utilization	1						1	
		time behavior	2		1				1	
reliability	availability	1						1		
	maturity	2				1			1	
maintainability	analysability	2			1		1			
	reusability	3		1	1		1			
compatability	co-existence	1						1		
	interoperability	2						1	1	
security	authenticity	1						1		
portability	adaptability	2	1					1		
	installability	1						1		
Quality in Use	context coverage	flexibility	2	1				1		
	effectiveness	effectiveness	3			1	1	1		
	efficiency	efficiency	4		1		1	1	1	
	satisfaction	pleasure	4	1	1	1				1
		trust	5	1		1	1	1		1
usefulness	5			1	1	1	1	1		

Figure 4.3. Development Criteria and Quality Characteristics Associated with Responses

Table 4.6. Values Addressed by Responses

<b>Platform Value</b>	<b>Design Value</b>	<b>Research Value</b>
<b>Response 1</b>		
Platform-independent environment with no installation (C1, C5, C9)	Data can be retrieved from cloud hosted by Pavia systems (C1)	Research methods are consistently executed through app (C2)
Collaboration is possible via RxPave, a web-based service (C1, C7)	Security is added through single-step verification log-in portal (C1)	App brings unique research to software (C4)
		RxPave makes contents of underlying research accessible for free (C11)
<b>Response 2</b>		
Time to evaluate all checkpoints or perform repetitive calculations is negligible (C1)	Users can evaluate all treatment simultaneously (C1)	Development revealed research errors and revision criteria that are addressed in the resulting service (C14, C15)
	Actions intend to minimize data entry requirements (C10)	Process revisions reduce perceived complexity, makes research concepts more accessible (C3, C8, C10, C11)
	Hides calculation complexity from user by default, but makes information available in the report (C4, C8, C10, C12, C13)	Details of calculations are preserved for research and validation purposes (C2, C3, C8, C11, C12, C13)
	Flexibly allows certain inputs to be blank but still generate results and be updated by others or at a future time (C3, C7)	
<b>Response 3</b>		
Digital medium allows app to offer non-experts on-demand access to external and in-app guidance for inputs (C3, C5, C8)	system audits user inputs to minimize occurrence of unexpected or trivial results (C3, C13, C15)	Triggers and warnings are based on findings from research and only presented when relevant and triggered by inputs (C3)
Users can update their results from any device with internet access (C7, C9)	Optional details can be hidden, allowing users to customize report displays to support user-specific objectives (C8, C10)	results include enough detail in to reproduce results externally (C3, C12)
	Dynamically generated explanations tell users how inputs affect results, helping users spot errors easily (C3, C13)	

<b>Platform Value</b>	<b>Design Value</b>	<b>Research Value</b>
<b>Response 5</b>		
Web-based platform allows data entry to be potentially distributed across multiple users (C1, C4)	Duplication reduces data entry time for projects w/ multiple segments, allows for flexible partitioning of projects (C1, C8)	App allows comparison of alternatives evaluation across segments or projects (C11)
	User feedback is a channel to provide developers with criteria for improving RxPave app functionality and guidance (C6, C7, C15)	User feedback allows researchers to identify knowledge gaps preventing users from proceeding (C6, C7, C15)
<b>Response 6</b>		
TIB's input allows them to become partially involved in development (C6)	Testing revealed differences in procedure and input interpretations, and limits of research methods (C14, C15)	
	Research was revised during development prior to release (C7, C8, C15)	
<b>Response 7</b>		
Training is interactive through in app support as -needed (C3, C4, C8, C12)	Technical details are available on demand for experts, but hidden by default for non-experts (C8, C10, C12)	Technical details are available on demand for experts, but hidden by default for non-experts (C8, C10, C12)
	In-app support repeats key details from research, allowing training to be part of the app use experience (C3, C8, C10)	Key points of research are translated into a format that can be understood by a wider audience (C3, C8, C12)
		Smaller pieces of research information are presented to users only in relevant contexts based on input values (C3, C10)

		Primary Characteristic	Subcharacteristic	Associated Responses	Development Value	Platform Value	Research Value
ISO Model	Quality in Product	functionality	functional appropriateness	R2 R3	5	2	4
			functional completeness	R2 R4	6	2	4
			functional correctness	R2 R4 R6	7	2	6
		performance efficiency	resource utilization	R1	2	2	3
			time behavior	R2 R5	6	2	5
		compatibility	co-existence	R1	2	2	3
			interoperability	R1 R6	3	2	5
		usability	accessibility	R1 R2 R3 R4 R5 R7	13	7	13
			appropriateness recognizability	R2 R3 R4 R6 R7	10	4	10
	learnability		R2 R3 R6 R7	8	3	9	
	operability		R2 R3 R5 R7	9	4	9	
	user error protection		R2 R3 R4 R6 R7	10	4	10	
	user interface aesthetics		R3 R4 R5 R7	7	4	7	
	reliability	availability	R1	2	2	3	
		maturity	R3 R6	2	1	3	
	maintainability	analysability	R2 R4	2	2	3	
		reusability	R2 R4 R5	6	2	4	
	portability	adaptability	R1 R7	8	3	6	
installability		R1	4	3	6		
security	authenticity	R1	2	2	3		
Quality in Use	efficiency	efficiency	R1 R2 R3 R5	7	3	5	
	effectiveness	effectiveness	R2 R3 R4	9	5	9	
	satisfaction	pleasure	R4 R5 R6 R7	7	3	8	
		trust	R2 R3 R4 R6 R7	10	4	10	
	usefulness	usefulness	R1 R2 R3 R4 R6	10	5	10	
context coverage	flexibility	R2 R7	6	2	6		

Figure 4.4. Associations Between Quality Subcharacteristics and Intended Value

## 4.9 DISCUSSION AND INFERENCES FROM OBSERVATIONS

### 4.9.1 *General Inferences*

*Responses generally do not address characteristics typically handled by developers*

This investigation is primarily concerned with how researchers can impact final product through the development process, particularly how research concepts are conveyed to consumers. Consequently, it is important to identify software characteristics which researchers are less capable of influencing. 5 primary ISO characteristics and their subcharacteristics appear under-represented by responses (Reliability, Security, Maintainability, Portability, and Freedom from Risk). For RxPave, the expression of these characteristics was subcontracted to a developer (Pavia Systems and TriSight). Moreover, some ISO subcharacteristics are generally less applicable to a web-based service (e.g. physical comfort, health and safety risk mitigation), and some do not apply specifically to RxPave (e.g. accountability, non-repudiation). Thus, research-oriented efforts have a limited ability to impact these and their subcharacteristics. From this perspective, it may be noteworthy that such Responses addressed any of these characteristics at all (e.g. analyzability). Accordingly, a more accurate interpretation of this work may be an investigation into software qualities that research-oriented efforts are most capable of fostering.

*Researcher efforts should focus on incorporating characteristics associated with usability, functional suitability, satisfaction, and efficiency.*

Results suggest that researchers address stakeholder goals by fostering early user involvement in development and focusing on software usability. Satisfaction and Usability characteristics were addressed by all responses, and functional suitability and efficiency were addressed by over half. These characteristics may also be related: incorporating usability features and ensuring functional suitability are key characteristics that can address desires for greater perceived workflow efficiency and consequently, user satisfaction. Moreover, the top 5 addressed subcharacteristics suggests an association among user trust, perceived usefulness particularly with product usability subcharacteristics. These findings echo literature regarding the technology acceptance model (TAM), in which perceived usefulness and perceived ease of use are identified as key indicators of technology acceptance and thus, success (Davis 1989; Wang et al. 2016).

*ISO characteristics partially or indirectly address criteria of research quality*

ISO 25010 characteristics only partially addresses how software can incorporate research effectively. Consequently, several additional characteristics are identified to draw greater attention to software qualities address the quality of research presented through software (Table 4.7). Quality in research is not intended to imply a separate quality model, but rather a repackaging of existing ISO subcharacteristics to more address research values. That is, terms are not intended to achieve the same atomicity as ISO characteristics.

Although these terms may be partially (if not fully) defined by existing ISO characteristics, the values they address are essential research requirements that deserve highlighting. Generally, research qualities are partially defined by subcharacteristics such as accessibility, functional appropriateness, efficiency, operability, learnability, usefulness, trust, or flexibility. For example, Functional Suitability partially applies to research because research quality can be characterized in terms of completeness, correctness, and appropriateness. From this perspective, the identified research quality characteristics are still useful as development criteria.

Table 4.7. Characteristics Added to ISO 25010

<b>Subcharacteristic:</b>	<b>Research Fidelity</b>
Definition:	Degree of exactness to which research is translated into software
Rationale:	Research methods may be modified during the development. Users must be informed how the changes would alter a user's expectations of results compared to the original research model. The development effort required several adjustments but preserves the original methods
<b>Subcharacteristic:</b>	<b>Result Reproducibility</b>
Definition:	Degree to which users of a software can reproduce results outside of the software environment (e.g. manually or another software)
Rationale:	Reproducible results is a common criterion for demonstrating scientific validity and research integrity. RxPave provides enough instruction such that users can reproduce results from information included in the report.
<b>Subcharacteristic:</b>	<b>Immediacy of Access</b>
Definition:	Ease to which users can locate information needed to operate the software or service as intended. That is, the degree to which background information is on-demand or easily findable when needed.
Rationale:	RxPave's tries to reduce circumstances where users stray from the app to seek help for proceeding. In-app guidance is hidden by default but users may access them on-demand in several forms and in varying levels of details within the app. This serves both expert and non-expert audiences.
<b>Subcharacteristic:</b>	<b>Context Awareness</b>
Definition:	Degree to which a software contextualizes and presents relevant points from research for users to consume
Rationale:	RxPave's input validation feature translates research into a set of logic-based warnings triggered by user inputs. Consequently, the app strategically exposes users to meaningful research recommendations only when they are relevant to a user's actions.
<b>Subcharacteristic:</b>	<b>Research Transparency</b>
Definition:	Degree to which a software presents research concepts clearly and with adequate level of detail, regardless of subject complexity
Rationale:	Complexity may be inherent to a research method, but its presentation could be simplified for non-expert users. RxPave reports results on several levels of detail to shield casual users from unnecessary complexity but makes such details available to advanced users (e.g. results of intermediate calculations).
<b>Subcharacteristic:</b>	<b>User Interactivity</b>
Definition:	Degree to which users are involved as codevelopers during the research translation, initial development, and thereafter
Rationale:	TIB's involvement during development and model validation led to several model revisions and the identification of inputs that needed additional clarification in the app. Accordingly, additional variables were added to the model to help diagnose issues with user inputs in RxPave

#### 4.9.2 *Identification of Competency Criteria (CC)*

Assessment of RxPave's development criteria and responses reveals ISO characteristics that were frequently and comprehensively addressed by research efforts (e.g. usability, satisfaction). Such characteristics are interpreted as ones which researchers can impact most greatly during development, and consequently are important to focus on. Lessons learned from RxPave's development are now generalized into a set of software competencies, or a checklist collecting essential characteristics and abilities that research-based software should be capable of demonstrating. This list can also be used to assess existing research-based products.

##### *CC1. Research-based software acquires additional funding to survive initial development.*

The development contract for RxPave is only intended to support initial software development and two years of hosting release. For this reason, additional funding sources will be required to sustain hosting or further development (Muench et al., 2010). While it is common for developers to monetize software use to generate income, this may contend with desires to make software (and research) accessible for free.

##### *CC2. Software should not impose recommendations on users but help them choose.*

RxPave provides information that support a user's ultimate decision, including additional considerations that may require further investigation. Moreover, RxPave is generalized for use outside of TIB. This allows each agency to control how the app is incorporated into their workflows while exposing them to new research concepts.

##### *CC3. Software should be precise regarding how faithfully it incorporates research methods*

Research procedures and engineering standards are frequently updated with best practices. Users must know the specific research methods a software uses to produce results in order that future results to be comparable. Thus, a software must not only relate version details, but developers should also ensure software outputs match the expectations of its end users and stakeholders.

##### *CC4. Software highlights key results and allow users to hide further details.*

Software usability was identified as a characteristic which a researcher could influence during development. In RxPave, results are structured to provide users with an overview followed by

more detailed information that can be hidden. It was important to preserve some of these details because users may review them to determine whether the result is valid, or because the detail may be useful elsewhere. To generalize this, software should address users of different levels of expertise by allowing them to hide (but not eliminate) more complex details and thus avoid overwhelming newer users.

*CC5. Software provides enough details for results to be reproduced outside of the software.*

Expanding on the previous competency, researchers may validate results by reproducing them through their own methods. To gain user trust, such details can be included in the software's outputs. In RxPave, this is addressed in the detailed reports for each paving method and providing details of the computation methods in the marketing site. Like CC4, this competency also intends to improve software transparency.

*CC6. Software allow users to learn through their experience of using the software by presenting research recommendations only when relevant to the user.*

In lieu of a standalone user manual, RxPave's trains users through in-app support and suggests resources to users based on their inputs. This means that research information or the contents of a user manual are presented to users only when it is relevant to them. The research information is formatted in short, concise messages that help users understand the consequences of their inputs. Thus, training is self-paced: optional for experienced users and easily accessible to non-experts.

*CC7. Software prevents users from generating unusable results.*

This competency intends to reduce input errors that can produce unexpected, incorrect, or trivial results. While data validation is common in software, researchers familiar with the methods are best situated to add more complex check. This may include checking whether inputs contradict each other or lay outside an expected range. For RxPave, a warning system was incorporated into the software by extracting input validation logic directly from the underlying research. When issues do arise, the interface provides informs users how to locate and address them.

#### *CC8. Software attempts to minimize effort needed for data-entry*

This competency addresses aims to reducing the amount of clerical time spent entering data and consequently maximize the value of a user's time spent. For example, RxPave allows users to duplicate segments to avoid re-entry of redundant project information. Other examples may include the ability to copy information directly into the software, providing default values, recommended value ranges, or providing additional learning resources to users. Thus, research efforts in development can affect the efficiency of software use and overall product usability.

#### 4.9.3 *The Value of Research-based Development*

Based on the assessment of RxPave's development, this study defines how research-based development can create value for the paving industry:

*Platform Value.* RxPave helps TIB convert a workflow into a paperless process and generalized for use by any US transportation agency responsible for maintaining low-volume roads. Moreover, the software chosen platform as a web-based application improves the accessibility and exposure of underlying research.

*Development Value.* Responses to RxPave's development criteria were primarily oriented towards creating a structured analysis environment that allows users to customize their learning and use experience. Thus, research-based software creates value by improving usability: allowing users of various expertise levels to learn the software at a self-paced rate and request help as-needed. This research considers this valuable because users are guided to meaningful results without requiring a standalone training session.

*Research Value.* Researchers familiar with the underlying research are well-positioned to impact development because they can identify the contexts where research is most relevant to present to users. This is considered valuable because a software medium helps advance research methods into practice as well as gain greater exposure. Moreover, the development process has provided opportunities to evaluate knowledge requirements that could prevent users from consuming the app as intended.

## 4.10 SUMMARY AND CONCLUSIONS

This investigation has presented a structured assessment of RxPave's development process with the intention of deriving development best practices. Lessons learned from RxPave's development

are generalized into eight competency criteria that address how research can be effectively incorporated into software intended for the paving industry. Such criteria were chosen because they reflect areas that research expertise was particularly impactful during the development process of RxPave (Table 4.8). Moreover, these competency criteria address the software characteristics frequently associated with the development criteria and responses identified for RxPave (Figure 4.1, Figure 4.2).

Table 4.8. Competency Criteria Generalized from RxPave's Development

<b>Criteria</b>	<b>What Software Should Do / Demonstrate:</b>	<b>Relevant Characteristic(s)</b>
1	Software acquires additional funding to survive initial development	Accessibility, Trust
2	Software should not impose recommendations on users but help them choose	Usefulness, Flexibility
3	Software should be precise regarding how faithfully it incorporates research methods	Functional Correctness, Research Fidelity
4	Software highlights key results and allow users to hide further details	Usability, Appropriateness, Recognizability
5	Software provides enough details for results to be reproduced outside of the software	Usability, Trust, Effectiveness, Usefulness
6	Software allow users to learn through their experience of using the software	Accessibility, Learnability, Efficiency, Time Behavior
7	Software prevents users from generating unusable results	Usability, User error protection
8	Software attempts to minimize effort needed for data-entry	Usability, Efficiency, Time Behavior

This research also identifies characteristics (in addition to ISO 205010's) that more specifically address how research is incorporated into software, such as procedural fidelity and result reproducibility. Software characteristics are defined to focus on research-specific qualities because they generally are not addressed by developers. Thus, this research identifies an area in which expertise in paving knowledge can influence the quality of software development.

Ultimately, this research intends to demonstrate the value of research about research in context of software: software or services can be given characteristics thought to provide value to its users in both streamlining workflow and knowledge transfer. Such efforts can help result in the early detection of procedural issues and errors, improved software error tolerance, gaps in knowledge and interpretation, and improved accessibility by non-experts. As the paving and construction industry seek to mobilize new and older generations of research-based software to support engineering needs, this investigation demonstrates that additional value generation is possible through strategic choices in development and the translation of research.

## Chapter 5. SYNTHESIS AND APPLICATION: LEVERAGING RESEARCH KNOWLEDGE IN SOFTWARE

### 5.1 SUMMARY OF FINDINGS: LESSONS LEARNED

#### *Key Findings of Investigation 1*

Agencies want to enable additional capabilities through IT-enabled software and services but are unclear on meaningful best practices or sustainable development strategies. As such, DOT issuance of mobile devices often lack specific purpose and miss opportunities for studying mobile IT benefits. The first investigation (Chapter 2) finds that DOTs and the general pavement industry issue a variety of devices to employees, but the preferred operating system for each depends on the platform. DOTs are particularly motivated by equipping its workforce with mobile technologies, but seldom provide device, software, or security training. Moreover, DOTs still adopt technology at substantially different paces. Appearing cautious towards outsourcing IT, many DOTs still prefer to internally manage data or software services. This practice stands in contrast to outsourcing of Engineering services to consultants, a common practice among state agencies and driven by desires to reduce full time employment as well as obtain expertise absent within the agency (Olsen et al. 2013b; Taylor et al. 2013; The PFM Group 2016). Consequently, platform-independence (or multi-platform availability, such as web-services) should be a prime consideration in software selections to accommodate a maximum variety of devices.

Investigations also reveal that agencies commonly allocate resources to creating tools that generally attempt to mobilize research concepts or methods into practice. DOTs see these efforts as valuable, as evidenced by the abundance of in-house software developed with similar goals. However, research efforts rarely directly result in software. Generally, these tools provide proof-of-concepts for new research methods, revise or improve upon existing analysis method from previous research projects or provide support for decision-making. Such efforts frequently struggle to sustain funding beyond their initially contracted development (AASHTO2016; Muench et al. 2010). While DOTs possess the construction domain knowledge to create software tools, they may lack the IT or development skills create practice-ready products. DOTs interested in translating research into such should consider development models that can sustain funding beyond original development and integrate both construction and IT industry domain knowledge.

*Key Findings of Investigation 2*

Consumption trends indicate that users seek knowledge content on-demand and frequently attempt to learn through their use experience. The second investigation (Chapter 2) found that users have consistently consumed Pavement Interactive, a web-based knowledge repository, as quick-reference tools over the last decade. This is evidenced by a combination of high acquisition rate from search engines, short page durations (a few minutes), and consistent return rates amid evolutions in audience demographics (location), traffic volumes, and modes of acquisition (device and platform choices). Given that nearly all content curates peer-reviewed and technical publications, the research component yields few if any directly comparable examples. Thus, this research also serves as second benchmark of PI, corroborating the findings of Muench et al. (2010).

By comparison, users spent more time on average in PaveXpress (particularly return users) and have created nearly 18,000 unique projects despite less than 2% of users viewing any of the available resources or knowledge made available for the service. Although the affiliation of most users was not inferable (i.e. users had commercial gmail, hotmail, or yahoo domains), over 250 unique government and educational subdomains were detected; the highest among any other kind of domains. While many interpretations are possible, the findings highlight a potential disconnect between content format and consumption behavior. Users are attempting to learn through using the service: this provides an opportunity to incorporate some of the otherwise unseen research content as an optional part of the use experience itself. Consistent with how users consume PI, a suitable format for such content may be referential and presented in contexts most relevant to the user as they experience ('fill out') the app. This kind of experiential learning contrasts with the more linear or structured approaches (standalone user manuals, dedicated training sessions) to learning the service or required background knowledge.

While the standard version of Google Analytics provides sufficient resolution to identify broad trends in behavior regarding website use and user preferences, it is insufficient to characterize user behaviors in greater detail by default. Although additional event tracking in GA would provide greater insight into more specific behavior, greater focus is placed on improving the delivery of research knowledge to users. Accordingly, agencies should evaluate the alignment between resources required to generate training documentation for research-based services and consumption habits of its end-users.

### *Key Findings of Investigation 3*

In addition to demonstrating quality characteristics in product and use, research-based software must also demonstrate quality in the process of translating research for software use. The third investigation (Chapter 3) focuses on identifying (or defining) criteria to evaluate the quality of translation of research into practice-ready software. As the project is a joint effort between government agencies (WSDOT, TIB, FHWA), private developers (Pavia Systems), and an academic institution (UW), this study also reveals the capacity of researchers to affect the translation and implementation of research into software through decisions in the design process. By documenting the development process, this research demonstrates how research content may be appropriately formatted for consumption through a web-based app. Starting with standard software quality characteristics defined by ISO to describe responses, the study also defines additional criteria that are necessary to specifically address the quality of research, for example: result reproducibility, procedural fidelity, and context awareness.

This study identifies how pavement researchers can positively impact the development of research-based software. More specifically, researchers were able to address value in terms of development and research quality. It was also necessary to identify additional software characteristics (beyond those included in ISO 25010) to address qualities that are more critical to researcher values. Ultimately, expertise from pavement engineers can have several positive impacts on the development process: early detection of procedural errors, improving software error tolerance, and improving accessibility to non-experts. The research culminates with a set of eight competency criteria or sets of software characteristics or abilities that research-based software should be capable of demonstrating (Table 4.8). These criteria generalize lessons learned from the development of RxPave and previous investigations into a checklist that agencies can use to evaluate other research-based software tools for use in the paving industry.

## 5.2 APPLICATIONS TO RESEARCH-BASED SOFTWARE FOR PAVEMENTS

The findings of this investigative body are now applied to assess the effectiveness of existing pavement research software (introduced in Chapter 1.1) using the competency criteria identified in Chapter 4. The author's research background and professional experiences with research-based software over the last six years provides additional rationale for observations and

recommendations. Each assessment characterizes the gap between a software practice and the state of research it encompasses, as well as inform potential response efforts.

### 5.2.1 *Assessment: Pavement Design Methods Revisited*

Empirical methods can be executed relatively quickly and are among the most frequently used methods in practice among US DOTs (Figure 1.4, Figure 1.6). Although newer and more accurate pavement design methods exist (Chapter 1.4.2), widespread practice of empirical methods are likely to continue until agencies can resolve the technological and data challenges surrounding MEPD's calibration and agency-wide practice. Pavia Systems developed PaveXpress with the intention of bringing empirical pavement design to a web-based platform. Table 5.1 applies the competency criteria defined previously to identify how pavement design software could generally improve upon its delivery of research content.

### 5.2.2 *Assessment: Life Cycle Cost Analysis Revisited*

The distribution of strategies DOTs has undertaken to implement LCCA software suggests practices vary widely and suggests that they generally struggle to incorporate user costs. None of the existing tools are available in web-based formats and thus, recommendations here may be used to inform future development efforts (such as PaveXpress LCCA). A primary challenge of using LCCA software is having relevant data to support input values, or comparable projects from which values could be potentially inferred (Flannery et al. 2016). As such, availability and accessibility to required data is a key barrier and data collection policies are typically beyond the scope of software development itself. Table 5.2 evaluates two available LCCA software using the previously defined criteria competency and identifies considerations that inform future LCCA development efforts for agency practice.

### 5.2.3 *Assessment: Methods for Construction Planning Revisited*

The underlying research and concepts behind CA4PRS remain fundamental today in ABET accredited civil engineering programs: construction equipment, scheduling, planning, safety, cost analysis, and engineering economics. Given the software's substantial learning curve and the paucity of resources that specify its knowledge requirements, CA4PR is a challenging software to

learn. Table 5.3 below uses competency criteria to identify what a potential redevelopment effort for CA4PR should address.

Table 5.1. Competency Assessment for Pavement Design Software

CC	Assessment of Currently Available Software for Practice
1	PaveXpress Design is one of the few web-based options available but has no active funding to address accumulating bugs or updates. Agencies must consider the value of allocating resources to preserve such tools or accept limited alternatives.
2	PaveXpress avoids being overly precise in its recommendations, limiting reported accuracy for pavement thickness to the nearest 1/2 inch. Structural number and intermediate calculation are provided so that users can perform their own conversions to physical thickness. The service provides links to resource to assist report interpretation.
3	For rigid pavements, PaveXpress uses a modified version of AASHTO98 to simplify calculations but replicates AASHTO93 exactly for flexible pavements. Methods for porous pavements are available as experimental methods but not validated for practice. These points are conveyed in standalone support documents.
4	PaveXpress allows users to enter inputs directly or provide additional inputs to have a value calculated from research methods (e.g. subgrade modulus). Tooltips and tutorials are available through small icons, but not required. In some contexts, users can choose alternative methods to perform assessments and create comparable results. The report currently offers little to no customization regarding detail of results, however.
5	PaveXpress reports few important intermediate calculations, and users cannot request different levels of detail. Additional intermediate calculations would be useful to those interested in modifying or hybridizing the procedure, validating PaveXpress against external calculations, or diagnosing discrepancies with greater precision.
6	Most variables include tooltips that define inputs, clarify format expectations. Instructional videos are available for each section of inputs (up to 7 depending on project type). However, recommendations for variable inputs are limited.
7	To avoid unintended uses, the service makes certain analyses available for combinations of road classifications and pavement types. Most variables are validated for format, but feature no checks to assess whether inputs combinations are realistic
8	Some attempt is made to reduce complexity by allowing users to override calculations, as well as choices regarding how certain values are approximated (e.g. design life ESALs). Results are rounded to the nearest half inch and ranges are limited to applications 6-16 inches, so further reduction of model complexity is possible, e.g. through visually interactive solution tables. Further strategies to facilitate data entry may include allowing users to define default values or recommended input ranges.

Table 5.2. Competency Assessment for LCCA Software

CC	Assessment of Currently Available Software for Practice
1	The software is still available through the FHWA has not updated its research contents since its initial release in 2002. Pavia systems is currently in the process of re-imagining this tool for web-based use with no scheduled public release date.
2	Both RealCost and PaveXpress avoid being overly prescriptive by visualizing results that allow users to support their own decisions or conclusions.
3	Procedural fidelity is difficult to determine given the multiplicity of alternative methods for estimating specific inputs (e.g. lane capacity, user cost). Because the methods rely on outdated design standard, users must accept this or calculate such parameters externally prior to using either software. The application should directly clarify which individual methods are used in the analysis.
4	Both RealCost and PaveXpress attempt to customize apparent complexity by providing users with alternatives for entering certain inputs. Users can incorporate statistical uncertainty by describing certain inputs probability distributions rather than single deterministic values. LCCA methods rely on reference tables subject to research updates (HCM methods, user costs, etc.). However, users are unable to change the way methods operate in the service but can enter values calculated separately from the software.
5	Much of the underlying complexity is hidden from the user, making it impractical (but still possible) for users to reproduce externally. Underlying methods are not available in the user manual for RealCost, but through external links to research and methods on FHWA's website. Traffic calculations that provide the basis for user cost calculations is unclear and could greatly benefit from clarification in the report. Probabilistic results are difficult to verify externally save other than repeating simulations.
6	PaveXpress attempts to present research concepts through tooltips. The learning curve for LCCA is complicated by including standards that average users may be unfamiliar with (e.g. traffic engineering, geometric design). The overall structure of LCCA's procedure is not immediately apparent to users in the app itself. As best, the user manual only provides instructions for navigating the app and requires external resources to provide a more complete explanation of background research concepts.
7	PaveXpress and RealCost provide limited checks for logical consistency among inputs and attempt to narrow pathways to unmeaningful results through tooltip recommendations. Additional warnings would be beneficial by auditing lane capacity calculations, unexpected rates (e.g. traffic mitigation measures).
8	The nature of inputs for LCCA is highly repetitive due to the repetition of maintenance events, hourly traffic data, and calculations for lane capacity. Project alternatives often have only slight variations. Both software address this by allowing duplication of maintenance events (and associated data) which users can subsequently edit. Only RealCost tool allows users to set up some default input values or agency-specific preferences, and entry of traffic data is equivalently tedious (24 inputs for each pattern).

Table 5.3. Competency Assessment for Construction Productivity Software

CC	Assessment of Currently Available Software for Practice
1	Intellectual property for CA4PRS was transferred to Pavia Systems in 2016. Currently, efforts are underway between CalTrans and Pavia systems to re-imagine the software as a web-based service. No public release date has currently been set.
2	The software provides a structured environment to perform productivity, traffic, and cost estimations simultaneously. While resulting reports provide details that reinforce the strength of its findings, the user manual provides little guidance regarding how users should interpret the report and improve their simulations.
3	Functionally, the software successfully combines methods from research and existing standards into a single interface. However, precise calculations details frequently absent from the user manual or software itself. Thus, it is challenging to determine how faithfully the software reproduces methods from research, or whether new methods were introduced to facilitate development.
4	Users have limited customization options for methods or data borrowed from standards (e.g. HCM, user cost values). Users cannot update these values manually and must resort to workarounds cause results to align with expectations. The software contains some customization features: default rules for closures, changing unit systems, default unit cost prices, and adjusting simulations settings for probabilistic analysis.
5	Many calculation methods used in the software are implicit and not fully explained in the user manual (e.g. truck cycle times and lift sequences for HMA pavements). Consequently, it is challenging for new users to understand whether results are reasonable, or for experts to quickly check intermediate calculations for verification. Moreover, probabilistic results are not exactly reproducible by nature.
6	In-app guidance or training is largely absent, and the software largely relies on the user manual to provide instruction to users. Several inputs feature help buttons, but the actual support provides frequently does little to help users proceed or diagnose issues
7	The software does not validate data entry, frequently allowing users to enter invalid or inconsistent inputs. This frequently cause the software to shut down unexpectedly and provides no context for the user to troubleshoot the issue. Expect users may be able to detect these, but new users will typically struggle to identify incorrect inputs.
8	Many users (particularly new ones) struggle to know what reasonable input values are and have requested recommended ranges or default values for help. Projects with multiple segments can duplicate existing segments to reduce entry time. Data entry for traffic data on an hourly basis is tedious and required for each new project.

### 5.3 IMPLICATIONS TO AGENCY PRACTICE AND PAVEMENT RESEARCH

American Society of Civil Engineer's (ASCE's) vision for the Civil Engineer in 2025 (2007) highlights five areas of competency, including "Innovators and Integrators of Technology" but observes that:

*...civil engineers are sometimes viewed as reluctant to embrace new technologies ...the civil engineer's first impulse may be to follow current regulations and implement what has worked well in the past. That may provide a level of comfort for the practitioner but slights potential performance and life-cycle cost opportunities for the client and the ultimate users*

*...Government, academic, and private research initiatives often carry out their work in a context of fragmentation, without resources being focused for greatest impact. Civil engineers must become engaged and serve as leaders across all sectors for advances in research to be achieved, accepted, and implemented. Such cross-sector coordination ties into the civil engineer's goal of integrating a variety of new technologies into their projects: Applied research with clear practical application must receive adequate support. Learning from past engineering failures remains important, as does promoting multi-national exchanges so that civil engineers can learn best practices...*

Software based on pavement engineering research makes construction data actionable in practice, providing structure to and association among research concepts. In this manner, such software allows data to retain the potential for providing analytical value, including and extending beyond its initially intended use (e.g. a project) as well as making archiving data more purposeful. Synthesizing the previous investigations, four discussions address the larger implications of this work in the context of software development for agency use and ACSCE's vision for the civil engineer of 2025.

#### 5.3.1 *Emerging Technical Skills for Civil and Environmental Engineers*

ASCE's vision implies civil engineers will expand their required knowledge base or skillsets needed to leverage technology effectively. However, this vision does not identify technical skills explicitly nor how these skills can be incorporated into traditional civil engineering curriculums. A primary DOT objective for technology integrations is to maximize the time engineers spend on meaningful tasks as opposed to clerical ones. Based on the issues currently faced by the paving industry and the lessons learned from this body of research, the author recommends appending

several technical skills. Alternatively, agencies may also consider the list of added capabilities substantial enough to warrant its own full-time position, team, or department.

*Ability to translate research into code and think abstractly*

This research demonstrates the extent to which academic efforts can affect the development of software, as well as limits. Researchers generally have the best understanding of research concepts and are best positioned to ensure such concepts are properly incorporated into software. Accordingly, researchers in pavement engineering may be required to demonstrate a higher baseline ability to translate research concepts into a language understood by developers. Hence, a basic proficiency in coding or understanding of development conventions is vital.

*Ability to process and model raw data.*

Agencies are dealing with greater volumes of incoming data and at increasing velocities. Engineers may be increasingly tasked with managing such datasets in ways that allow data to be reused for later purposes. Accordingly, engineering should possess a greater capacity to: extract and manipulate larger volumes of data (coding skills); query and connect different data sets (data modelling skills); reshape data fluidly between database and spreadsheet formats to accommodate analysis (data analytics); and generate interactive data visualizations.

*Ability to document information or knowledge for later use*

Agencies want to use technology to assist in capturing the expertise of its workforce so that it remains accessible to other and future employees to consume. Consequently, engineers must become proficient in documenting and storing information in ways that allow easy retrieval and formatted so that viewers can further manipulate or extract information from them. That is, documentation practices should be increasingly flexible and decreasingly one-size-fits-all.

*Ability to incorporate the needs of private, academic, and public stakeholder in development*

In this research, each institution supplies a core expertise that makes the software development more purposeful and appropriate: academic institutions provide expertise in research and insight regarding learning; public organizations provide resources and identify parameters for useful practice; private developers supply expertise to transform research prototypes into practice-ready

services. Each institution is providing a vital perspective that collectively maximize the resulting tool's effectiveness, and as such, civil engineers must be capable of understanding and incorporating the objectives of each in development efforts.

### 5.3.2 *The Life-Cycle of Data: A Data Driven Perspective*

*The life of data must outlive the software that houses it for further value to be extracted*

The lifespan research-based software is often shorter than the practice of its underlying research. Discontinued development is a common reality, as is true for several case studies presented in this research (e.g. CA4PRS). To extend the value of results produced by software (e.g. for asset management), results and input data must be easily extractable from the software. Given this perspective, additional focus on the life-cycle of such data is warranted. Moreover, data is not useful simply in archived form; greater focus should be placed on what makes it useful.

There are several immediate implications of a data centric perspective: first, archived data often incurs a small storage cost to host but not all data is inherently valuable. However, it may be difficult to anticipate which data is worth preserving. Second, software without data extraction features can limit the value of the data and software. Third, without proper documentation, archived results may be not be reproducible or comparable.

This discussion should interest agencies who seek to understand how choices in software adoptions can address goals to retain a knowledgeable and capable workforce across generations of a specific software tool. Indeed, the added considerations for supporting IT infrastructure and documentation may partially explain why software adoption efforts require more resources and time than agencies initially estimate.

### 5.3.3 *Harnessing Connections between Research Methods*

The flow of data across multiple research-based software in pavement engineering should inform which research methods are the most viable candidates for software application.

Examining the flow of data through these methods has revealed these commonalities and associations, including most research-based software presented in this work. Such connections between software are increasingly identifiable as more software tools were developed and (indirectly) define boundaries between concepts through data requirements. Moreover, such

boundaries also suggest that some topics are modular and can be disaggregated from a software package for other applications.

The same construction data is frequently shared among concepts, and the results of analyses often have cascading consequences in other associated tools. But as these software features multi-disciplinary methods within civil engineering, data silos among input data may complicate the effective practice of these methods. Whether data silos exist among departments or technological platforms, the research methods are highly data driven and their preservation and leverage are inherently data-oriented. While it is unclear whether the industry exploits data connections between methods, this research highlights potential connections that could streamline data pipelines for existing and associated concepts (Figure 5.1).

The figure illustrates four classic pavement engineering topics represented by the software examined in this work, potentially related research processes, and the types of construction data or information that flows through them. For example, a construction engineering software like CA4PRS requires inputs from pavement design (material layers and thickness) as well as concepts from traffic (lane capacity and user delays), and subsequently supplies information to asset management related efforts (life cycle cost analysis). Moreover, some of the data supporting these processes is essential to facilitating accurate life-cycle based processes ('Related?'), such as Life Cycle Assessment, and Environmental Product Declarations.

While new research or standards may update practices and cause certain software tools to become obsolescent, the connections between research concepts would remain relevant. For example, regardless of how pavement design methods change, the methods always produce the same type of actionable information: geometry and structural requirements from which construction productivity methods are based. This discussion compliments the previous regarding why a life-cycle perspective for construction data is relevant: the multiple connections defined by data are relevant even as practices changes, and thus data preservation may be of commensurate importance as preserving the software that acts on it.

Peer-reviewed literature tends to place heavier focus on creating or identifying new concepts, and less frequently on finding the connection points between software. Research-based software provides an opportunity to identify links between research knowledge and software, as well as research opportunities to better characterize the cascading impacts of specific input data on a larger set of engineering analyses.

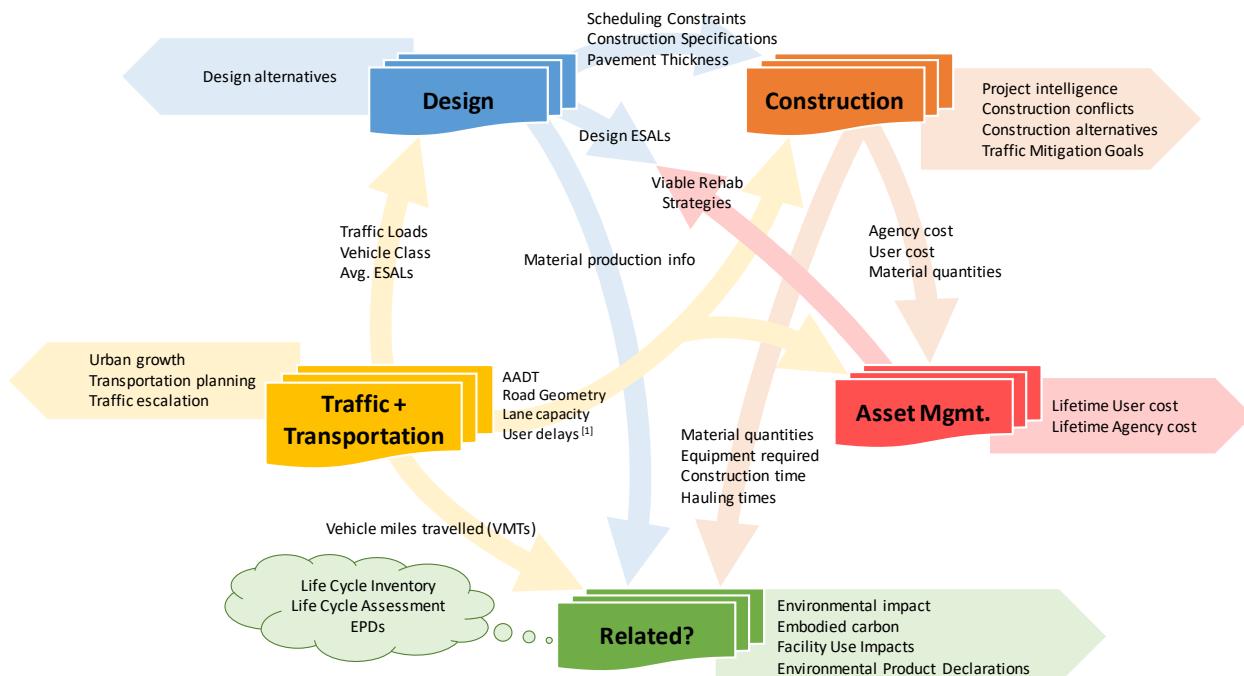


Figure 5.1. Data Connections Among Pavement Engineering Software

#### 5.3.4 Knowledge Transfer and Outsourcing: Competing Intentions

*Research-based software could address the contention between outsourcing expertise consultants and efforts to harness in-house expertise and experience.*

While outsourcing may address immediate needs for expertise missing in-house, such actions leave less opportunity to generate further in-house expertise or providing learning experiences for less-experienced employees. Moreover, literature has found that while DOTs commonly outsource engineering expertise to consultants, they are less willing to outsource IT responsibilities compared to most industries (Taylor et al. 2013; The PFM Group 2016). Collectively, such actions suggest that agencies are unclear how to train and retain a more capable (competitive) workforce while reducing operational costs.

This research has shown how strategically developed research-based software can potentially mitigate this contention by addressing training and knowledge requirements through quality documentation and the product itself. The process of translating research into software provides an opportunity to extract actionable parts of research and identify the appropriate contexts in which the research knowledge is relevant. Moreover, this process audits the research itself by identifying translational issues (steps must translate into machine language), errors in research or

updates to standards, potential knowledge barriers, further research opportunities for validation, or connections with other associated research methods. The benefits of addressing such considerations manifest in the internal logic of the software and more visibly through documentation and resources offered with (or in) the service. Thus, research-based services may be an appropriate medium to incorporate the expertise extracted from more experienced employees, as well as for inexperienced employees to acquire this knowledge.

## 5.4 CONCLUSIONS

State transportation agencies have sought to mobilize pavement research into practice through various digital tools such as software and web-based services. Facing an impending retirement bubble, a less-experienced workforce must handle a larger road network with fewer human resources. Consequently, agencies have trended towards outsourcing engineering expertise while seeking ways to capture and leverage the expertise of the existing workforce. To inform these long-term agency objectives, this body of research performs three independent investigations that characterize the types of values agencies may extract from developing and consuming research-based software in the pavement engineering industry.

The first investigation on information technology consumption trends over the last decade reveals that agencies are still seeking guidance in how to realize the value of information technology and software by making investments more purposeful and worthwhile. A second investigation of Google Analytics data available for two web-based services reveals additional consumption trends on a user-level. Analysis of available data implies that users value services as reference tools but spend insufficient times to suggest thorough consumption of content. Moreover, the data suggests users value the ability to request information as-needed and attempt to learn the app through their use experience rather than through structured training resources. The findings of these two investigations are subsequently used to inform the development of RXPave, another research-based web-app. This third investigation documents the development process and uses standard software quality characteristics defined by ISO to determine how researchers can maximize their impact on the resulting tool in terms of effectively delivering research knowledge to its users. Resulting from these investigations, eight software competency criteria are identified to create guidelines for evaluating the quality of research manifested through the service itself (Chapter 4.9.2). These criteria are finally applied to three well-established research concepts

in pavement engineering and their corresponding software to inform the state of their practice relative to research.

Regarding platform value, this work finds that researchers can influence the final product by creating precise development requirements and expectations, but otherwise have minimal ability to influence the specific value users receive from the platform itself. The investigations find that users often enjoy passive platform benefits such as: improved access to content due to multi-platform or platform-independent mediums such as web-based services; a channel in which user can communicate with developers and agencies; and an increased capacity to collaborate through file-sharing. Although this research was unable to describe user behavior precisely, this research found minimal evidence of project collaboration for the web-based app. One explanation may be that platform capabilities are frequently enhanced by evolutions in baseline IT capabilities, but not necessarily harnessed in practice. Therefore, this research recommends that agencies develop precise competency criteria to help them select software or services that strongly align with agency platform needs. In addition to addressing the product itself, such criteria should also encompass the quality of training documentation and available guidance through the service interface itself. Defining such criteria may help agencies distinguish between purposeful development features versus passive benefits that would automatically result from the chosen platform.

This work also finds that development and research value are difficult to disaggregate because development decisions frequently address both types of value, even if indirectly. Development value ultimately refers to how development decisions benefit the user and focuses more on the format and presentation of content to the user, including training documentation. By comparison, research value refers to how the process of development informs, improves, or extends the body of existing research and focuses more on findings revealed through process of research translation and development.

In terms of development value, this work finds that a strategic formatting and presentation of content within the service itself can address the resulting product's perceived competency and usability. Prior investigations show that users consume knowledge resources as quick-reference tools and request knowledge on-demand. To deliver content that aligns with this observed behavior, this work recommends that development efforts attempt to incorporate learning into the experience of using the app itself. This creates an opportunity to incorporate development value because researchers are most capable of identifying the use contexts or circumstances in which

relevant research information can best guide users to meaningful results while also providing an opportunity for learning. However, not all research methods can be adequately addressed through referential documentation or in-app guidance alone, and not all documentation efforts are effectively consumed. Unstructured learning content may be appropriate for simpler methods, but complex or data-heavy methods may justify more traditionally structured instruction or additional in-person training. Even in such cases however, research and developers may add value by generating more interactive, referential documentation to supplement structured training requirements.

In terms of research value, this investigation concludes that the process of translating research and developing software effectively forces an audit of the underlying research itself. In addition to standard software quality characteristics defined by ISO, this research identifies criteria necessary to adequately address the quality of research translation. The work defines a set of eight competencies that can be used to assess other research-based software in pavement engineering (Chapter 4.9.2) and a checklist of potential documentation contents (

Table 4.5). Effectively, efforts to create research-based products help transform what tend to be research prototypes from proofs of concept into practice-ready tools. By applying these competencies to examples of research-based software (Chapter 5.2), this research demonstrates that the translation process can: reveal errors in the underlying research and provide a basis for revisions, identify contexts in which appropriate guidance can resolve knowledge gaps or data barriers, and reveal additional patterns in consumer behavior. Such information can be extended into additional research opportunities by identifying further applications for input data, result outputs, or integrations with associated research concepts. Overlapping with themes of development value, the processing of auditing research may also document quality by ensuring its format is more purposeful and better aligned with consumer behavior in addition to agency goals.

Ultimately, this work has found that research-based software provides an infrequently addressed medium for providing knowledge content or training and attempts to benchmark a decade's worth of industry interactions with information technology and research in practice. Given the relatively shorter lifespan of software versus the timeline of research in practice, this work underscores agencies' challenge of sustaining continued development and funding beyond proofs of concepts. While technology evolutions continue to improve baseline software

capabilities, this research recommends that agency data governance plans better incorporate a life-cycle perspective of data to support greater future attempts to leverage data across multiple services and beyond the life of a software itself.

An agency's interest in and ability to support research-based development may be driven by presently available funding and the types of work being prioritized at a particular time. As such, long periods may elapse before proofs-of-concept from research receive funding for development into software. In this manner, development of research-based software may be substantially driven by federal and local funding levels because they influence the types of road projects pursued, and consequently, the research concepts well aligned for practice. As such funding is cyclical, questions regarding criteria for technology selection will remain relevant in the future. It is therefore in an agency's best interests to recognize and develop quality criteria for software that best addresses the needs of their agency and most importantly, its ultimate consumers.

Research on research-based software is a niche topic in construction engineering that may become an increasingly valued avenue of research because it attempts to mitigate barriers separating research and practice. Moreover, the industry's growing affinity for deploying information technology may herald a new generation of construction engineers whose core skill sets feature greater familiarity with and competency in computer science, data science, and information technology to compliment those traditionally expected of a civil engineer

## 5.5 RESEARCH EXTENSIONS

### 5.5.1 *Enabling Associated Research Concepts*

This body of research attempts to synthesize and assess a decade of software practices by examining a set of previous efforts to develop software from construction engineering research. However, the research concepts presented in this work are motivated by the author's associated research, professional, and teaching experiences, access to software intellectual property and private use data. Other collections of research concepts likely exist within civil or even construction engineering and are similarly unified through results or data in-common.

Ultimately, this research embodies a shift in research focus in which identifying the multiple data connections takes priority over the specific data connections within a specific piece of software (Rezgui et al. 2011). Consequently, this research recommends tracing such data

connections to identify associated research concepts that becomes easier to mobilize as a result of existing software or data uses. The goal here should be to identify methods that can be enabled by harnessing existing data prior to launching efforts to collect new data just to support to method. As suggested in Figure 5.1, life cycle inventory, life cycle assessment, and environmental product declarations are three such examples of immediate conceptual ‘neighbors’ of pavement engineering concepts. These are data-driven concepts heavily rely on key pavement design decisions that affect pavement geometry and material production, as well as construction logistics which contribute to embodied carbon calculations.

### 5.5.2 *Questions Requiring Further Investigation*

#### *Criteria for Documentation*

This research also establishes that observed consumption habits do not align well with traditionally structured training documentation. However, it is unclear how the appropriate extent of documentation can be determined. In this research, documentation has been frequently addressed a weakness of research-based development but that researchers are qualified to generate this content. Further investigation could address criteria for research software documentation to improve software quality. These efforts should reveal criteria that help agencies produce more cost-effective documentation that better aligns with the consumption habits of its intended users. Research of this nature can inform which concepts are appropriate (or inappropriate) for consumption through software or reveal the additional learning requirements that cannot be addressed by in-app documentation alone.

#### *Limitations to Google Analytics*

The resolution of Google Analytics data was able provide general behavioral trends regarding acquisition and general use levels but unable to inform precise user behavior during app interactions. Although extracting greater resolution data is possible, it is unclear whether such efforts would be useful. While such analytics could provide finer details regarding the app’s health and performance, the data isn’t actionable without specific questions. Whether this intelligence of software health can be leveraged has yet to be established.

### 5.5.3 *Relevant Avenues of Research*

*Should research-based software be free to access or a paid service?*

Research-based software requires a sustainable source of funding to maintain hosting requirements or updates to software functionality. However, it is unclear how research-based software released as freeware can sustain continued funding to support future development or additional content without monetizing the service. Conversely, monetizing service use may reduce the software's accessibility and exposure of its underlying research. Further research may help identify viable development strategies for research-based software. As well, clarifying the boundaries between ownership of data and research knowledge may become increasingly important as more research concepts are translated into software. While agencies have yet to address these potential barriers, their consideration remains essential to the advancement of research-based software.

#### *Gamification and Learning Systems*

A key concern of agencies is to improve and retain a knowledge, competitive staff of employees across workforce generations. Research-based software may help mitigate training requirements, but the way such software delivers training has substantial room for improvement. In this regard, the video game development industry may have meaningful recommendations for software documentation best practices. The video game development is \$90+ billion-dollar industry that places substantial emphasis on data security and privacy among its user (a growing concern among agencies) (WePC 2019). The median age of video gamers players worldwide is 33-37 (WePC 2019), suggesting that the engineering workforce may see a larger percentage of users highly familiar with training conventions presented in video games and entertainment software.

The video game design industry has also addressed software documentation and training content through a vast library of diverse products for nearly 30 years. Video games handle the user's learning experience in four distinct manners, and the success of each is product specific (Davis 2009; Fahey 2016; Fletcher 2010; Suddaby 2012). These are:

- **No training resources:** Software is intended to rely on a user's knowledge, instinct, or external/community-based information (inappropriate otherwise)
- **Static Exposition:** Information is presented in a standalone, non-interactive and often linear manner; users are likely to disrupt their use experience to reference information repeatedly throughout their learning experience
- **Guided Tour Space:** Users are guided in an interactive, self-paced manner through a simplified version of the actual software environment; the linear experience demonstrates

one possible pathway to completion, supplies example data, and provides more explicit warnings regarding unintended or erroneous user actions

- **Context-based learning:** Short sets of instructions or bits of knowledge are introduced in specific, relevant contexts triggered by user interactions; these lessons can blend into the software's interface or disrupt the use experience until acknowledged by the user

Video games trending towards the later methods have encountered greater success (Jamieson, 2015; Suddaby, 2012), and such methods resemble the recommendations identified for RxPave. Therefore, research into alternative training strategies for research-based development can inform efforts to improve knowledge transfer within DOTs. Such research efforts would help enable a long-desired ability in the field of civil engineering: the ability to predict the potential consequences of changes to data in a cascade of inextricable engineering analyses, on-demand.

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## APPENDIX A. LIST OF ABBREVIATIONS

Table 5.4. List of Abbreviations

<b>Abbreviation</b>	<b>Description</b>
<b>AASHO</b>	American Association of Highway Officials
<b>AASHTO</b>	American Association of Highway Transportation Officials
<b>CA4PRS</b>	Construction Analysis for Pavement Rehabilitation Strategies
<b>CalTrans</b>	California Department of Transportation
<b>CC</b>	Competency Criteria (of Research Based Software)
<b>CIC</b>	computer integrated construction
<b>DIKW</b>	Data, Information, Knowledge, Wisdom
<b>DOT</b>	Department of Transportation
<b>ESAL</b>	Equivalent Single Axle Load
<b>FHWA</b>	Federal Highway Administration
<b>GA</b>	Google Analytics
<b>ISO</b>	International Standards Organization
<b>IT</b>	Information Technology
<b>JIT</b>	Just-in-Time (aka On-Demand)
<b>LCA</b>	Life Cycle Assessment
<b>LCCA</b>	Life Cycle Cost Analysis
<b>LCI</b>	Life Cycle Inventory
<b>MEPD</b>	Mechanistic-Empirical Pavement Design
<b>MnDOT</b>	Minnesota Department of Transportation
<b>NAPA</b>	National Asphalt Pavement Association
<b>NCHRP</b>	National Cooperative Highway Research Projects
<b>PI</b>	Pavement Interactive
<b>PX</b>	PaveXpress
<b>ROI</b>	Return on Investment
<b>SaaS</b>	Software as a Service
<b>SCAP</b>	Small Cities Arterials Program (grant program through TIB)
<b>SCPP</b>	Small Cities Preservation Program (grant program through TIB)
<b>SHRP2</b>	Strategic Highway Research Project (2)
<b>STA</b>	State Transportation Agency
<b>STIC</b>	State Transportation Innovation Council
<b>TAM</b>	Technology Acceptance Model
<b>TAM</b>	Technology Acceptance Model
<b>TIB</b>	Washington Transportation Improvement Board
<b>TRB</b>	Transportation Research Board
<b>TxDOT</b>	Texas Department of Transportation
<b>UC</b>	University of California
<b>UW</b>	University of Washington
<b>WAPA</b>	Washington Asphalt Pavement Association
<b>WSDOT</b>	Washington Department of Transportation

## APPENDIX B. MEPD IMPLEMENTATION SCHEDULES

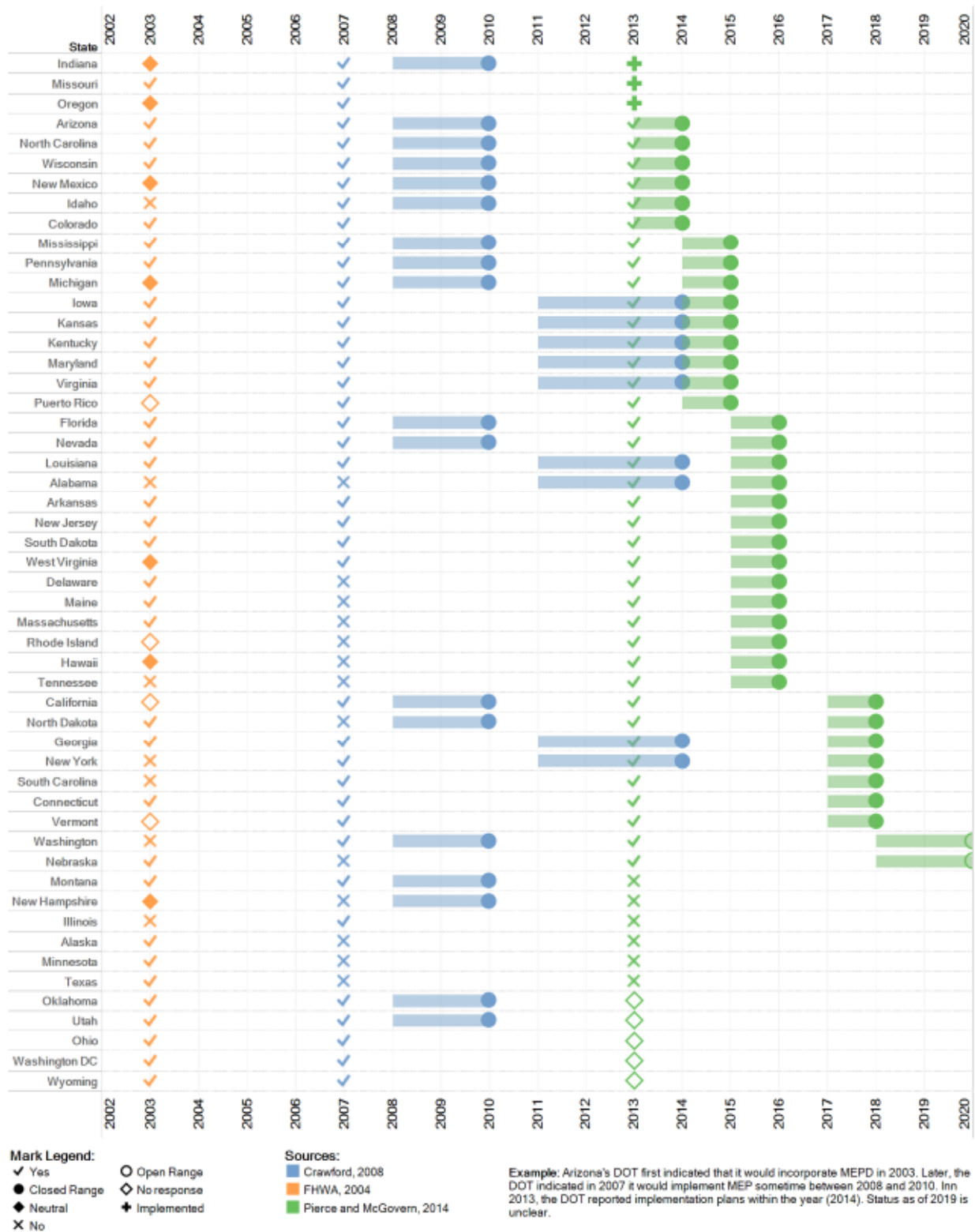


Figure 5.2. MEPD Implementation Schedules

## APPENDIX C. THE LIFE-CYCLE OF DATA

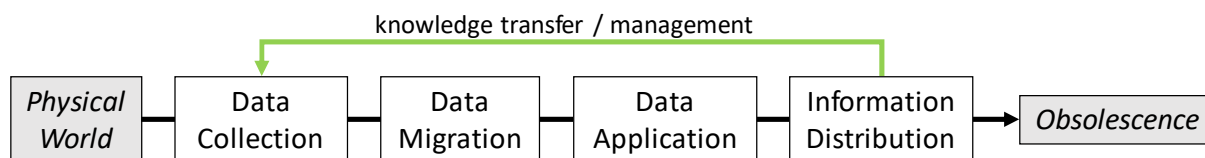


Figure 5.3. The Life-Cycle of Data

Figure 5.3 depicts how the author perceives DOT's interacting with data based on observations from literature. The figure generalizes the life of data at each life-cycle phase and separately from software that might interact with it:

The life-cycle of data begins when raw data is collected from the physical world by a human or device (agents) and ends when value can no longer be extracted from it (obsolescence). Between these two phases, software products are tools that interact with data at different phases of its life-cycle, whether they simply transfer data or convert the data into meaningful information. Moreover, software interacts with data in multiple phases categories. For example, cloud storage may handle data migration and distribution but not the collection or application of data.

By framing software in terms of how they interact with data, this research goal can be more simply stated as an exploration of whether software can help agencies avoid the data obsolescence phase (i.e. allow results from data application to be re-collected as data for other purposes). Accordingly, the research explores how data can be leveraged to advance knowledge transfer or allow additional data value to be recovered for future purposes.

Table 5.5. Interpretation of Data Life-Cycle Phases and Software Interactions

<b>Phase</b>	<b>Interpretation of Data-Software Interaction</b>
<b>Data Collection</b>	Raw data is collected from the physical world whether manually by a human or automatically by a device (agent)
	<i>Examples: field data collection via tablet, material barcode scanners, vehicle detection</i>
<b>Data Migration</b>	Data is translated into or collected in digital form and migrated from the point of collection to a centralized system for later access. Data migration can be performed manually or automated via an agent or software product, and data may also be postprocessed into a specific format at this point.
	<i>Examples: migrating data to cloud storage or database, document repositories</i>
<b>Data Application</b>	Software operates on data for an application that results in usable information, whether for immediate decision support or asset management. In addition to generating usable information, software can edit, reshape, or reformat the data to facilitate the desired use.
	<i>Examples: plan review, report generation, specifications generation, LCCA, decision-support, GIS, pavement design, cost-benefit analysis</i>
<b>Information Distribution</b>	The results of data applications are distributed for consumption after they have served their initially intended purpose (if applicable). Distribution (and subsequently, consumption) can be performed manually, automated via software, or a mixture depending on the goal.
	<i>Examples: PDF reports, cloud storage, project dashboards, asset management database</i>
<b>Obsolescence</b>	The obsolescence phase represents a data phase in which agents or humans can no longer extract additional or future value from the data without expending additional resources to salvage or recover it. After initial use, improperly distributed data may become inaccessible or obsolete due to loss, corruption, or incompatibility. In this state, data can incur cost in the form of reduced storage space or generating data storage costs.
	<i>Examples: legacy databases with incompatible architecture, outdated files with no version support, flash applications, broken service links</i>

## APPENDIX D. DISAMBIGUATION: DIKW













Frameworks that discuss the relationship among data, information, knowledge, and wisdom (DIKW) are well established in research and are generally portrayed as hierarchical: data appears at the base of a pyramid and wisdom at the top. Ackhoff's knowledge pyramid (commonly referred to as the DIKW pyramid) is among the most widely and implicitly accepted model in both formal research and practice (Ackoff 1989; Rowley 2007). In this framework, data given context is processed into information; aggregation of relevant information results in the production of useable knowledge, and knowledge eventually fosters wisdom.

Over time, additional interpretations relating DIKW include changing the pyramid's shape, direction of flow, tier content, or by adding attributes such as volume, utility or capacity for action (Frické 2009; Rowley 2007; Sivarajah et al. 2017). Although the DIKW pyramid has been widely accepted as true (Rowley 2007), a number of researchers have criticized or rejected the framework and its alternatives altogether (Rowley 2007; Weinberger 2010). These researchers have cited imprecise or inconsistent definitions (Frické 2009), vague or unclear transformation processes, lack of actionable interpretation, or exclusion of relevant factors such as time and metrics for utility (Sivarajah et al. 2017). Other researchers have imposed less structured interpretations (e.g. the 'Data Lake') (EMC2 EMC2; i-SCOOP n.d., n.d.), effectively avoiding discussion regarding the transformation of information (Gandomi and Haider 2015). Yet others debate whether the pyramid still applies to agents with artificial intelligence, further raising question whether wisdom is uniquely human attribute (Jashapara 2004; Rowley 2007). Overall, literature generally agrees on several points. First, information is a collection of relevant data given specific purpose through the context of use. As well, knowledge is the logical extension and further contextualization of information. However, researchers are unclear on the precise process regarding certain transformations: information to knowledge, knowledge to wisdom, and vice-versa).

To avoid ambiguity, knowledge management or knowledge transfer are used in the current work to refer to the treatment of data, information, or knowledge subsequent to its generation, acquisition, publication, or initially intended use. In this way, conventional definitions for data and information are preserved while allowing for more flexible interpretations regarding their extension into knowledge or wisdom.

## APPENDIX E. VERSIONS OF THE WORLD WIDE WEB

Distinctions between Versions of the World Wide Web are intended to capture common development virtues over the available life of the internet. These distinctions also relate the different capabilities among websites from each generation and the groups of people who were able to access them. Santos (2015) describes the functional differences between Web versions in terms of the capabilities of different ‘actors’ (organizations, people, businesses, and devices) to consume or produce content and the intent of each generation (Figure 5.4)

Generation	Virtue Democratized	Portals (Large Orgs.)	Individuals (Small Companies)	Agents (Devices)
Web 1.0	access to information			
Web 2.0	the ability to produce content	 	 	
Web 3.0	the capacity to apply context (act on knowledge)	 	 	 

Legend: ● Produce ○ Consume

Figure 5.4. Distinctions between World Wide Web Generations

In terms of technological capabilities, this research interprets web generations as follows:

- Web 1.0 refers to the ability of users to access static information online that is displayed through portals produced by large organizations. Users of Web 1.0 sites have no capacity to participate or contribute content.
- Web 2.0 collectively refers to the a new set of capacities offered: content both consumed and produced by users, improved collaboration and community driven data, and more flexible and multiple representations of information (Muench et al. 2010). This is the prevailing paradigm for the state-of-the-practice.
- Web 3.0 broadly refers to state-of-the-art development features that go beyond the better-defined capabilities of Web 2.0 services in this research. Though what qualifies as Web 3.0 is contentious, definitions reflect design principles that are distinct from but build upon those guiding Web 2.0. One distinguishing feature of Web 3.0 sites is the notion that mobile agents (e.g. tablets, smartphones) are capable of consuming and processing data. In practice, this means that agents possess the capability of applying contextual knowledge for the first time ever (i.e. programmed intelligence) to act on incoming data, previously a capacity available only to human agents.

Ultimately, these distinctions between Web Generations clarify expectations for software performance and functionality in terms of the prevailing current era (Web 2.0 capabilities) versus next generation (Web 3.0).

## APPENDIX F. RXPAVE DOCUMENTATION (EXPANDED)

Table 5.6. Summary of Documentation Efforts

<p><b>Overview and Marketing</b></p>	<p>The overview is a single document that describes the intent and scope of the development effort, providing context for its usage and perceived benefits:</p>
<p><i>for funding entities, first time visitors</i></p>	<ul style="list-style-type: none"> <li>▪ Intended use outcomes and key features included to facilitate outcome</li> <li>▪ Intended use audience, including basic knowledge requirements</li> <li>▪ Perceived potential impact and benefits</li> <li>▪ Stakeholders (performing and funding entities), development history</li> </ul>
<p><b>Development Background</b></p>	<p>Contents provide context for development and research efforts, effectively summarizing the state of practice in relationship to the state of the art:</p>
<p><i>for funding entities, researchers and academics</i></p>	<ul style="list-style-type: none"> <li>▪ Circumstances, motivations, and drivers for the app development</li> <li>▪ Summary of source research content (or body of research if applicable)</li> <li>▪ Disambiguation from other similar research, processes, or apps</li> <li>▪ Contextualization of the intended app use in broader construction workflows</li> </ul>
<p><b>Knowledge Transfer (Training and Guidance)</b></p>	<p>Knowledge transfer is addressed by a set of actions that intend to provide or relate:</p>
<p><i>for researchers, skeptics, and non-expert users</i></p>	<ul style="list-style-type: none"> <li>▪ In-app support that explains each individual input and general instructions</li> <li>▪ Training for operating the application and interpreting resulting reports</li> <li>▪ Required knowledge to use and interpret service, including a concise explanation of technical procedure performed by the app</li> <li>▪ Data requirements or relevant considerations prior to using the service</li> <li>▪ Curated resources providing additional information, including source research</li> </ul>
<p><b>Frequently Asked Questions</b></p>	<p>Document anticipates and addresses frequently asked questions:</p> <ul style="list-style-type: none"> <li>▪ Include an FAQ that addresses general questions about intended use, development and administration of RxPave, and guidance for software use</li> <li>▪ Include additional learning materials to address more nuanced or complex aspects of the underlying model (e.g. more in-depth descriptions of pavement distresses and treatments)</li> </ul>

## APPENDIX G. CHARACTERISTICS ASSOCIATED WITH RESPONSES (EXPANDED)

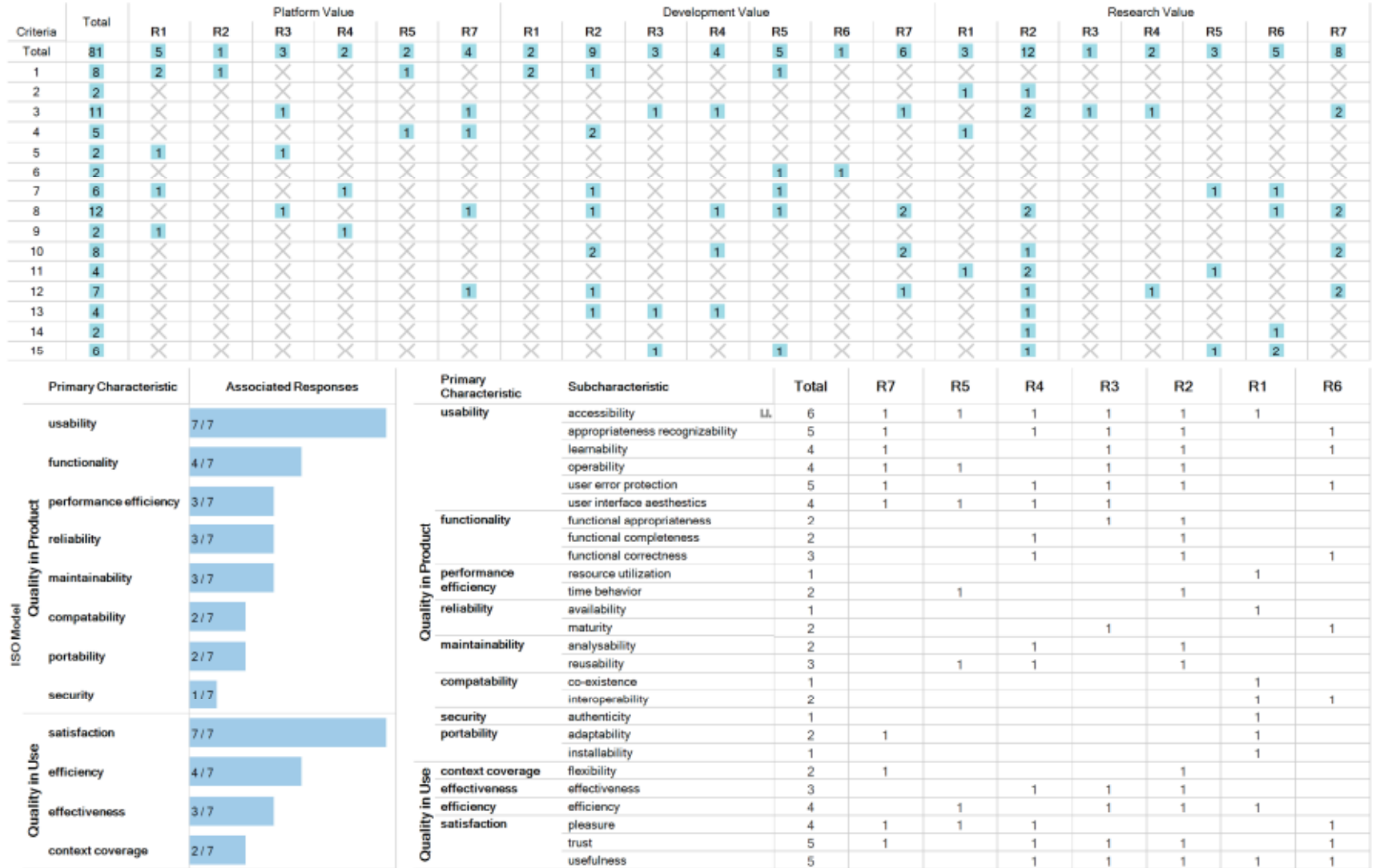


Figure 5.5. Development Criteria and Quality Characteristics Associated with Responses

## VITA

James Feracor received his B.S. in Civil Engineering in Civil and Environmental Engineering (CEE) at the University of California at Berkeley in 2007, and an M.Sc. in Civil Engineering Systems from the same department later in 2009. Throughout his master's program, he was the graduate student instructor (GSI) and later head GSI for a sophomore level course in MatLab programming.

After moving to Washington, he began a second master's program at the University of Washington's CEE program in 2013 focusing on construction engineering. In 2013, James was accepted to the Valle Scholarship and Scandinavian Exchange Program and studied geothermal engineering at the Haskoli Islands (University of Iceland) in Reykjavik. Upon returning, James had co-authored his first conference paper with Marta Ros Karlsdottir performing a life-cycle assessment on a district geothermal heating system in Iceland.

In 2015, James continued into the doctorate program in the same department, which was rebranded as the Construction, Energy, and Sustainable Infrastructure program. Throughout the program, he has enjoyed many diverse research opportunities, including prototyping web-based apps featuring methods from pavement research with Pavia Systems, LED lighting retrofits in the UW tower, sustainability rating systems for pavements with the Greenroads Foundation, and grant funding selection criteria for TIB's small cities programs. Throughout his time at UW, James has been a teaching assistant for over 10 quarters for junior and senior level undergraduate courses in construction. James completes his academic journey in June 2019.

Afterwards, James will work with Thornton Tomasetti's Digital Design Group as a Technologist supporting the company's global operations through data and software. Touched by the mentorship of his primary advisors at UW, James' new goals are to apply his knowledge of construction, data science, and sustainability to foster a new generation of digital tools that revolutionize the industry delivers construction.