TEXAS A&M UNIVERSITY
Zachry Department of
Civil & Environmental Engineering

ACPA RESEARCH TECHNOLOGY & INNOVATION COMMITTEE

Real Time Curing Control

For Concrete Pavement Construction

Dan Zollinger
Texas A&M University

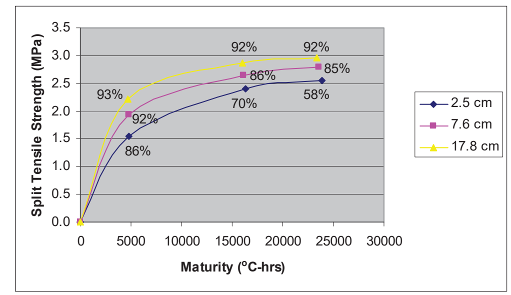
CP TECH CENTER/ACPA WEBINAR

Real Time Curing?

- Strength and Durability:
  - Low surface concrete strength

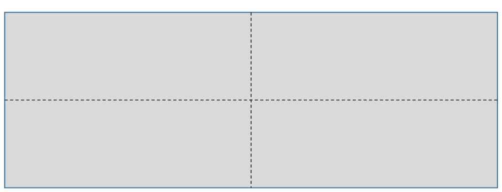
Application Rate (AR)

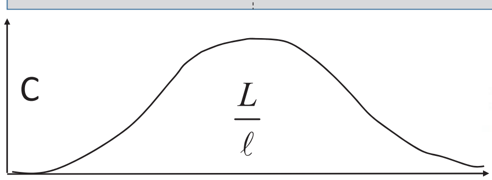
Application Time (AT)



Real Time Curing?

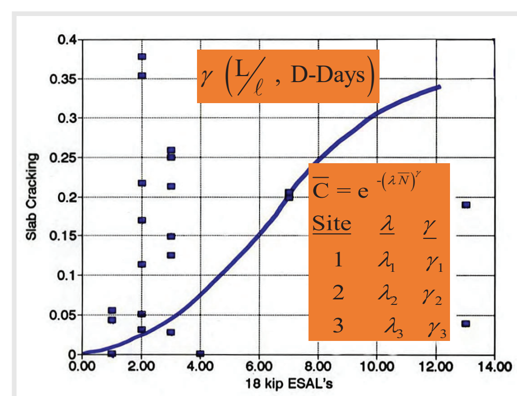
- Warping: Delamination, warping and top down cracking



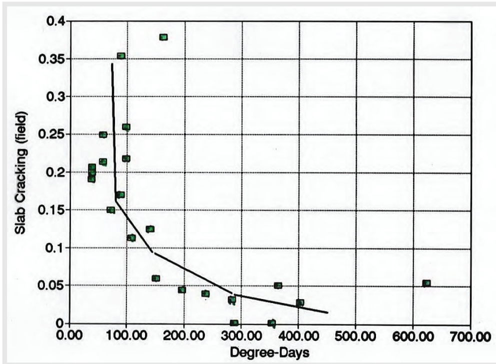


- Built-in Set

Field Performance Fatigue Cracking



Performance vs. Climatic Conditions



Pavement ME Cracking Model

$$CRK = \frac{1}{1 + C_4\, FD^{C_5}}$$

The M-E PDG program uses the calculated top-down and bottom-up fatigue damage factors to calculate percent cracking as follows:

where,
CRK = predicted amount of bottom-up or top-down cracking
FD = calculated fatigue damage associated with bottom-up or top-down cracking
National calibration:
C4 = 1
C5 = 1.98

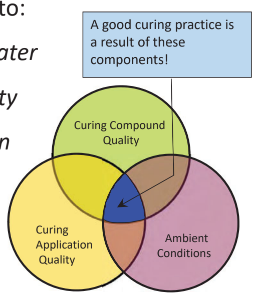
The total predicted percent cracking is calculated as follows:

$$\%Cracking = CRK_{bottom-up} + CRK_{top-down} - CRK_{bottom-up} \times CRK_{top-down}$$

$$Log(N_f) = C_1\left(\frac{1}{r}\right)^{C_2}$$

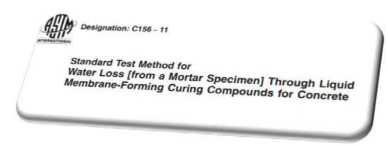
Quality Curing?

- Curing should **managed** to:
  - *Maintain hydration water*
  - *Reduce surface porosity*
  - *Facilitate strength gain*



- Depending on the project circumstances and limitations
- → Different curing requirements

Curing (ASTM C 156/C309)



- Limitations of ASTM C 156:
  - Focus on water retention
  - Have several limitations
    - Limited to fixed test conditions & application rate
    - Difficult to interpret for field application
- Challenges:
  - New curing technologies: lithium, post treatments
  - Timing of multiple applications
  - What constitutes quality curing?

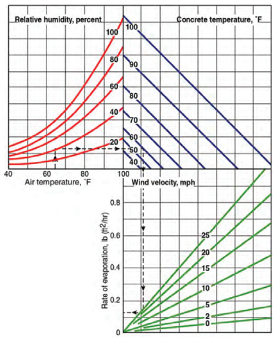
<u>Is water loss early a bad thing or not?</u>

ACI 305R: Potential Evaporation (PE)

- Curing cabinet:
  - Temperature: 100 ± 2 ºF
  - RH : 32 ± 2%

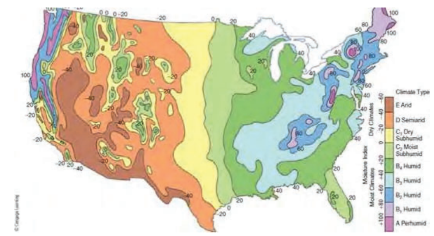
The PE for ASTM C 156 is 0.066 lb/ft²/hr.

PE og 0.20 lb/ft²/hr is critical but in Texas can go up to 0.600 lb/ft²/hr.

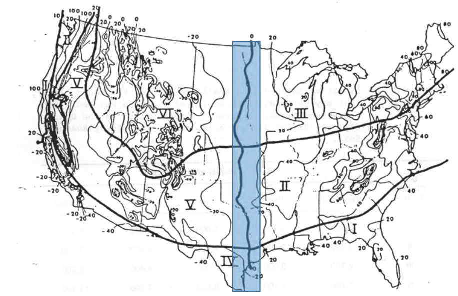


ACI 305 R

Thornthwaite Climatic Regions for TMI

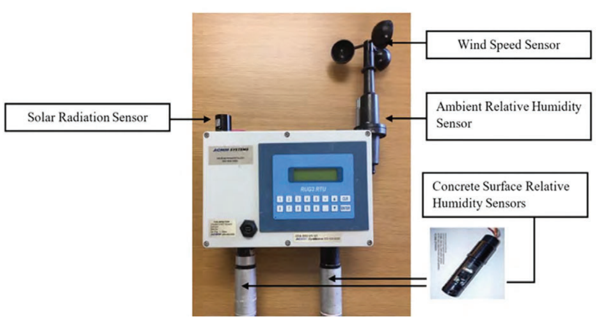

Supply (precipitation) vs. Demand for Water

Potential Evapotranspiration



REGION	CHARACTERISTICS
I	Wet, no freeze
II	Wet, freeze – thaw cycling
III	Wet, hard-freeze, spring thaw
IV	Dry, no freeze
V	Dry, freeze – thaw cycling
VI	Dry, hard freeze, spring thaw

Petra Base Station



Petra Base Station
- Dew Point and dry bulb data
- Ambient temperature
- Wind speed
- Solar radiation

Evaluation Index (EI)

- EI is defined as:

$$EI = \frac{t_f - t_a}{t_s - t_a}$$

where

t_f = the equivalent age of the filtered curing condition
t_s = the equivalent age of the sealed curing condition
t_a = the equivalent age of the ambient curing condition

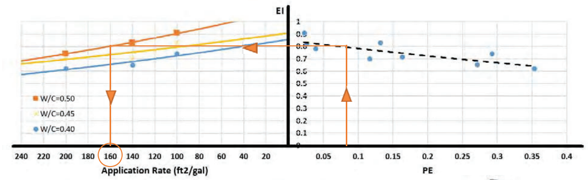
Base Station: Lab or Field

Laboratory

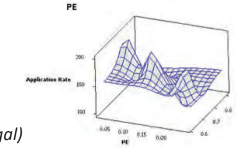
Field

Laboratory Characterization

(WRM – 1625)

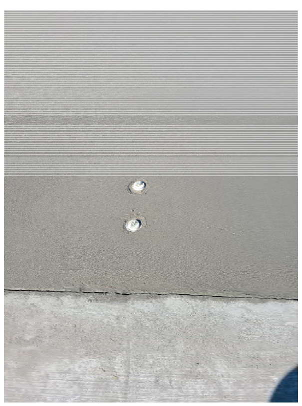


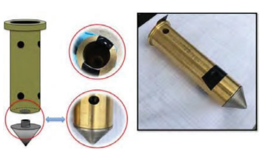
- *Step 1: Determine PE (for instance, PE=0.08)*
- *Step 2: Required EI (minimum EI is 0.8)*
- *Step 3: Get AR from the left chart*
  (based on w/c, the required AR is 160 ft2/gal)



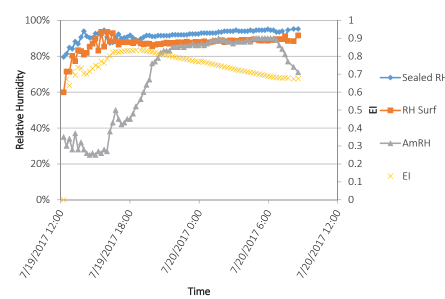
$$EI = -0.637(PE) + \frac{AR}{1000} + 0.707$$

Base Station: Installation

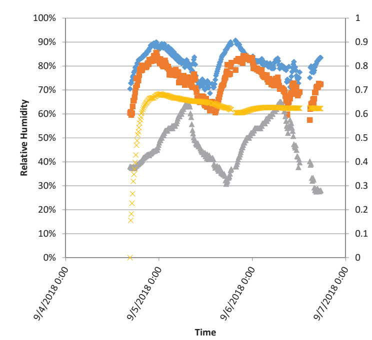




Curing Effectiveness Output Data

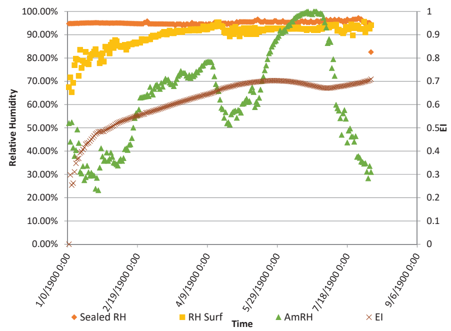


Cleveland, Tx



Roseville, Ca

Curing Effectiveness Output Data



Chicago, Illinois

GSSI Pavement Scan 2.0 (GPR)

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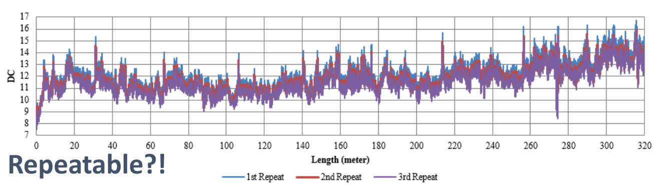
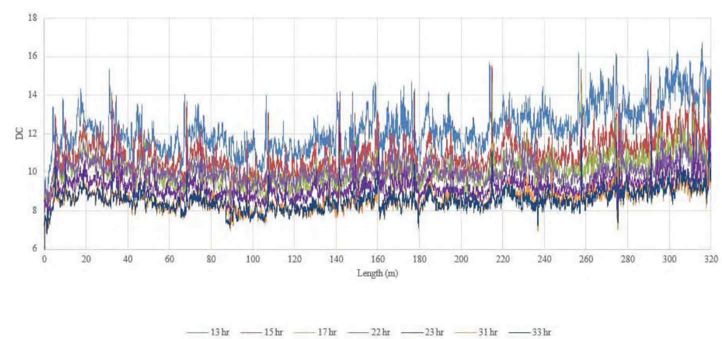


Repeatable?!

GSSI Pavement Scan 2.0 (GPR)

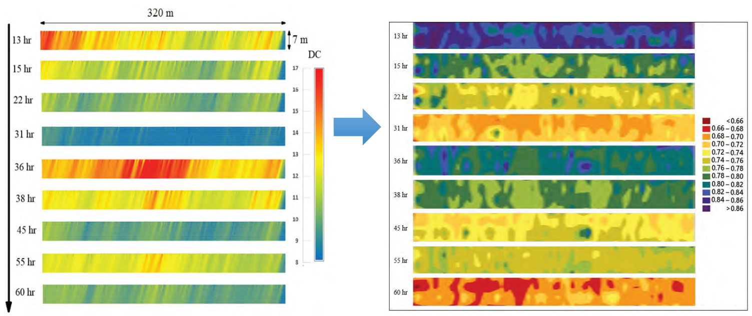


Dielectric constant Vs. Time

Contoured Results: Hourly

DC contour by GPR

Generated EI from GPR results based on reference curves



Petra Base Station/GSSI Pavement Scan 2.0 (GPR)

Effectiveness Index (EI)

Control & Specification

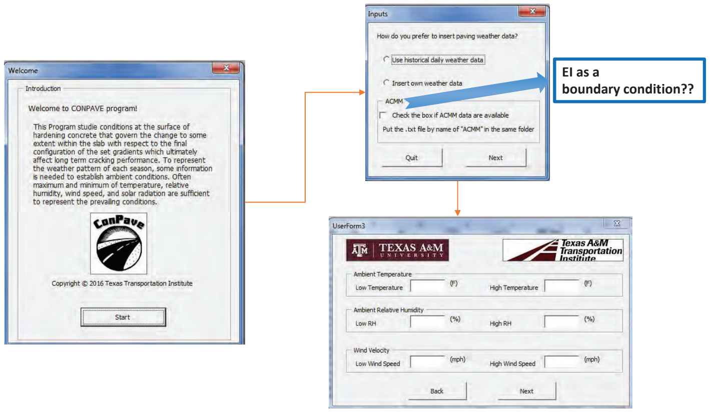
- Equipment Reconfiguration
  - Rate of application
  - Pressure/rate of travel
  - Bar height
- Specification Reconfiguraton
  - Upgrade ASTM 309/156
  - Monitor application rate?
  - Monitor quality?
- Contractor Incentive?
- Address New Methods and Materials

Curing Table

Table 1 Cart speed for low and high set curing conditions (ft/min).

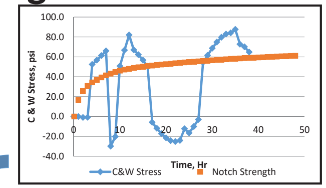
PE	Set	WRM 1150						WRM 1625					
		7 AM-10 AM	10 AM-3 PM	3 PM-7 PM	7 PM-10 PM	10 PM-3 AM	3 AM-7 AM	7 AM-10 AM	10 AM-3 PM	3 PM-7 PM	7 PM-10 PM	10 PM-3 AM	3 AM-7 AM
0.02-0.04	LOW	10.8	12.3	13.6	13.9	14.3	11.7	13.1	15.7	16.2	16.7	17.3	14.7
	HIGH	15.3	17.2	19	19.6	19.8	16.6	18.4	22	22.8	23.5	24.1	20.4
0.04-0.06	LOW	10.4	11.3	12.3	13.2	13.8	10.9	12.6	14.5	15.1	15.9	16.6	13.8
	HIGH	14.1	15.5	16.8	17.9	18.5	14.9	17	19.7	20.4	21.4	22.4	18.5
0.06-0.08	LOW	10.3	10.9	11.8	12.8	13.3	11.1	12.2	13.9	14.1	15	15.9	13.3
	HIGH	13.5	14.3	15.3	16.7	17.1	13.5	16	18.3	18.4	19.6	20.7	16.8
0.08-0.10	LOW	10.3	10.6	11.5	12.3	13.3	10.5	12.4	13.4	13.8	14.8	15.7	13.1
	HIGH	13.1	13.5	14.4	15.7	16.6	13	15.5	16.8	17.4	18.7	19.7	16.2
0.10-0.12	LOW	10.2	10.3	11.2	12	13.2	10.1	12.4	12.8	13.5	14.4	15.3	12.7
	HIGH	12.5	12.5	13.5	14.5	15.2	12.6	15.1	15.6	16.3	17.5	18.5	15.7
0.12-0.14	LOW	10	9.9	10.6	11.2	12.6	9.7	12.3	12.3	13	13.7	14.6	12.5
	HIGH	11.7	11.5	12.3	12.9	14.4	11.9	14.3	14.2	15.1	15.7	16.8	15.1
0.14-0.16	LOW	8.9	9.6	10.2	10.2	11.3	9.5	11.6	11.9	12.2	13.2	14.3	11.9
	HIGH	9.8	10.7	11.4	11.9	12.7	11.1	12.7	13.1	13.5	14.4	15.7	13.8
0.16-0.18	LOW	8	8.7	9	9.2	10.6	8.5	11	11.3	11.7	12.4	13.2	11.3
	HIGH	8.6	9.4	9.6	10.4	11.5	9.6	11.7	12.1	12.5	13.1	14.1	13.1
0.18-0.20	LOW	7.7	8.2	8.5	9.1	10	8.2	10	10.7	11	11.6	11.9	10.5
	HIGH	8.5	9.1	9.4	10	11	9.3	11.1	11.8	12.2	12.8	13	12.6

Simulation of Paving Conditions



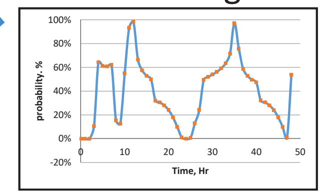
Crack Control and Sawcutting

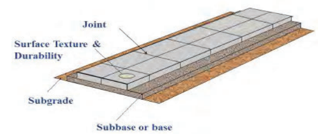
- **Crack Control Factors**
  - Mixture Proportions (cement, water, etc.)
  - Weather Conditions (wind, solar, etc.)
  - Method of Construction
  - Method of Curing
  - Base Support
  - Jointing Patterns



Tensile stress > 50% of the concrete's tensile strength

Cracking





Assumed symmetry of JCP slabs

Research and Development: Long Term Impact

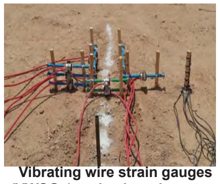
Test Program

Measuring curing effectiveness from depth

Dial Gauge

Dielectric measurement

Crack meter

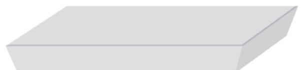


Vibrating wire strain gauges (VWSGs) and a thermistor tree

Questions/Comments: Submit Online

ASTM C 156

- Measurements: weight loss of mortar
- Specimen dimension:
  - top 6 by 12 in.
  - bottom $5^1/_4$ by $11^3/_4$ in.
  - thickness 2 in.



- Curing cabinet:
  - Temperature: 100 ± 2 ºF
  - RH : $32 \pm 2\%$

Productivity Study of ACPA Members

Omar Swei, Faculty of Applied Science
David Gillen, Sauder School of Business
Anuar Onayev, Faculty of Applied Science

March 2021

If you are interested in participating in this study, please visit:

https://imlab.civil.ubc.ca/productivity-study/

About the team

- Dr. Omar Swei is a faculty member in the Department of Civil Engineering at The University of British Columbia.
- He received his graduate training at MIT in the Department of Civil & Environmental Engineering and Engineering Systems Division.
- His research centers on the development and implementation of operations research methods to improve the design, construction and maintenance of infrastructure systems.

About the team

- Dr. David Gillen is a Professor in the Sauder School of Business and Director of the Centre for Transportation Studies at The University of British Columbia
- Dr. Gillen has published over 100 books, technical reports, journal papers, conference presentations, and other articles in various areas of transportation economics, including measuring infrastructure productivity at airports, ports and the impact of the US Aviation Network on industry productivity.

About the team

- Mr. Anuar Onayev is a graduate student in the Department of Civil Engineering at The University of British Columbia.
- Mr. Onayev completed his undergraduate studies in Civil & Environmental Engineering at The University of Vermont.
- He has presented and published his research around infrastructure management and productivity growth at venues such as TRB.

Learning Objectives

- The importance of productivity and why FHWA, BLS, state DOTs, and others are interested in the performance of ACPA's members
- The goals of our proposed productivity survey of ACPA members
- The ways in which this work complements other initiatives (e.g., asphalt market share and prices) led by ACPA
- The data needs and outcomes of this study

BLS has revisited the measurement of aggregate productivity growth

Results suggest positive productivity growth except for highways!

Industry	Direct labor	Direct and subcontractor labor
Single-family housing: regression method	1.1	1.2
Compound growth	0.4	0.7
Multifamily housing: regression method	3.7	1.9
Compound growth	3.4	2.6
Highways (compound growth)	0.0	–2.2
Industrial construction (compound growth)	5.3	5.5

Sveikauskas et al. (2018)

The BLS findings motivate us to revisit highway construction

- Are firms really becoming less efficient over time?
- Could the evolving operating context be the reason?
  - Increase emphasis placed on users
  - Spending on concrete vs. asphalt
  - Spending on M&R?
  - Are state DOTs aware of these repercussions?
- What can be gleaned to improve productivity for firms?

Several key decision-makers are interested in measuring and improving highway construction productivity

- U.S. Federal Highway Administration
- U.S. Bureau of Labor Statistics
- State DOTs
- Study provides ACPA the opportunity to engage with owners and key decision-makers at the federal and state level

Benefits to ACPA Members that Participate in Our Study

- Engagement with key decision-makers
- Report to state DOTs, FHWA, etc. detailing the implication of current practice on contractor productivity and costs of production
- Availability to participating members an internal report detailing techniques to improve their productivity

Some examples of factors that influence a firm's productivity

Firm choices

- Capital investments
- Managerial choices
- Labor and equipment utilization

Operating Environment

- Owner specifications
- Market concentration
- Expenditures on M&R vs. capital outlays

Participants who partake in the survey will receive a report outlining....

1. Key productivity drivers for highway construction
2. Effects of utilization of capital, labor, and material inputs on productivity levels
3. Effects of various project-related factors on productivity levels

Allow contractors to identify mechanisms to improve their productivity

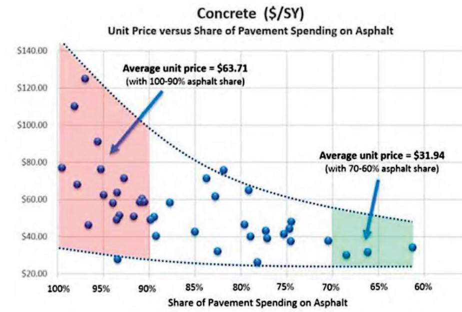
A bulletin report that will be published for state DOTs and partnering ACPA members listing…

1. Effects of operating environment (e.g., market share) on productivity for the industry
2. The effect of state DOT decisions on productivity rates and construction costs

Improve the operating environment and competitiveness of ACPA members

This work can complement ACPA's previous initiatives

Firm-level data will enable us to quantify the mechanisms affecting productivity and costs



ACPA (2016)

Study data requirements

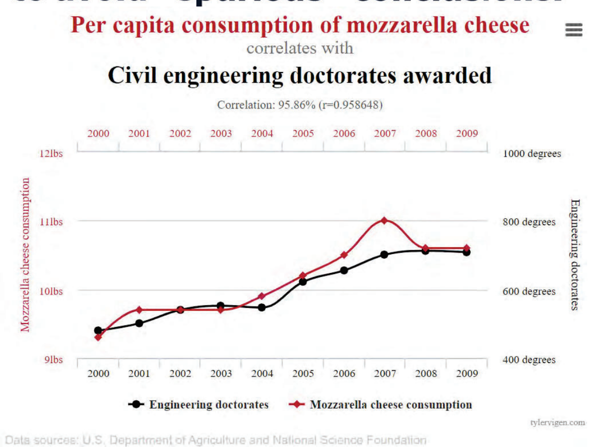
Project-level data

- Cost reports for project
- Contract info for project (e.g., procurement mode)
- Project location

Fiscal Year Data

- Total output (e.g., square yards, revenue)
- Ownership info (e.g., consolidation?)
- Capital investments and depreciation

Why do we need to collect so much data? In order to avoid "spurious" conclusions.



Why do we need so much data?

1. To identify the key factors affecting productivity rates and cost for contractors

2. Control for heterogeneity in our data since multiple factors will be changing simultaneously:
   - Is the number of civil engineering PhDs really driving mozzarella consumption?
   - Need to capture not just correlation but also causation

Example Data

Source:	Example(s):	Why are we collecting it?
Historical firm information	Ownership; Headquarters; Operation states; Size (i.e., # of employees);	We need to be able to control for the dispersion in sizes and geographical locations of firms. Our goal is to identify what factors affect ALL firms (small and large).
Cost reports	$$$ and Quantities of inputs (capital, labor, materials, energy); Activity/job types; Revenues and Expenses; Duration;	To calculate a Total Factor Productivity, we need to disaggregate cost and quantity data by type of input. By tracking associated activity types, we can identify how various design features of a project change resource allocation. This helps to identify optimal allocation strategies.
Year-end fiscal statements	Capital investment; Asset depreciation;	Such information helps us to identify how managerial practices affect a firm's productivity on an aggregate level.
Contract information	Type of contract; Special value-time clauses; User costs;	This helps us understand how the demand (from state DOTs) changed over time and how it affected the productivity of individual firms on individual projects.

Data Security and Management

- We have worked with our IT department at UBC to set up a private, secure mechanism for members to share their information.
- No private information will be released or shared as part of this study
- High-level insights will be disclosed with ACPA and members prior to its dissemination

Short-Term and Long-Term Study benefits

- Engage with key stakeholders and decision-makers
- Learn insights (confidentially) around ways to improve productivity rates and reduce production costs
- Make owners aware of the impact of their choices on contractors
- Achieve these goals at a fairly low cost (i.e. your time)

Thank you!

Omar Swei, oaswei@civil.ubc.ca

David Gillen, david.gillen@sauder.ubc.ca

Anuar Onayev, aonayev@mail.ubc.ca

If you are interested in participating in this study, please visit:

https://imlab.civil.ubc.ca/productivity-study/