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BIG DATA IN RAILROAD MAINTENANCE PLANNING

The University of Delaware's Railroad Engineering and Safety Program hosted its fourth annual conference focusing on uses of Big Data in Railway Engineering and Maintenance on December 14 & 15, 2017.

The conference is organized annually by Dr. Allan M. Zarembski, Professor of Practice and Director of UD's Railroad Engineering and Safety Program and Dr. Nii Attoh-Okine, professor of civil and environmental engineering. The conference has grown from 50 attendees with a discussion on "what" the railway industry wants to do with big data, to over 220 registrants and "how" the industry is using big data, in just four years. It attracted attendees from Europe, South America and throughout US and Canada.

Amtrak president, Wick Moorman addresses the Big Data in Railway Engineering and Maintenance Conference.

The conference was kicked-off by UD's President Assanis, who welcomed attendees from major railways, transit systems, railway suppliers and contractors, and academia (see Photo). President Assanis spoke of the new "Big Data" initiative at the University of Delaware and its importance in the future growth of the University. The keynote speaker, Mr. Charles "Wick" Moorman IV, President of Amtrak, set the stage for two days of technical sessions by discussing the challenges that the railway industry faces, and how Amtrak is taking advantage of big data and cutting edge data science to increase safety and productivity. This was further emphasized by a special panel composed of the Chief Information Officers (CIOs) of the Union Pacific Railroad, Amtrak and SEPTA who talked about the growing importance of data collection, data management, and data analysis in meeting the numerous challenges facing railways and transit systems today. This special panel was chaired by Amtrak president "Wick Moorman" (see photo)

Seven technical sessions, comprising over 35 technical presentations, were held over the two days with a focus on railroad industry needs and applications. Presentations included railway industry needs identified by major railway CIOs and railroad speakers, Federal Railway Administration driven big data requirements, case studies from railways and suppliers, and theories and techniques currently in use. The future direction of Data Analytics was also highlighted by the two Academia sessions which highlighted how the industry is

Dare to be first.
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using cutting edge Data Science techniques to solve practical problems. Some of the presentations showed a significant return on investment to the railways for implementing such techniques.

UD President Assanis welcomes the attendees

The big data conferences and the recent award of a five-year Tier 1 University Transportation Center (UTC) program (in conjunction with the University of Nevada at Las Vegas and Virginia Tech) for "Improving Rail Transportation Infrastructure Sustainability and Durability." has allowed UD's Railroad Engineering and Safety Program to expand and upgrade its research capabilities. UD's railway engineering and safety program is currently using big data to forecast the life of railroad track components and help railways and suppliers understand how to take advantage of "mountains" of inspection and maintenance data through cutting edge engineering and data science research. These activities are performed in conjunction with several railroad companies that are providing data for UD engineers to analyze.

Zarembski and co-organizer Attoh-Okine are already building the program for the 2018 event, which will be held in December 13-14, and look forward to continued success disseminating, not just important research, but application of the research to the railroad and transit industry.

Message from the Director

Our hearts go out to those affected by the recent pedestrian bridge failure at Florida International University in Miami. This bridge failed shortly after the structure was placed into service, via a sudden and catastrophic collapse of the structure, which caused six fatalities. The cause of failure is currently unknown, and there is an on-going investigation being performed by the National Transportation Safety Board. The bridge itself was built using accelerated bridge construction (ABC) techniques, at an institution that has a national reputation for innovative research in this area, and a federally funded university transportation center (UTC) focused on ABC.

Following this tragedy, just a few days ago, Mississippi Governor Phil Bryant ordered the closure of traffic across 83 dangerously deteriorated county bridges in Mississippi. This list has grown to 106 bridges, with the declared state of emergency allowing the governor to mandate closure of the bridges and to have Mississippi DOT workers provide assistance with the closure process.

Both of these recent events point to the myriad and difficult challenges associated with bridge construction and bridge maintenance, as well as the critical role that bridges play in our nation's transportation infrastructure. The traveling public expects bridges to "just work", as any in-service bridge failures will almost certainly result in significant loss of life. However, much of our existing bridge infrastructure has reached the end of its service life, with many bridges being structurally deficient, functionally obsolete, and in some extreme cases of deterioration, a true danger to the traveling public. Replacement of these structures, when sufficient funding is available, must be performed extremely quickly, with as little disruption to the traveling public as possible.

Juxtaposed against this backdrop, available funding for infrastructure maintenance, rehabilitation, and replacement of our existing bridge inventory at the city and county level ranges from limited to nonexistent in many locales. Even at the state level, there is often insufficient funds to address all of the most pressing bridge-related problems, and significant decisions must be made about which problems to spend money on first. Moreover, the never-ending pressure to "get in, get out, and stay out" that is ever present in the transportation infrastructure community is particularly strong in the bridge community, as many bridges are by their very nature already transportation bottlenecks.

Articles in this newsletter describe the "Big Data in Railroad Maintenance Planning" conference that was held at the University of Delaware, as well as activities by faculty, staff, and students at the Transportation Research Board 97th Annual Meeting in Washington, DC. Our hearty welcome goes out to the inaugural class of UD's new Construction Engineering and Management program, which is housed in the Department of Civil and Environmental Engineering; we expect lots of great collaborations between those folks and our on-going DCT activities. Please read the technical article on "Determining Work Zone Lane Capacities." Mark your calendars for the upcoming Research Showcase scheduled for May 9 in Dover and the Roadway Management Conference, which will be held October 15-17, 2018 in Gettysburg, Pennsylvania.

Here's hoping that spring gets here soon!

One of the largest annual gathering of transportation professionals and researchers concluded in mid-January. The Transportation Research Board (TRB) annual meeting, scheduled from January 7th through January 11th was held at the Walter E. Washington Convention Center in Washington, DC. A number of sessions and workshops focused on the spotlight theme for the 2018 meeting: *Transportation: Moving the Economy of the Future.* Among the more than 10,000 policy makers, administrators, practitioners, and representatives of government and industry attendees was a contingent from the University of Delaware.

Rachel Chiquoine, a doctoral student and new fellowship recipient from the Dwight David Eisenhower Transportation Fellowship Program, gave a presentation entitled, "Patient Travel Behaviors during a Public Health Biological Event Requiring Points of Dispensing" on the first day of the meeting.

William Baker, a doctoral student, attended the Council of University Transportation Centers (CUTC) 2018 Awards Banquet held in conjunction with TRB. Will was selected for the UTC Student of the Year Award from the Mid-Atlantic Sustainability Transportation Center.

Mingxin Li, research scientist in the Delaware Center for Transportation, presented two posters during the meeting related to nanostructured fertilizer for sustainable roadside landscapes.

Other posters included topics as varied as the impacts of sea-level rise on non-motorized transportation, automated and connected vehicles, land use planning, reducing stormwater runoff and bikeshare ridership.

University of Delaware faculty and professional staff member attendees included Rusty Lee, Christopher Meehan, Andreas Malikopoulos, Willett Kempton, and Mingxin Li.

Notes from the Delaware T²/LTAP Center

Delaware T²/LTAP

Roadway Management Conference Returns

For many years, the Mid-Atlantic Transportation Technology Transfer (T²) Centers and Local Technical Assistance Programs (LTAP) hosted the Roadway Management Conference, which moved around between Delaware, Maryland, Pennsylvania, Virginia, and West Virginia. It was last held in 2008 in West Virginia and proved to be very popular. However, the credit crisis put an end to out-of-state travel for many of us for several years and the RMC had to be suspended. Well, many of you have beat the drum for its return and the Mid-Atlantic Region is bringing it back.

The Roadway Management Conference will return October 15-17, 2018 in Gettysburg, Pennsylvania. Mark your calendars!

The **RMC** is intended for all practitioners who construct and maintain state, county, and municipal roads and streets. This group includes elected and appointed officials, city managers and clerks, public works managers, engineers, technicians, equipment operators, tradesmen, laborers, supervisors, and contractors.

A survey was circulated last winter; many of you responded to both encourage us to revive the RMC and to inform us of topics of interest. Based on feedback from the survey, we are planning sessions that include bridge preservation, maintenance, and inspection, in addition to high-friction surface treatments, box culvert and pipe best practices, micro-surface and slurry seals, chip seal, brines for winter maintenance, MUTCD updates, sign installation and maintenance, stormwater MS4 issues, trenching safety, smart work zones, personnel and personal skills, and others. We also plan to have multiple outside displays and demonstrations such as chainsaws and wood chipper safety, concrete finishing and testing, equipment displays, and more.

Our planning for the RMC began in earnest at our October Regional Meeting in Lewes, Delaware. We made great progress and our plan is to provide you with more details later this spring. Meanwhile, you can see a draft agenda and other details on the RMC website https://roadwaymanagementc.wixsite.com/home , which will evolve as details emerge.

We know that our local transportation agencies struggle with many challenges and sometimes just getting out to talk to colleagues from other areas, share their experiences, hear new ideas, and examine equipment up-close can bring us closer to solutions. So our goal will be to put together an RMC that you'll want to attend and that you'll be glad you did. So mark your calendar now and stay tuned for more details.

Undergraduate Program in Construction Engineering and Management Welcomes Inaugural Class

In the 2016/2017 academic year, the Department of Civil and Environmental Engineering at the University of Delaware embarked on a journey to offer a new undergraduate degree program in construction engineering and management (CEM). Today, there are 20 students enrolled in the program majoring in construction and more are considering transferring into the program. These students have officially embarked upon their journey into leadership of the profession in the future and UD expects graduates to make a difference in all sectors of the construction industry, including engineered and heavy highway construction.

Establishment of this degree program was strongly encouraged by the engineering and construction industry and with strong support of UD alumni who have established successful careers in construction. The development effort began with hiring of the first program director, Dr. Edgar Small, who brings more than 25 years of construction and infrastructure management experience and a passion for construction engineering education to the position.

The undergraduate program was established to provide students with the skills and abilities to lead the profession in the future. "As the industry evolves and progresses, the construction enterprise has become more complex and technically demanding," Small says. "The increasing need for engineers prepared to meet the challenges of construction management has been recognized by industry, addressed by professional societies and accrediting bodies, and validated through market studies." With this well documented need, the program must develop students for future achievement as construction professionals. Students need to be well prepared in engineering fundamentals; in construction fundamentals like estimating, scheduling, equipment and law; and in new technologies, such as BIM and the use of drones. The program was developed following an in-depth evaluation of all existing accredited construction engineering programs worldwide and with consultation and involvement of the professional community.

The resulting program offers a 4-year, 126 credit hour program with significant added value. First and foremost, the program is designed following ABET accreditation requirements, which give the graduates a path towards professional engineering licensure. Also, all students in the program will be required to participate in a 26-week co-op experience. This enables students to gain valuable practical experience to complement their classes without extending their degree program beyond 4 years. Furthermore, all students are required to complete a certificate of business essentials offered by UD's Alfred Lerner College of Business and Economics or to pursue additional classes towards a minor in business administration. Lastly, the program has been developed with an international perspective and all students have the opportunity to participate in 4-week concentrated study of international construction as part of a study-abroad program.

Start-up of the program, including the hiring of Small as director, was enabled by a major gift from an industry partner. Industry partners have further sponsored research experiences for undergraduate students, visiting faculty opportunities and development of facilities. These partnerships have enabled the department to develop the curriculum and is facilitating establishment of the program. These efforts have been successful with the inaugural class of 20 construction engineering students and more success in the long-term is expected. Ideally, giving current resource availability, the program will produce a minimum of 20 undergraduate students each year.

To support this objective, the department is in the process of hiring two full-time faculty members. Applications have been received from excellent candidates from around the world and department faculty are currently preparing for on-campus interviews with the objective of having new professors join the faculty in the 2018/2019 academic year. Future growth is expected at the graduate level with both research-oriented graduate degree programs and on-line, class-only masters' offerings. To support

(Continued on page 6)

UD Engineering Students Learn from Visiting Job-sites and Exposure to Practice

future graduate growth and to expand our service to the profession, additional faculty are required. Small plans to expand the program with the hiring of three additional research-oriented faculty to increase the construction group to six faculty members in the future.

The academic instruction offered is designed to advance in partnership with the professional community from all sectors of construction, including engineered and heavy construction. Connecting the industry to the classroom provides benefits for both the students and the profession. "Regional construction and engineering firms will undoubtedly benefit from graduates of this program, who will not only hold a degree in construction engineering but also acquire a skill set of applied practices and hands-on experience relative to the business," noted Small. Students' academic career is in turn enhanced through knowledge of best practices in the field. Ideally, such students would graduate ready to hit the ground running and make a difference in their chosen profession.

UD's construction engineering and management program is unique in the area and is ideally situated in the region. While there are construction management options available, these options do not provide an engineering foundation necessary for professional licensure and essential for providing engineered solutions within the construction process. Select universities do offer civil engineering or architectural engineering but such programs have limited construction exposure. UD offers the only construction engineering program in Northeast region and Mid-Atlantic corridors. No other program exists from Washington, DC to Maine. UD is ideally situated to serve the construction engineering resource needs within the region in the future and welcomes the involvement of transportation construction professionals to be part of the development.

2018 Spring Research Showcase

Wednesday, May 9, 2018
11:30—2:00
Paradee Center
69 Transportation Circle
Dover, DE

You are invited to attend our 2018 Transportation Research Showcase. View poster displays and talk to Principal Investigators from the University of Delaware and Project Managers from DelDOT. Showcase projects include many areas, e.g., Environmental, Bridge Engineering & Management, Traffic, Planning, Policy, Pavement & Materials and Construction, among others.

Please come and enjoy a light lunch while viewing the presentations . Taste a sample of UD Creamery Ice Cream! Admission is free but you must register to attend!

Click here to register

RESEARCH

As each project is completed, a final technical report will be available on the DCT website: http://www.ce.udel.edu/dct

IRIB Ongoing Structural Health Monitoring

The Indian River Inlet Bridge represents a significant investment in infrastructure for the State of Delaware. This funding supports ongoing evaluation of the bridge and preservation of its state-of-the-art structural health monitoring system. Ending 8/31/2019

Principal Investigators: Michael Chajes and Tripp Shenton, *Department of Civil and Environmental Engineering*

Project Manager: Jason Arndt, *Bridge Design*

Snow Plow Route Optimization

The goal of this research is to develop a mathematical model for optimizing snowplow routing in order to minimize the total snowplow truck travel distance and travel times. Ending 5/4/18

Principal Investigator: Mingxin Li, *Department of Civil and Environmental Engineering*

Project Manager: Jason McCluskey, *Division of Planning*

Field Measurement of the Dynamic Impact Factor for Buried Culverts

This research is aimed at field investigation of the actual dynamic load effects on buried culverts. The final product is expected to be a refined methodology for estimating the impact factor for buried culverts. Ending 11/4/18

Principal Investigator: Kalehiwot Manahiloh, *Department of Civil and Environmental Engineering*

Project Manager: Ping Jiang, *Bridge Section*

Integrating Zero-Valent Iron and Biochar Amendments in Stormwater

Data from a field demonstration stormwater treatment system using biofilter media amendments for removing nitrogen will be used to develop preliminary guidelines for DelDOT, which will assist the agency with compliance of the Total Maximum Daily Load (TMDL) regulations for bacteria and nutrients in surface waters. Ending 5/6/18

Principal Investigators: Paul Imhoff, Daniel Cha, Pei Chiu, Julia Maresca, *Department of Civil and Environmental Engineering,* Mingxin Guo, *Delaware State University*

Project Manager: Mark Harbeson, *Transportation Management Center*

Evaluation of New Data Sources for Planning and Operations FY17 & FY18

This project will provide DelDOT a demonstration of what some new sources of cell phone data can provide for information and how it would be useful for both operations and planning. Ending 8/31/18

Principal Investigator: Rusty Lee, *Department of Civil and Environmental Engineering*

Project Manager: Michael DuRoss, *Division of Planning*

FY18 Regional Travel Demand Modeling Support

Assist DelDOT with developing, maintaining, applying and evaluating its travel demand forecasting model that is used not only by DelDOT but also by the state's two metropolitan planning organizations. Ending 8/31/18

Principal Investigator: Rusty Lee, *Department of Civil and Environmental Engineering*

Project Manager: Michael DuRoss, *Division of Planning*

2017 DelDOT Municipal Agreements Project

The goals of this project are for student interns to conduct a careful review of all known agreements that exist between DelDOT and Delaware municipalities, documenting the boundaries of the agreement and its applicability to roadways systems. Ending 12/31/18

Principal Investigator: Rusty Lee, *Department of Civil and Environmental Engineering*

Project Manager: Karen Brittingham, *Division of Planning*

Fall 2016 and Summer 2017 Processing of DelDOT-TMC Bluetooth Data for Travel Time and Speed Measurements

This project entails transforming raw Bluetooth data into a useable form for DelDOT and processing the data into average time and speed between sensors and comparing average speed with posted speed limit to get an indication of delay. Ending 8/31/18

Principal Investigator: Ardeshir Faghri, *Department of Civil and Environmental Engineering*

Project Manager: Mark Eastburn, *Division of Planning*

ITS Support for Bicycle and Pedestrian Application Development FY17

The aim of this project is on development of software tools and application that focus on the needs of pedestrians and cyclists. Ending 6/30/18)

Principal Investigator: Chandra Khambhamettu, *Computer and Information Sciences*

Project Manager: Paul Moser, *Division of Planning*

Statewide Traffic Data Analysis and Evaluation – FY17

Analysis and evaluation of potential methods for the TMC and for Division of Planning for

(Continued on page 8)

testing and implementing improvements to measurement of travel speeds and congestion, which are key elements of prioritizing projects.

Ending 5/31/18

Principal Investigator: Rusty Lee, *Department of Civil and Environmental Engineering*

Project Manager: Gene Donaldson, *Traffic Management Center*

FY17 Completion of the DelDOT Construction Intern Project

This project supports efforts by interns to document via video, construction methods and best practices within the Route 301 construction project. Ending 8/31/18

Principal Investigator: Rusty Lee, *Department of Civil and Environmental Engineering*

Project Manager: Javier Torrijos, *Division of Planning*

Exploratory Field Monitoring of Pile Downdrag

The goal of this project is to measure field data related to the performance of installed deep foundation elements that are used to provide structural support for bridges.

Ending 12/31/18

Principal Investigator: Christopher Meehan, *Department of Civil and Environmental Engineering*

Project Manager: Jason Hastings, *Bridge Section*

Developing Methodologies to Convert Time of Day Person Schedules to Travel Demand Model Inputs for Evaluation of PRT System Designs

Develop the methodologies for a student trip table and faculty/staff trip table that may consist of multiple O-D tables or other methods determined to be best for modeling purposes. Ending 6/8/19

Principal Investigator: Rusty Lee, *Department of Civil and Environmental Engineering*

Project Manager: Michael DuRoss, *Division of Planning*

Innovative Applications and Utilizations of TMC Data

The aim of this project is to thoroughly review the data collected by the Traffic Management Center, test its accuracy and reliability and as part of the final deliverable,

provide a table detailing what units of DelDOT can use the TMC data. Ending 6-8-19

Principal Investigator: Ardeshir Faghri, *Department of Civil and Environmental Engineering*

Project Manager: Mark Eastburn, *Division of Planning*

Using "Big Data" to Enhance the Transit Planning Process and Transit Users' Experiences

The focus of the research is to better understand how current and prospective transit users are able to use and respond to transit system operations through technology, social media, and "big data"-type resources.

Ending 6-8-19

Principal Investigator: Mingxin Li, *Department of Civil and Environmental Engineering*

Project Manager: Jaren Kauffman/Bruce Allen, *Division of Planning*

Latest Innovative Approaches to Intra-agency Skill-Based Resiliency for DelDOT

The main objective of this research is to evaluate the most recent developments in the area of skill-based resiliency. Strategies most appropriate for the unique context of DelDOT will be listed and ranked. Ending 6-8-19

Principal Investigator: Mingxin Li, *Department of Civil and Environmental Engineering*

Project Manager: Jaren Kauffman/Bruce Allen, *Division of Planning*

Evaluating Biochar Amendment of DNREC Biosoil-14 Bioretention Medium

As a follow-up to field tests, this project will evaluate the performance of DNREC Biosoil-14 (standard DNREC bioretention mix) with and without biochar amendment on nutrient removal and plant growth. Ending 6-30-18

Principal Investigators: Paul Imhoff, *Department of Civil and Environmental Engineering*

Mingxin Guo, *Delaware State University*

Project Manager: Sara Esposito, *Maintenance & Operations*

Fall 2017 and Summer 2018 Processing of DelDOT-TMC Bluetooth Data for Travel Time & Speed Measurements

The main purpose of this project is to process and analyze the Bluetooth data collected by the Traffic Management Center for travel time and speed measurements throughout the state. Ending 8-31-18

Principal Investigator: Ardeshir Faghri, *Department of Civil and Environmental Engineering*

Project Manager: Mark Eastburn, *Division of Planning*

On-Call Development and Logistics for Video Analysis of Intersections and Roadways for Planning and Evaluation

This project aims to further develop software, hardware, and processes to gain observational insights into our transportation system from the use of multi-spectral imaging and other remote sensing technologies.

Ending 12/31/18

Principal Investigator: Chandra Khambhamettu, *Computer and Information Sciences*

Project Manager: Paul Moser, *Division of Planning*

Determining Work Zone Lane Capacities

By Mingxin Li, Arde Faghri, Ruimei Fan

Safety and mobility for users and personnel on the worksite and efficient flow of traffic through work zones is a major concern to practitioners, researchers, managers, or transportation officials. The Federal Highway Administration (FHWA) requires all the state DOTs to develop a Traffic Management Plan during the design phase of road construction and maintenance projects. Following the FHWA requirement, state DOTs perform work zone traffic analyses to select appropriate lane closure strategies based on predicted capacity, queue lengths, user costs and crash rates for work zones to reduce construction times and minimize impacts on the motoring public. While work zone processes and procedures differ significantly from state to state, they all focus on developing increased capacity and efficiency through the work zone or within the adjacent corridor. ***Figure 1*** illustrates a typical work zone on a multilane signalized corridor in Delaware.

Figure 1: Work zone at Summit Bridge Road, Delaware
(Photos taken on January 29, 2017 at Summit Bridge Road)

The determination of appropriate time periods for lane closures is a balance between the needs of the construction crews to complete the work in a timely manner as well as providing the least amount of delay to motorists approaching and traveling through the work zone. The capacity of the work zone can be estimated by establishing a relationship between speed reduction and the primary factors impacting the work zone capacity. Currently, the Delaware Department of Transportation (DelDOT) refers to the Work Zone Safety and Mobility Procedures and Guidelines document, more specifically Table-2 of the Guidelines: "Measured Average Work Zone Capacities" to determine capacity values within work zones on uninterrupted roadway facilities.

The purpose of this study was to provide the Delaware Department of Transportation (DelDOT) with a review of the state-of-the-practice tools for managing work zone safety, estimating the traffic mobility impacts at work zones and developing Delaware-specific values much like those found in the DelDOT Work Zone Safety and Mobility Procedures and Guidelines and the 2010 HCM to represent work zone lane capacities on multilane signalized roadways.

Our analysis of the issues is informed by a comprehensive review of the approaches taken by researchers and practitioners for the estimation of capacity in construction work zones to mitigate traffic delays caused by such closures in past research. An annotated bibliography of over 60 references is presented which is concerned primarily with work zone capacity model. A literature search of the 50 state transportation agencies, as well as the District of Columbia were conducted to determine what innovative practices of work zone operations are being utilized to determine the capacity at work zones. However, not all states have formalized a policy that can be used for estimating the traffic impacts of work zone lane closures. Since many traffic flow analysis tools applied to work zones do not consider congestion characteristics such as queue length and delay, we provide a systematic review of software developed to perform the work zone capacity analysis and to help quantify queue length and travel delay times. We also explore how to help mitigate traffic delay problems.

The presentation of analysis methods used to evaluate traffic conditions under work zone operations is separated into two components: freeways and multilane signalized arterial, because performance measures used to characterize these two roadway types are different. Since traffic flow on most of multilane signalized roadways in Delaware does not exceed the work zone capacity, it is more difficult to estimate true value of work zone capacity. To this end, we propose a new methodology to determine work zone capacity distribution based on the probabilistic speed-flow-density relationships. Data in terms of the traffic flow, speed, density, lane occupancy in work zones were collected in six work zones on freeways in California and twenty-five work zones on multilane signalized roadways in Delaware. To calibrate queue discharge rates, the volume, speed and occupancy data are extracted from the Performance Measurement System (PeMS) (2016) covering from 05/18/2015 to 06/05/2015. (***Figure 2***).

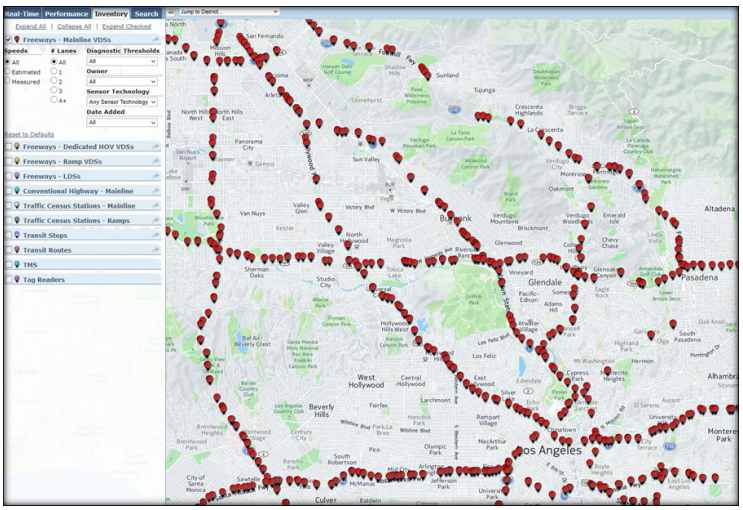

Figure 2: Map of the PEMS traffic monitoring network in Los Angeles Area

Data quality is a significant concern in traffic data archiving. ***Figure 3*** shows the fundamental diagrams (FD), which reflect the fundamental car-traffic speed-flow-density relationship that are valuable in building confidence in the quality of our analysis data.

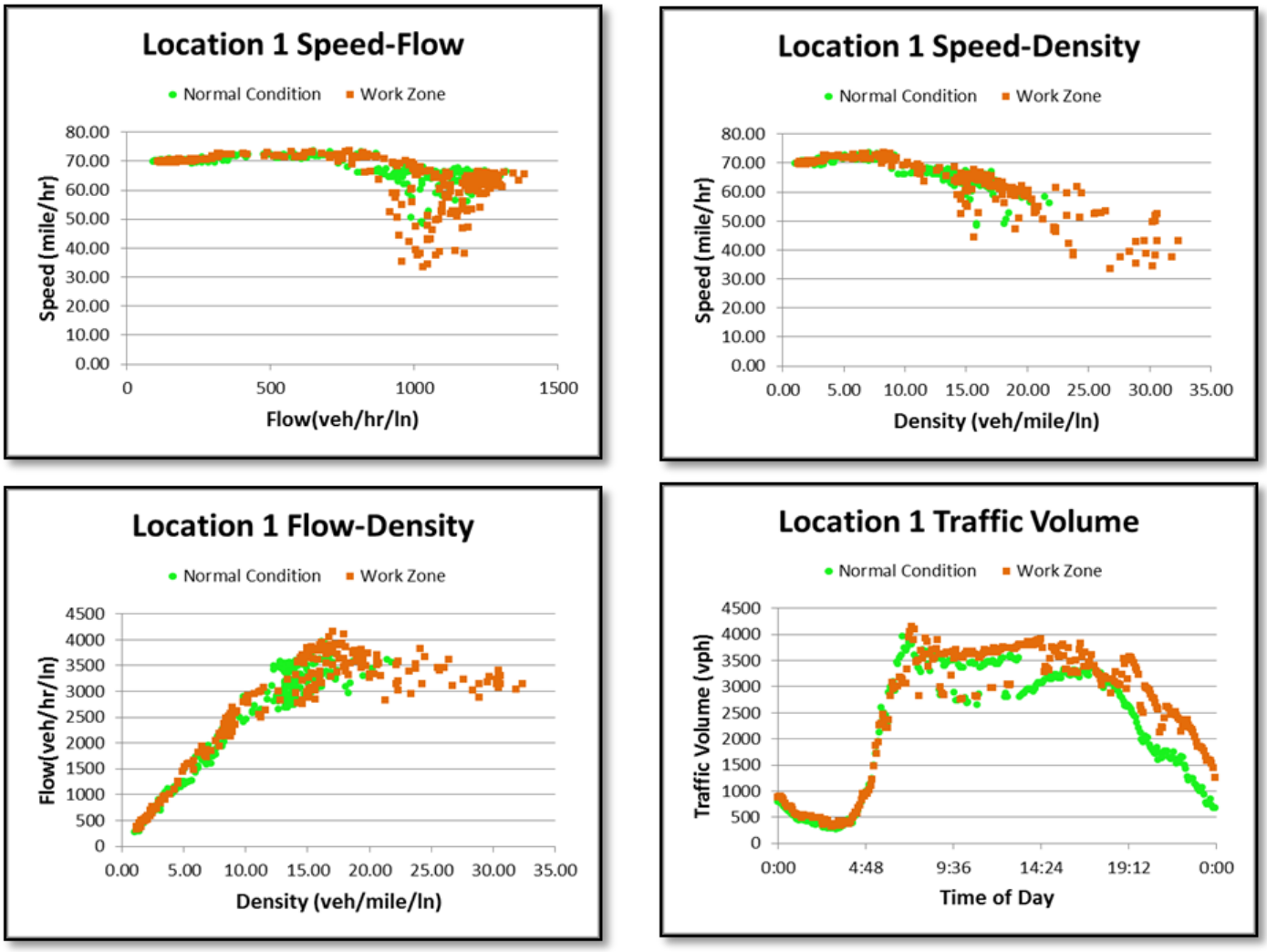

Figure 3: Field data plots showing the fundamental diagrams

Note that, instead of using travel time, we use the distance-weighted travel time rate (in minutes per mile), an important measure of traffic performance to exclude the variability caused by trip distance. The standard deviation and mean travel time rate are computed for every 5 minute interval based on real-data.

Figure 4 shows a robust linear relationship between the mean travel time rate and its standard deviation ($R^2 = 0.99$ for 10% sample data; $R^2 = 0.97$ for 100% sample data).

Although the relationship between the standard deviation and mean of space headway was apparently linear (*Figure 5*), the coefficient of determination ($R^2 = 0.79$ for 10% sample data; $R^2 = 0.71$ for 100% sample data) were both smaller than for standard deviation and mean of travel time per distance. Similarly, the results in *Figure 6* shows that there is a significant linear relationship between standard deviation of queue length ($P < .001$), although the data appear to be more scattered with a lower coefficient of determination in regression ($R^2 = 0.67$ for 10% sample data; $R^2 = 0.71$ for 100% sample data).

Sites selected for evaluation differed on types of roads, traffic volume, section lengths, geometric characteristics, and time lengths of construction activities . After collecting the traffic data at work zone, the time series plots of flow, occupancy were studied to find how the presence of lane closure affects the flow.

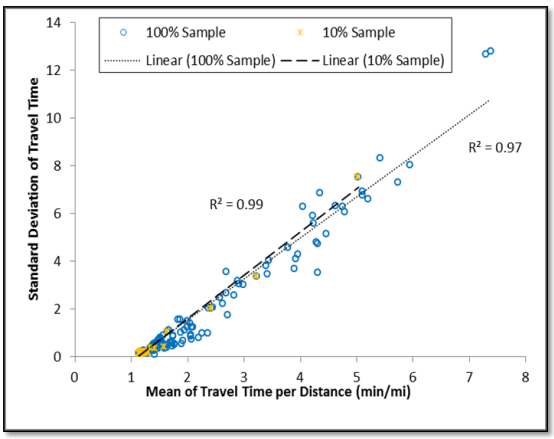

Figure 4: Mean travel time rate and its standard

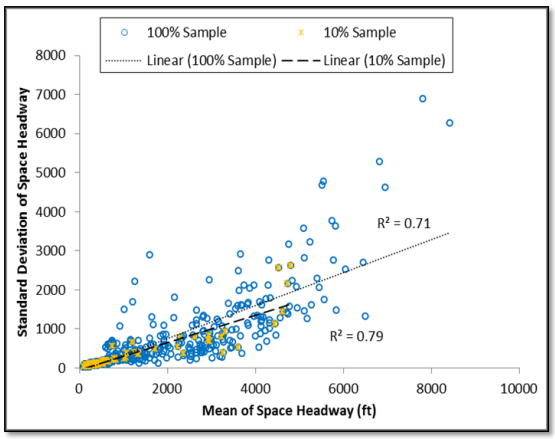

Figure 5: Mean space headway and its standard deviation

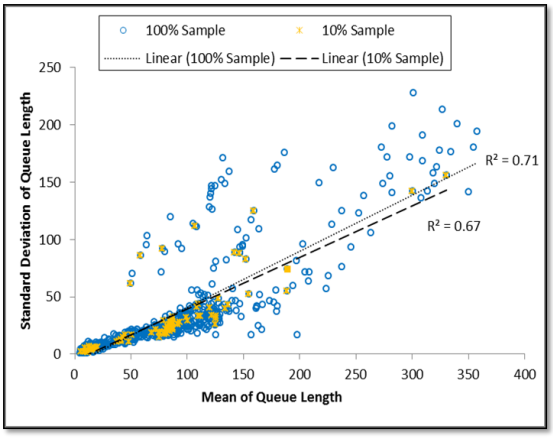

Figure 6: Mean queue length and its standard deviation

Two groups of plots were studied: time series plots for flow-occupancy scatter plots (***Figure 7***) and traffic flow vs. occupancy scatter plots (***Figure 8***).

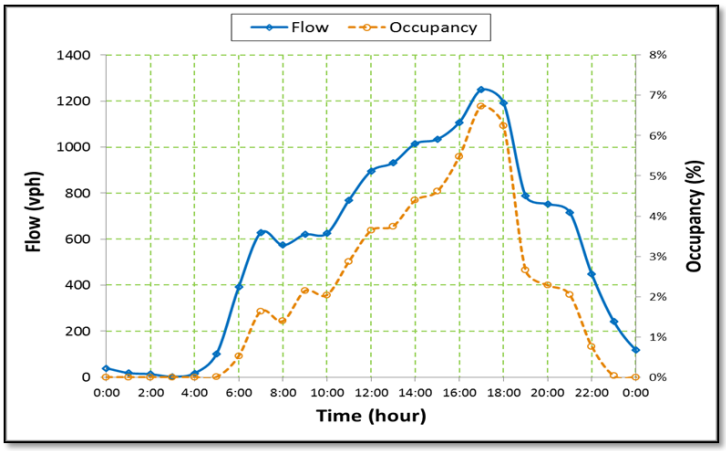

Figure 7: Time series plots for flow-occupancy scatter

Figure 7 and ***Figure 8*** are flow-occupancy scatter time series plots for Naamans Road between Foulk Road and I-95, Eastbound. There is little or no drop in speed with increasing flow, which indicates that vehicles at most of the work zones remained stable and close to the work zone speed limit, i.e., under uncongested conditions. The linear flow-occupancy relationship represents free flow condition, while the flow-occupancy curve shifts upward when relationships drivers proceed through the work zone with higher flow at given occupancy.

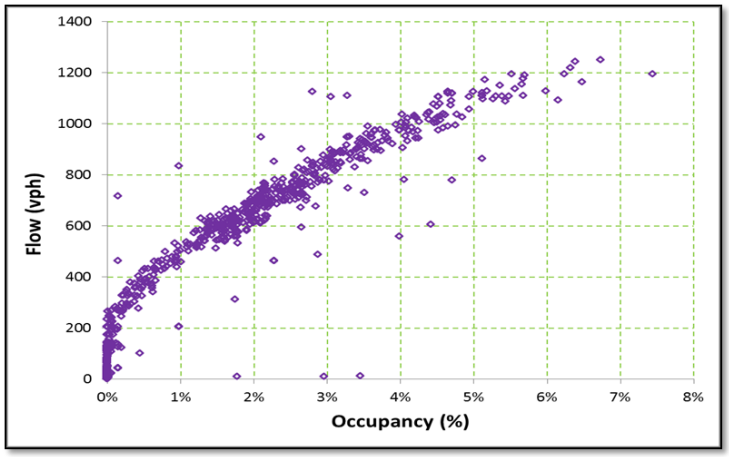

Figure 8: Flow vs. occupancy scatter plots, Naamans Rd., Foulk Rd. to I-95, EB

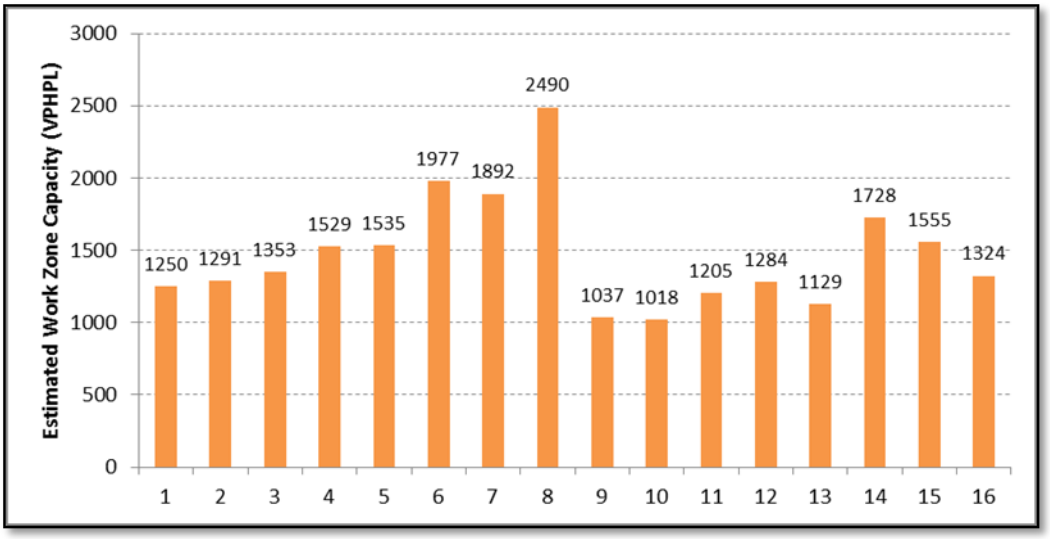

Figure 9: Work zone capacity distribution

The 25-site average capacities were 1475 vphpl for 15-min sustained flow (***Figure 9***). Notably, they were larger than the 1240 vphpl Highway Capacity Manual (HCM) based capacity values and currently used by DelDOT but lower than most values found in the nationwide survey. The proposed methodology can be helpful in evaluating the variability of work zone capacity and selecting better the work zone traffic control strategies to improve the capacity and construction staging.

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