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Advanced Highway Maintenance and Construction Technology Research Center

Department of Mechanical and Aerospace Engineering
University of California at Davis

Expanding Mobile Terrestrial Laser Scanning Capability and Capacity throughout Caltrans

Kin Yen, Stephen Donecker, Bahram Ravani &
Ty A. Lasky: Principal Investigator

Report Number: CA18-2729
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The purpose of this research included maintaining Caltrans' existing Mobile Terrestrial Laser Scanning (MTLS) capability and capacity in Northern California and expanding Caltrans' MTLS capability and capacity in Central and Southern California. The research methods included training Central and Southern California surveyors, providing deployment support for Central and Southern California, executing case studies for MTLS pilot projects, assessing agency needs to determine whether to share the existing MTLS system or to procure another system, updating MTLS specifications based on previous findings, and evaluating Central and Southern California IT resource needs for MTLS post-processing. AHMCT researchers worked with the Caltrans Office of Land Surveys as well as Caltrans districts in this project. The researchers also updated MTLS specifications in support of procurement and provided advice for the new MTLS system installation.

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LIST OF ACRONYMS AND ABBREVIATIONS

Acronym	Definition
AASHTO	American Association of State Highway and Transportation Officials
AHMCT	Advanced Highway Maintenance and Construction Technology Research Center
ASCII	American Standard Code for Information Interchange
CAD	Computer-Aided Design
Caltrans	California Department of Transportation
CHP	California Highway Patrol
CSDS	California Surveying and Drafting Supply
DC	Direct Current
DMI	Distance Measuring Instrument
DOE	Division of Equipment
DOT	Department of Transportation
DPAC	Division of Procurement and Contracts
DRISI	Division of Research, Innovation and System Information
DSRC	Dedicated Short Range Communications
DTM	Digital Terrain Model
FHWA	Federal Highway Administration
FOV	Field of View
FTP	File Transfer Protocol
GB	Gigabyte
GE	General Electric
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
HP	Hewlett-Packard
IMU	Inertial Measurement Unit
IT	Information Technology
KML	Keyhole Markup Language
KMZ	Compressed KML
LAS	Log ASCII Standard
LCD	Liquid-Crystal Display
LiDAR	Light Detection and Ranging
MAIT	Multidisciplinary Accident Investigation Team
MB	Megabyte
MMITSS	Multi-Modal Intelligent Traffic Signal Systems
MMS	Mobile Mapping Suite
mph	Miles Per Hour
MS	Microsoft
MTLS	Mobile Terrestrial Laser Scanning
ODBC	Open Database Connectivity
OHS	Overhead Sign
OLS	Office of Land Surveys
OoP	Office of Photogrammetry
PCS	POS Computer System
POS	Position and Orientation System
POSPac	Position and Orientation System Postprocessing Package
QA/QC	Quality Assurance / Quality Control
RFQ	Request for Quotation
rpm	Revolutions Per Minute
SAE	Society of Automotive Engineers
SATA	Serial AT Attachment

Acronym	Definition
SHP	Shapefile
SMB	Survey Management Board
SR	State Route
SSD	Solid State Drive
TAG	Technical Advisory Group
TAM	Transportation Asset Management
TB	Terabyte
TLS	Terrestrial Laser Scanning
UPS	Uninterruptible Power Supply
USB	Universal Serial Bus
USDOT	United States Department of Transportation
UTM	Universal Transverse Mercator
Ver.	Version
WGS84	World Geodetic System 1984

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We also thank Larry Orcutt, Robert Myers, Jason McMillan, Angela Wheeler, and the talented staff at the Caltrans Division of Equipment for their active and excellent support on the MTLS vehicle integration, maintenance, upgrade, and repair. Their work was instrumental to the safe, successful, continuous operation of the MTLS vehicle. We also thank Tony Tavares and the Division of Maintenance for their support of this research and for traffic control during MTLS operations. The authors acknowledge the dedicated efforts of the AHMCT team who have made this work possible.

EXECUTIVE SUMMARY

Under previous research [1] the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center at the University of California-Davis worked with the California Department of Transportation (Caltrans) Office of Land Surveys (OLS) to successfully provide training, technical support, and evaluation for the Mobile Terrestrial Laser Scanning (MTLS) system used by Caltrans districts in Northern California. The current research is a continuation of the evaluation performed in prior research titled "Mobile Terrestrial Laser Scanning Workflow Development, Technical Support and Evaluation." Under this research, AHMCT provided support for the MTLS capabilities of Northern California Caltrans surveyors and expanded the capability and capacity for Caltrans MTLS use, including expansion into Central and Southern California. The MTLS research projects fulfilled all of Caltrans Division of Research, Innovation and System Information's (DRISI) five stages of deployment.

The primary objective of the research was on maintaining and expanding Caltrans MTLS capability and capacity. This research maintained Caltrans MTLS capabilities in Northern California and expanded the capability and capacity for MTLS into Central and Southern California. It provided the necessary technical support, including minor system repairs and troubleshooting, in support of Caltrans field testing and regular use. For more significant issues, AHMCT researchers acted as a liaison and provided local MTLS system support as well as worked with the Caltrans OLS and the MTLS system provider to diagnose and repair the MTLS system. The research project tasks included:

- Task 1: Form a Technical Advisory Group
- Task 2: Continue deployment support for Northern California's use of MTLS
- Task 3: Evaluate Central and Southern California's Information Technology (IT) resource needs for MTLS post-processing
- Task 4: Assist Caltrans in training staff on MTLS operations
- Task 5: Provide deployment support for Central and Southern California use of MTLS
- Task 6: Perform case studies for specific MTLS projects
- Task 7: Document existing MX8 MTLS system usage
- Task 8: Develop/modify MTLS specifications and Request for Quotation for procurement of a new MTLS system
- Task 9: Provide overall MTLS-related IT infrastructure requirement review and recommendations
- Task 10: Documentation and Reporting

Lessons Learned

- Maintaining spare parts has reduced system down time. A spare Distance Measuring Instrument (DMI) was purchased for each of the MTLS systems (MX8 and VMX-1HA) during this project. The spare MX8 DMI has reduced the MX8 DMI failure down time to only one day from one week.

- Trident Version 7.1 or higher (the latest version of MTLS post-processing software) should be used since Caltrans is currently deploying Microsoft Office 2013 statewide (see

Chapter 2). All Caltrans MTLS workstations have been upgraded to Trident Version 7.3 during this project and do not experience any conflict with 32-bit Microsoft Office.

- MTLS specifications were updated to ensure that the maintenance and service plan from the vendor covers:
    - Free loaner component should any component fail, and
    - Repair and/or replacement of components.
- MTLS deployment has been successful and yielded accurate data due to the development and rigorous application of good and consistent workflow.
- Access to a tool to automatically extract Geographic Information System (GIS) data for MTLS data management would help. Such a tool has been developed in separate research and deployed in Caltrans District 4 [4].
- The Request for Quotation procurement process worked well for purchasing an MTLS system.
- Caltrans Division of Equipment (DOE) staff were instrumental in the installation and deployment of both MTLS systems.
- The second MTLS system improved MTLS availability for time-sensitive projects, such as a California Highway Patrol (CHP) Multidisciplinary Accident Investigation Team (MAIT) survey.

Recommendations

- With an accommodating budget, spare parts should be purchased and maintained in order to reduce system down time:
    - Several extra 43 mm Heliopan Digital Ultraviolet/Infrared filters should be purchased and available as spares
    - Other spare parts, such as a computer motherboard, interface board, power supplies, UPS, and inverter, should be considered.
- A custom shipping case (e.g. Pelican case with custom-cut foam) should be used to better protect the camera pods for international shipping.
- When shipping the system, screw-on lens caps should be used instead of snap-on lens caps.
- Due to personnel changes via retirement or promotions, ensuring continued availability of trained MTLS surveyors requires continued training or peer-to-peer training.
- MTLS users should provide mutual support and pass on institutional knowledge to new MTLS surveyors. OLS hosted two three-day-long peer-to-peer workshops to exchange and document MTLS best practices for data post-processing and feature extraction. The peer-

to-peer workshops were valuable in gathering the best ideas from all MTLS users. A few districts have used their current MTLS users to train new MTLS users.

Future Work

- Provide deployment support for both the Trimble MX8 and the Riegl VMX-1HA MTLS systems

- Support MTLS data management and distribution:

    - MTLS data backup policy
    - MTLS data retention policy (raw and post-processed MTLS data)
    - MTLS data sharing policy
    - Visualization for MTLS data availability

- Support Caltrans in updating Chapter 15 of the Caltrans Surveys Manual

CHAPTER 1: INTRODUCTION

Background

Under previous research [1] the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center at the University of California-Davis worked with the California Department of Transportation (DOT) (Caltrans) Office of Land Surveys (OLS) to successfully provide training, technical support, and deployment support for the Mobile Terrestrial Laser Scanning (MTLS) used by Caltrans' Northern California districts. Under the current research, AHMCT maintained support for the Northern California MTLS capabilities and expanded its capability and capacity, including expansion into Central and Southern California.

Research Objectives

Results from previous research [1-3] by AHMCT and Caltrans OLS have shown increased employee safety, reduced costs, and expedited delivery of State transportation improvement projects with the use of MTLS. Caltrans has already realized the benefits of MTLS in its northern districts under previous AHMCT research [1, 3]. Caltrans OLS has recognized the need to expand MTLS capability and capacity into its central and southern districts in order to realize the full potential of MTLS throughout California.

The research objectives included:

- Maintaining Caltrans' existing MTLS capability and capacity in Northern California and expanding Caltrans' MTLS capability.
- Expanding MTLS capacity into Central and Southern California. The research included training Central and Southern California surveyors as well as deployment support for Central and Southern California. In addition, the MTLS survey personnel's responsibilities were updated.
- Performing case studies for MTLS pilot projects.
- Updating MTLS specifications based on previous findings in support of procurement of the next-generation MTLS system.
- Evaluating Central and Southern California's Information Technology (IT) resource needs for MTLS post-processing.

Formation of a Technical Advisory Group

In the beginning of the project, AHMCT worked with Caltrans to form a Technical Advisory Group (TAG) composed of representatives from the Caltrans districts, Caltrans OLS, district surveyors, AHMCT researchers, and Caltrans Division of Research, Innovation, and System Information (DRISI). This advisory group set project objectives, goals, and schedule and task details. The TAG and an MTLS user group met regularly throughout the project to discuss and solve any problems encountered.

Dissemination of Results

An AHMCT researcher and Caltrans OLS personnel have presented the MTLS deployment progress regularly at Survey Management Board (SMB) meetings. DRISI presented the Caltrans MTLS deployment results in the Federal Highway Administration (FHWA)/American Association of State Highway and Transportation Officials (AASHTO) Transportation Asset Management (TAM) Webinar 19: Data Acquisition, Collection, and Methods.[1]

[1] http://www.tam-portal.com/wp-content/uploads/2016/02/TAMwebinar19-20160210a.pptx

CHAPTER 2: CONTINUE DEPLOYMENT SUPPORT FOR NORTHERN CALIFORNIA MTLS USE

AHMCT has, under previous research, helped to establish MTLS capability and capacity for Caltrans' Northern California region. AHMCT also supported Northern California's MTLS deployment.

This task focused on the following two areas:

1. Support to ensure continuous MX8 MTLS operation
    a. Phone and email support for MTLS users having issues with MX8 hardware and related software deployment
    b. Upgrade system components for system improvements
    c. Support for repair and maintenance services
    d. Support for software upgrades
    e. Support for sensor calibration/bore sighting
    f. Attend MTLS user meetings and provide MTLS deployment status updates to the SMB.
2. Support expansion of MTLS capability and capacity for Northern California by
    a. Training new personnel on the deployment of the MX8 MTLS system and related software
    b. Developing workflow and assisting with pilot projects for MTLS new applications and customers.

Support MX8 MTLS Operation

Solid State Drive Upgrade

The Trimble MX8 came equipped with four conventional 3.5" 2-Terabyte (TB) data hard drives [1] with spinning platters mounted in trayless drive bays as shown in Figure 2.1. The trayless drive bays allow the data hard drives to be ejected for in-office data copying using a Universal Serial Bus (USB) drive dock. In February 2015, an AHMCT researcher replaced the original data drives with Samsung 850 EVO 1-TB 2.5" Serial AT Attachment (SATA) III internal solid-state drive (SSD) (MZ-75E1T0B/AM) hard drives enclosed in Icy Dock EZConvert 2.5" to 3.5" SATA/SSD hard drive converters. Four 1-TB SSD drives were purchased, for a total capacity of 4 TB. The SSD drive replacements increased file transfer speed and reduced data copying time. The SSD drives provided a higher data transfer rate (100 Megabyte (MB) per second (MB/s) to 130 MB/s) when used with a USB 3 drive dock connected to an office workstation. However, there was no measurable difference in data transfer speed when copying data from the MTLS vehicle computer to a USB 3 external drive. The on-board USB 3 controller in the vehicle data collection computer limits the maximum data transfer rate. The maximum transfer rate is about 50 to 60 MB/s when copying data using the data collection computer. Larger and faster SSDs may be employed in the future when SSD costs reduce. The current 1-TB SSDs provide sufficient storage for most MTLS projects. Larger SSDs may be needed for large-scale road network mapping.

Figure 2.1: MTLS trayless drive bay

Distance Measurement Instrument (DMI) Bearing Failure and Replacement

In March 2015, the Distance Measurement Instrument (DMI) was making a loud and unusual noise when the vehicle wheel was turning. This was due to a DMI bearing failure. Caltrans OLS bought an extra DMI at the time of the MX8 MTLS system purchase. The DMI on the vehicle was replaced with this spare DMI, shown in Figure 2.2. At the same time, rubber splicing tape (NSI Industries EWRT 3022.75) was put over the DMI connector to improve water resistance. The local Trimble dealer, California Surveying and Drafting Supply (CSDS), provided a replacement DMI unit as a spare under the terms of the system warranty.

Figure 2.2: MTLS system DMI mounted on the driver-side rear wheel

Recommendation:

- Having a spare DMI on hand reduces the down time for DMI replacement.

Applanix Position and Orientation System Computer System Repair

During a pilot project/data collection training at District 12 at the end of April 2015, the Applanix Position and Orientation System (POS) Computer System (PCS) failed to power on. After some diagnostics on the Applanix PCS power supply and discussion with Trimble technical support, the AHMCT research team traced the problem to the Applanix PCS. The Applanix PCS was sent back to Trimble Applanix for repair. Trimble provided AHMCT a loaner Applanix PCS for temporary use while Trimble repaired the original Applanix PCS. The loaner PCS was installed and configured by an AHMCT researcher with Trimble phone technical support so that the pilot projects and training could continue in District 12. The lever arm data and serial port output messages had to be configured for the MX8 system to function properly.

Trimble Applanix determined that the PCS power switch, located at the front panel, was broken, and the front panel circuit board, where the PCS power switch is connected, was replaced. The repaired Applanix PCS was then reinstalled a couple of weeks later at District 12. The Applanix PCS configuration was saved in the MX8 system computer. Consequently, if the PCS needs replacement in the future, the PCS configuration can be loaded quickly.

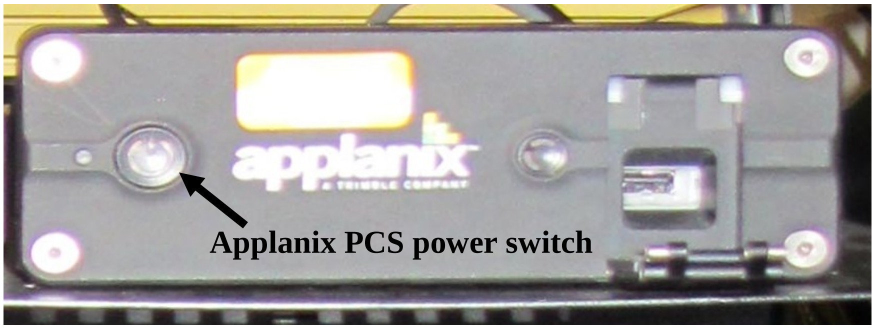

Figure 2.3: Applanix PCS

Modification of Camera Pods

In winter of 2014/2015, fog/water condensation appeared inside the front camera pod after driving the vehicle in heavy rain. The fog/water condensation slowly cleared up by itself. In June 2015, the camera pods (front and rear left, center, and right; back down) were sent to Trimble's Canada office for modification to reduce fog/water condensation build-up and reduce clearing-up time. Caltrans OLS and AHMCT personnel worked in the AHMCT machine shop to remove camera pods and Riegl laser scanners (see below section for reasons and details) from the sensor pod mounted on top of the MTLS vehicle. Trimble provided uninstallation and reinstallation instructions. After removing the camera pods and laser scanners, OLS and AHMCT personnel found that the rubber seals around the camera pods and laser scanners had deteriorated and cracked as shown in Figure 2.5. Trimble provided replacement rubber seals and extra fasteners for replacement along with the enhanced camera pods.

Figure 2.4: Sensor pod frame with the camera pods and laser scanners removed

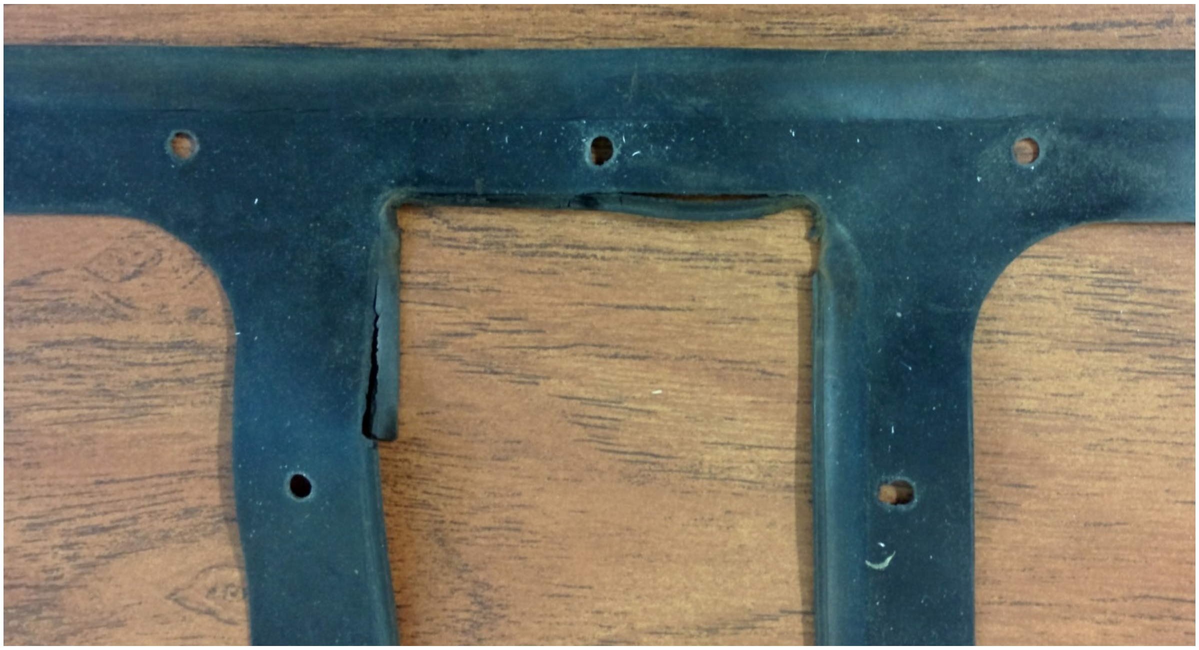

Figure 2.5: Cracking of camera pod rubber seal

Lens caps were installed to cover all camera filters during shipping to prevent scratches and other damage. Both screw-on and snap-on lens caps were used. During shipping back from Canada in July 2015, snap-on lens caps covering the front-center and back-center camera filters were crushed into the filters. As a result both the front-center and back-center camera filters were broken as shown in Figure 2.6. To get the MTLS back online and available for projects as soon as possible, AHMCT decided to do the filter replacements in the AHMCT shop instead of shipping the camera pods back to the Trimble Canadian office for repair. The original filters are 43 mm Heliopan Digital Ultraviolet/Infrared filters. However, the 43 mm Heliopan Digital Ultraviolet/Infrared filter was not widely available in the United States of America. They have to be special ordered and have about a six-week lead-time. Two B+W multi-coated 43 mm filters were ordered instead because of quick availability. However, a B+W 43 mm filter does not fit (only one thread was able to engage) onto the screw thread for the 43 mm filter on the camera pod. The B+W 43 mm filters were used temporarily with General Electric (GE) silicone II sealant to secure and seal the filter in place. The 43 mm Heliopan Digital Ultraviolet/Infrared filters arrived six weeks later. At that time, the B+W filters were replaced by the Heliopan filters. The Heliopan filters fit well with the screw threads on the camera pod, with all screw threads fully engaged. GE silicone II sealant was applied to seal the edge between the camera pods and filters.

Recommendation:

- For shipping, screw-on lens caps should be used instead of snap-on lens caps.
- A custom shipping case (e.g. Pelican case with custom-cut foam) should be used to better protect the camera pods for international shipping.
- Extra 43 mm Heliopan Digital Ultraviolet/Infrared filters should be purchased as spares.

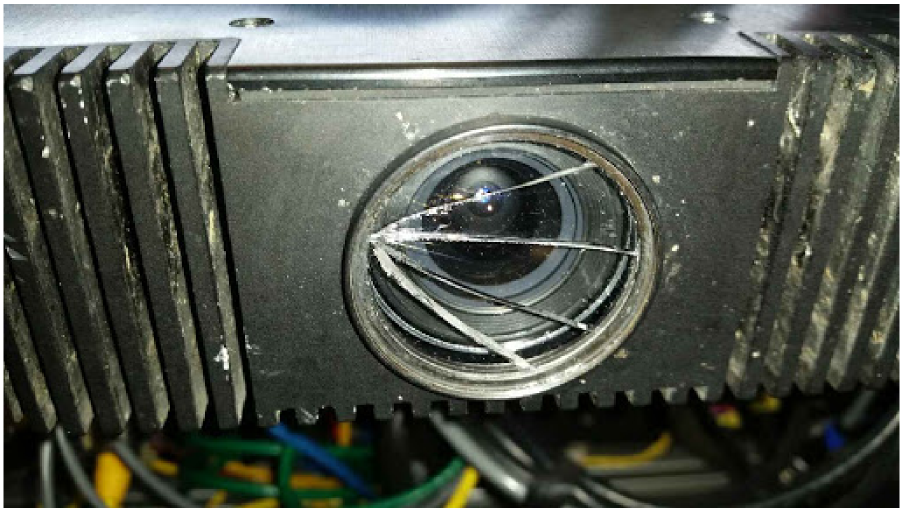

Figure 2.6: Broken front-center camera filter from shipping

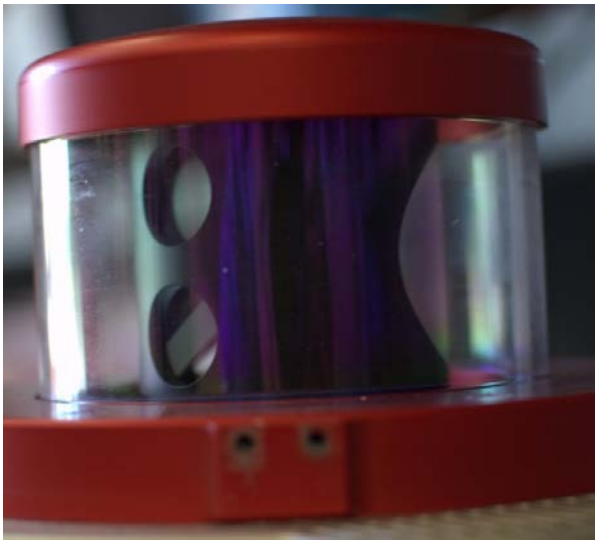

Figure 2.7: Haze/unknown deposit inside the scan window glass cover of the laser scanner

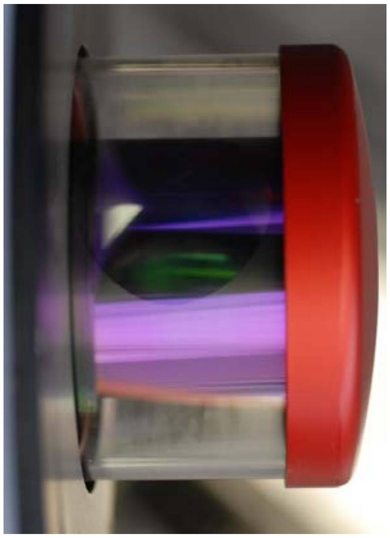

Figure 2.8: Haze/unknown deposit inside the scan window glass cover of the laser scanner

Performing Riegl Laser Scanner Service Package A at the Riegl factory

In June 2015, at the time of the camera pods' removal for service, both laser scanners were also removed for Riegl Service Package A maintenance services at Riegl's Austria factory. There were hazes or unknown deposit inside the scan window glass cover (see Figure 2.7 and 2.8) on both scanners. Before the scanners were removed, the AHMCT research team ran the Riegl software to download the services log data ("housekeeping" and "alert" files) from each laser scanner. The scanner log data files were emailed to Riegl. The Riegl Service Package A included scanner window cleaning, replacement of drying agent, a firmware update, and a nitrogen purge. The Riegl Austria factory shuts down for one month every year in July. The scanners were sent, serviced, and returned before the factory shutdown. Both scanners were installed along with the modified camera pods in the middle of July 2015.

Modify and Adjust Power Supply Voltage to Laser Scanner and Applanix POS

Following Trimble's instruction and recommendation, the power supply voltages to the scanners and the Applanix POS system were increased to the recommended voltage setting (28-Volt Direct Current (DC) for laser scanners and 14-Volt DC for the Applanix POS system). This was done after the camera pod and laser scanner re-installation by OLS and AHMCT personnel. The power supplies were removed for voltage adjustment and reinstalled afterwards.

Trimble Trident Capture Version 7 Software Upgrade

The data collection software Trimble Trident Capture was upgraded from version (Ver.) 4.8 to 7.0 after the camera pod and laser scanners' re-installation. One advantage of Trident Ver. 7.0 is the use of an SQLite database instead of the previous Microsoft (MS) Access database. The previous version of Trident requires the use of the 64-bit MS Open Database Connectivity (ODBC) driver which often conflicts with the 32-bit version of the MS Office being deployed statewide within Caltrans. Eliminating the use of the 64-bit ODBC driver in Trident Ver. 7.0 eliminates the downtime associated with resolving the 32-bit ODBC driver conflict in MS Office. Trimble provided the software installation files and upgrade procedures. The system (software and hardware) was tested afterward by collecting a full set of data and post-processing the data.

In addition, the Trimble Trident Capture Ver. 7.0 uses LA20 format instead of Log American Standard Code for Information Interchange (ASCII) Standard (LAS) 2.0 format for storing Light Detection and Ranging (LiDAR) data from the laser scanners. The new LA20 format results in files about 40% smaller than files in LAS 2.0 format. Consequently, Trimble Trident Capture Ver. 7.0 saves storage space and reduces time for data transfer. Furthermore, the new data collection software also reduces the number of steps for setting up a new project for data collection. Thus, it reduces time, labor, and the possibility of human error. The overall user experience of the new data collection software has been positive.

Known Bug: One known software bug was found and confirmed with Trimble. The Trident Laser Capture does not report the scanner scan rate correctly when the "All Targets" option is selected. The laser scanner is capable of outputting up to four targets per laser pulse. The user can elect to record "First Target," "Last Target," or "All Targets" in the Trident Laser Capture software. The software also provides real-time reading of the laser scan rate (scan mirror turn rate in revolutions per minute (rpm)). Accurate reading of the mirror scan rate would allow the user to make sure the mirror speed is up to the desired speed before beginning data collection. This is not a critical bug.

Recommendation:

- Trident Ver. 7.1 or higher (the latest version of MTLS post-processing software) should be used since Caltrans is currently deploying MS Office 2013 statewide.

Sensor Calibration/Bore Sighting

Whenever the sensors (laser scanners or cameras) are reinstalled back onto the MTLS sensor pod located on top of the vehicle, as done in July 2015, sensor alignment calibration or bore sighting is required. The Trimble MX8 has a specific calibration procedure which requires data collection along with post-processing in the office. Good calibration site selection is the first critical step. A good calibration site has the following characteristics:

- Intersections with buildings with large flat walls, flat roof, and sloped roof
- Flat inclined surfaces such as driveways, flat roofs, and flat concrete pavements are desirable
- Buildings with flat walls at varying distances away from the drive path
- Areas without tall trees which block both the laser to the flat surfaces and the Global Navigation Satellite System (GNSS) signal
- Relatively open sky for good GNSS signal reception.

Industrial parks and new residential areas (where there are fewer mature trees) are generally good calibration site candidates. Calibration site examples are shown in Figures 2.9 and 2.10.

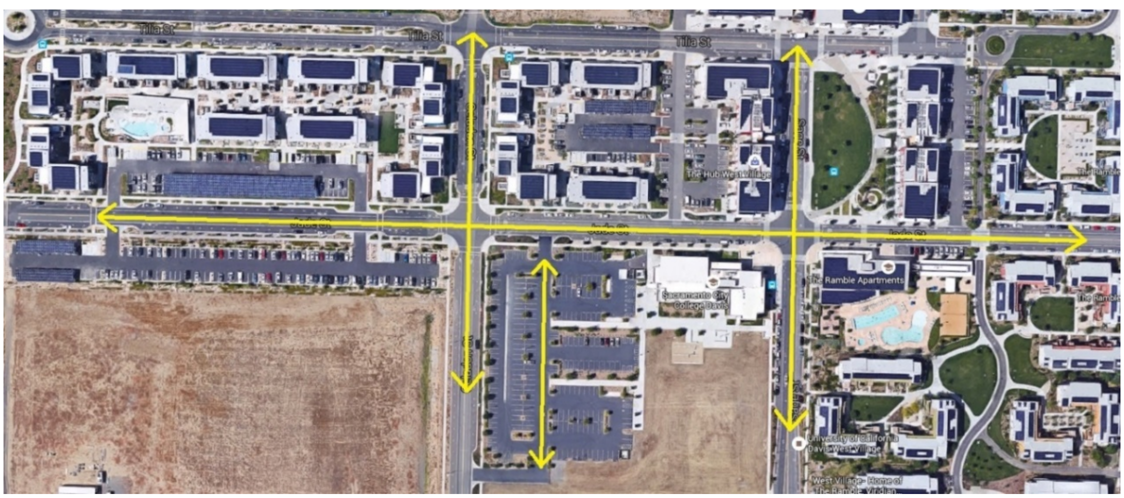

Figure 2.9: Google Map aerial image of UC Davis West Village used for MTLS calibration. Yellow lines are the recommended vehicle drive paths.

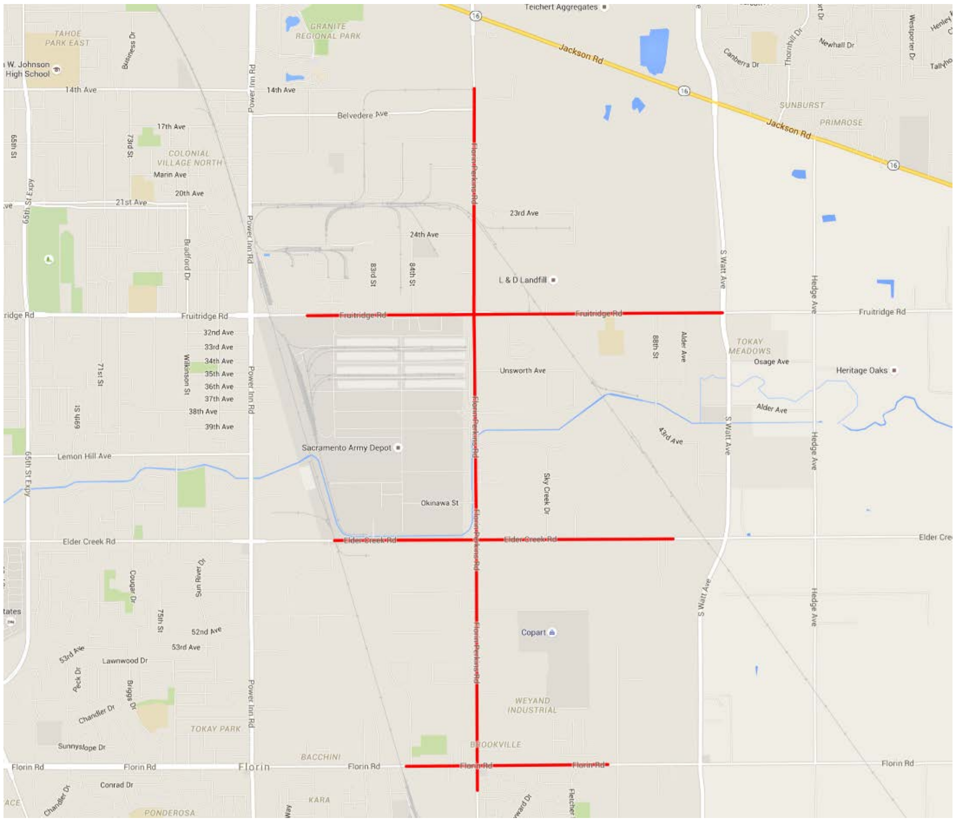

Figure 2.10: Google Map of an industrial park MTLS calibration site in Sacramento recommended by Trimble. Red lines are the recommended vehicle drive paths.

A dedicated GNSS base station must be set up to collect 1-Hz raw GNSS data at the time of data collection for two hours or more. The GNSS base station must be within 5 km of the calibration site for best results.

Data collection requirements:

1. Collection “runs” include driving past the intersection in all four directions repeatedly for at least two cycles. Three to four cycles are recommended. Figure 2.11, provided by Trimble, shows the planes/flat surfaces, run/drive paths, and buildings of a typical calibration site.

2. Vehicle speed 25 to 45 miles per hour (mph).

3. Laser scanner scan rate: 100 rpm.

4. Laser scanner measurement rate: ~ 300,000 points/s.

5. Imaging distance: 4 m.

6. Three to four intersections.

7. At least 45 min of GNSS/Inertial Measurement Unit (IMU) data

8. Drive around a block, a few full circles, and “figure 8” in a large parking lot after the initial 5 min static GNSS/IMU session.

9. MTLS operator must separate each drive path/run into a separate data recording or “run.” In other words, the operator must stop the data recording and start a new recording every time the vehicle is turned around and drives the same area again.

10. Calibrate using a minimum of 50 to 100 planes and a maximum of 200 planes (limited by current computing power).

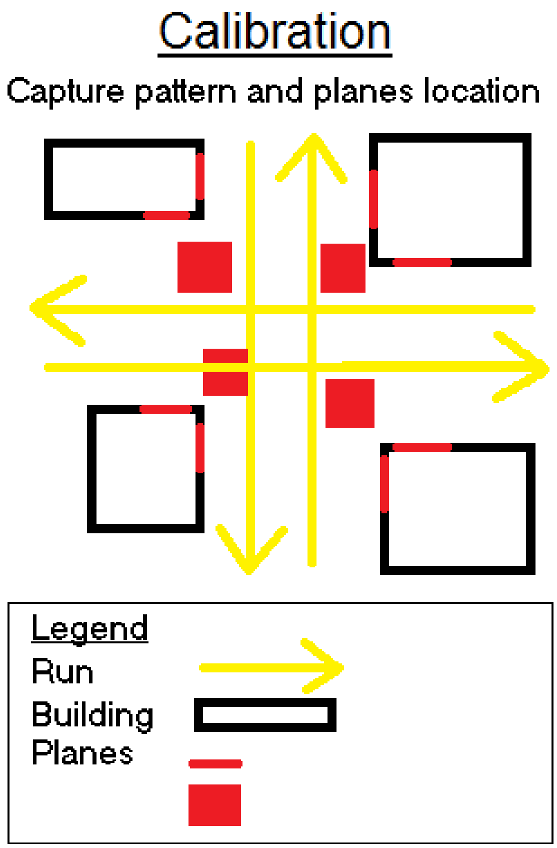

Figure 2.11: Drive path/run, intersection, and planes selection recommendations for MTLS sensor calibration/bore sighting (courtesy of Trimble)

Laser Alignment Calibration Problem

There was a problem with achieving a satisfactory laser alignment calibration for several months. During this time, five calibration data sets were collected at five different locations. In addition, the three intersections and two selected areas of the Sacramento industrial calibration site were scanned using a fixed terrestrial laser scanner (TLS). Trimble, Riegl, Caltrans, and AHMCT worked together to solve this issue with the highest priority. The cause was determined to be incorrect Riegl scanner factory calibration parameters uploaded during the scanner servicing in

Austria. Uploading the updated Riegl scanner calibration parameters to the scanners resolved the problem.

Batteries and Battery Separator Replacement

After four years of use, Caltrans Division of Equipment (DOE) replaced the two lead-acid batteries stored under the hood of the MTLS vehicle. The DOE mechanic also replaced the battery separator and upgraded the vehicle alternator. An AHMCT researcher worked with the DOE mechanic to test the MX8 MTLS system after the upgrade/repair. DOE staff's excellent support and vehicle maintenance were instrumental in keeping the MX8 MTLS vehicle running with minimal downtime.

Front Camera Housing Seal Repair

In the winter of 2016, water leaked into the MX8 front camera housing after driving in heavy rain. This caused fogging and moisture buildup on the camera filters and lenses. The front camera housing was opened to dry the camera housing and to replace the silica gel desiccant inside the camera housing. The photo below shows the blue silica gel desiccant inside the camera housing and the three digital cameras. Silica gel will change color from blue to pink when saturated with water. The silica gel is reusable after drying in an oven or microwave oven. Gasket lubrication was also added to improve the camera seal waterproof capability. Duct Seal, a malleable non-conductive sealing compound, may be used to seal the front camera housing opening edges in the future if required.

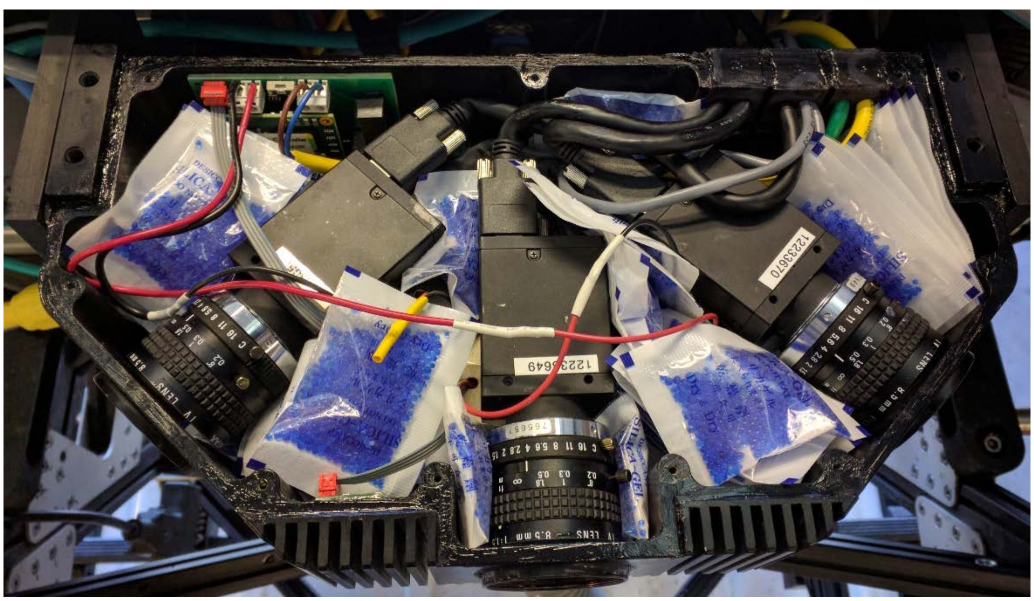

Figure 2.12: MX8 front camera housing packed with silica gel (blue packs) desiccant to keep the lenses from fogging

Trayless Data Drive Dock Replacement

The MX8 computer 3.5” hard drive docks on the server and client computers were replaced because the server computer dock was making an unreliable connection with the data storage hard drive. The new 2.5” drive docks support two additional solid-state drives. The photo below shows the new 2.5” drive dock installed in the server computer. Two spare solid-state drives are also stored at the bottom of the drive docks as shown in Figure 2.13.

Figure 2.13: Six bay 2.5” trayless drive cage installed on the MX8 server

<u>Expand Capability and Capacity for Northern California</u>

An AHMCT researcher trained a few District 4 surveyors in MTLS data post-processing in August and September 2014. The training primarily focused on workflow for overhead sign (OHS) extraction and asset management-related feature extraction. The District 4 OHS project is discussed in detail in Chapter 6 “Case Studies.” Nevertheless, District 4 surveyors needed new training on MTLS data post-processing due to the loss of two key MTLS personnel related to job changes. Two additional District 4 surveyors were trained on Trimble Trident MTLS post-processing software in October 2016.

Developing Workflow and Assisting with Running Pilot Projects for MTLS New Applications

The District 4 OHS project was a large-scale, network-wide MTLS project. A specific workflow was developed in conjunction with District 4 surveyors. The workflow was refined during the course of the project’s data post-processing. Detail is available in Chapter 6.

Lesson Learned and Recommendations Summary

- With an accommodating budget, access to spare parts (e.g. DMI, computer, lens filters, interface board, power supplies, uninterruptible power supply (UPS), and inverter) would reduce system downtime.

- Check to make sure maintenance and service plans from the vendor cover:

    - Free loaner component should any component fail

    - Repair and/or replacement of components.

CHAPTER 3: EVALUATE CENTRAL AND SOUTHERN CALIFORNIA'S IT RESOURCE NEEDS FOR MTLS

MTLS post-processing places high demands on computing resources. In this task, the AHMCT research team evaluated Central and Southern California's IT resource needs before deployment of MTLS in Central and Southern California. The research team worked with OLS and district surveyors to help the participating districts establish the IT resources needed for initial MTLS deployment, and developed an estimate of future demands.

Resource evaluation included:

- Workstation hardware and configuration that conform to Caltrans IT
- Post-processing and feature extraction software needs
- Data storage for short-term and long-term deployment.

Computing Resources

Based on the MTLS deployment plan (developed in previous research) shown in Figure 3.1, certain IT resources must be identified, procured, delivered, and installed at participating districts before training and deployment of MTLS begins. Previous research projects as well as the experience from MTLS deployment in Northern California indicate that MTLS skills are highly perishable. To minimize degradation of knowledge between training and pilot project execution, IT computer resources must first be in place before training occurs. In the early stage of Central and Southern California MTLS deployment, an AHMCT researcher and OLS personnel met with managers from each district to seek their participation and support on MTLS deployment. The initial IT resources required were developed based on the number of participating districts as determined in the meetings with district management.

Based on previous MTLS software and Caltrans IT requirements, a Hewlett-Packard (HP) Z-820 workstation with dual monitors, shown in Figure 3.2, was procured by OLS for each Central and Southern California Caltrans district (5, 6, 8, 10, 11, and 12) that is participating in the MTLS deployment. The workstations were dedicated for MTLS data post-processing and not assigned to an individual user. In addition, a 4-TB portable hard drive was also provided to each participating district for transferring and storing MTLS raw data. The workstations have adequate internal storage for pilot and initial projects. OLS has also anticipated their MTLS project growth and allocated computing resources for future expansion and upgrades. Each district's need is being revised based on the MTLS deployment demands.

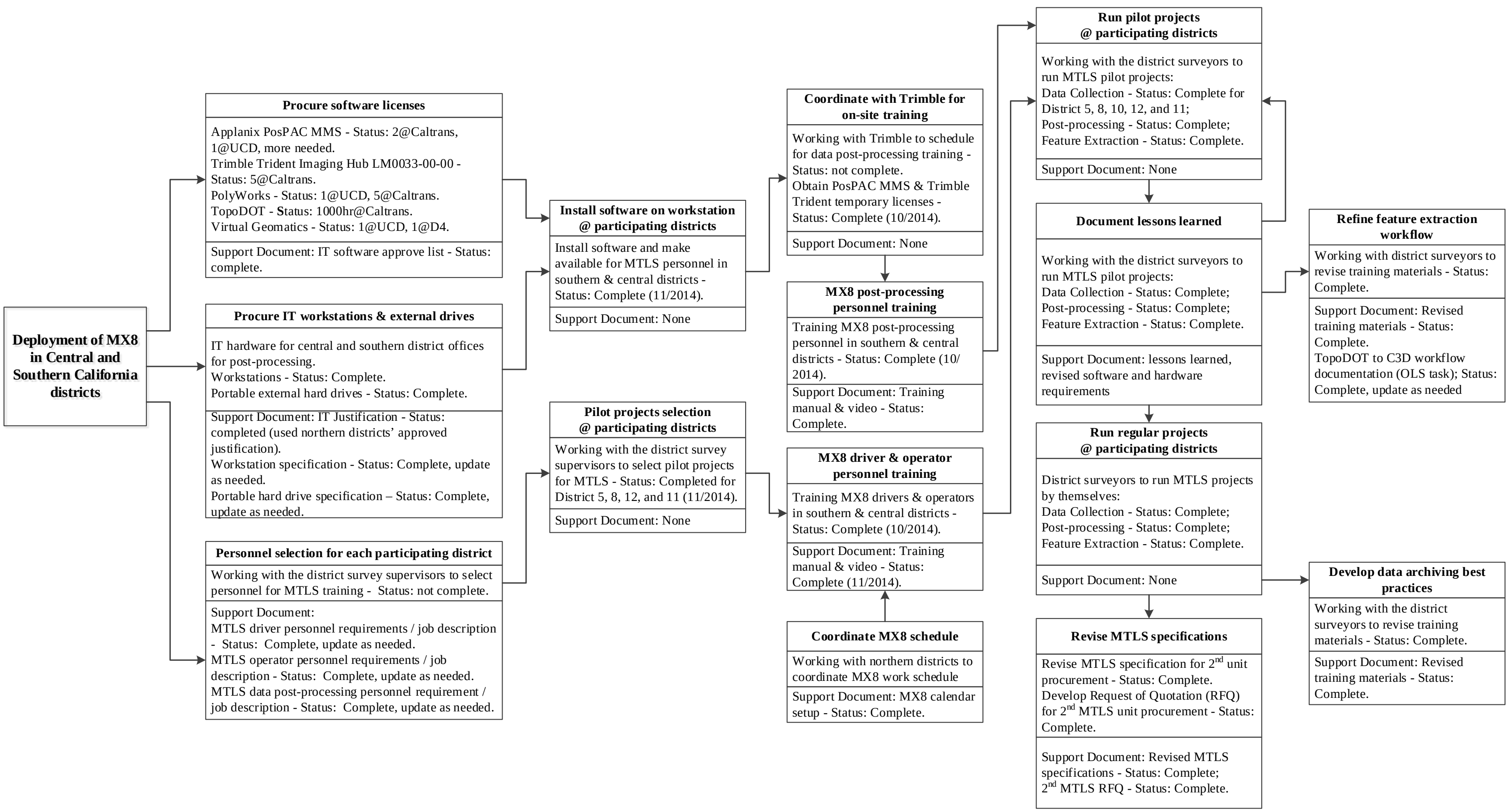

Figure 3.1: MTLS deployment plan for Central and Southern California (All milestones completed as of Nov. 2017)

OLS and AHMCT researchers updated the MTLS data post-processing workstation (HP Z-840) specifications in September 2016. The workstation specifications are available via an internal Caltrans OLS document entitled “Mobile Terrestrial Laser Scanning (MTLS) Roles, Responsibilities, and System Requirements Capabilities and Capacities.” This document was distributed to the MTLS users and the district managers for review. Their comments were incorporated into the current version of this report. The document will be updated as new computer workstation models become available and old models become obsolete. Additional workstations would be needed as the number of trained personnel for MTLS data post-processing and feature extraction increases. The number of personnel depends on the number of projects planned for a given district.

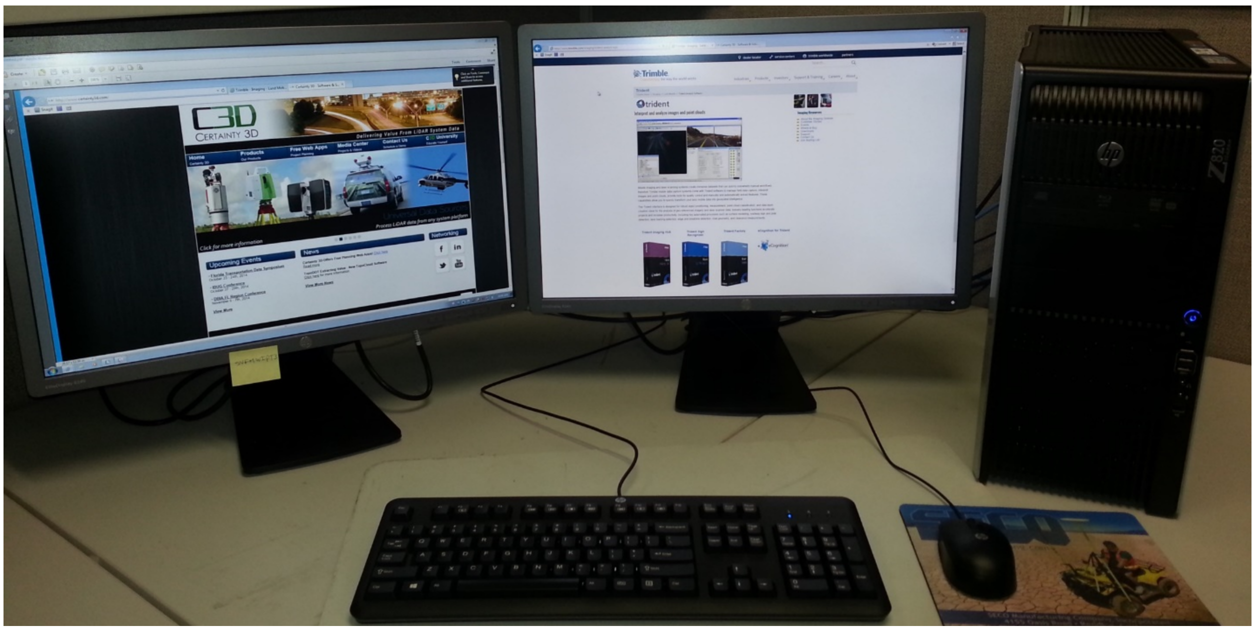

Figure 3.2: HP Z-820 Workstations

Post-Processing and Feature Extraction Software Licenses Required for Each Central and Southern California MTLS Deployment

Additional software licenses were purchased in anticipation of increased usage due to the increased number of users before MTLS deployment to Central and Southern California. Trimble Applanix Position and Orientation System Postprocessing Package (POSPac) Mobile Mapping Suite (MMS) and Trimble Trident software are used to post-process MTLS raw data to produce geo-referenced and registered point clouds. Certainty 3D’s TopoDOT, InnovMetric’s PolyWorks, Leica’s Cyclone, and Virtual Geomatics have been used for feature extraction. Caltrans has adopted TopoDOT as its primary feature extraction software.

Trimble Applanix POSPac MMS Ver. 7.2 is used to post-process raw GNSS/IMU data with GNSS base station(s) data to calculate the final accurate vehicle trajectory and orientation data. The existing two POSPac MMS USB dongle hardware licenses were upgraded to network server-based licenses. The POSPac MMS only required and acquired a license from the network server when certain functions (e.g. processing GNSS/IMU data with GNSS base station and “Find Base

Stations") were invoked by the user, unlike other programs which typically acquire a license during startup. The advantage of the Applanix approach is that users can set up the project and view processed result without using up a network license. Typically, users may use POSPac MMS for 30 min to 2 hours in GNSS/IMU data post-processing. Therefore, two POSPac MMS licenses should be sufficient for all envisioned Caltrans MTLS use. Based on usage history, no additional POSPac MMS licenses were purchased for the Central and Southern California MTLS deployments.

Trimble Trident software is used to combine the POSPac MMS solution with the laser scanners' measurements to produce a geo-referenced point cloud. In addition, Trident registers point clouds to ground control targets in order to yield higher-accuracy point clouds. This registration is particularly important in the vertical measurement. There are other Trident software features and functions that allow users to extract features from the data. These functions are not typically used. Trident software requires a license from the license server at startup. Typical Trident usage ranges from one day to one week for an MTLS project. At the beginning of this research, OLS had three Trident Hub licenses (provides basic geo-referencing and registration functionality) and two Trident Factory licenses (provides full semi-automated feature extraction functions). There were occasions when all five licenses were used after several pilot projects were executed in the MTLS deployments in Central and Southern California. To address this limitation, two additional Trident Hub licenses were procured and added to the license server. OLS has not subsequently experienced any more situations of running out of Trident licenses.

In anticipation of Central and Southern California MTLS deployment, OLS procured Certainty 3D's TopoDOT Enterprise 500 ("500 user-days of annual usage") software license for MTLS feature extraction in 2015. The TopoDOT license can be upgraded to Enterprise 1000 based on actual usage statistics provided by Certainty 3D's TopoDOT license server. OLS personnel also developed standard layers and a detailed workflow for converting TopoDOT data products into Autodesk Civil3D format for Computer-Aided Design (CAD) products for use by Caltrans Design customers. TopoDOT is currently being used throughout Caltrans' districts.

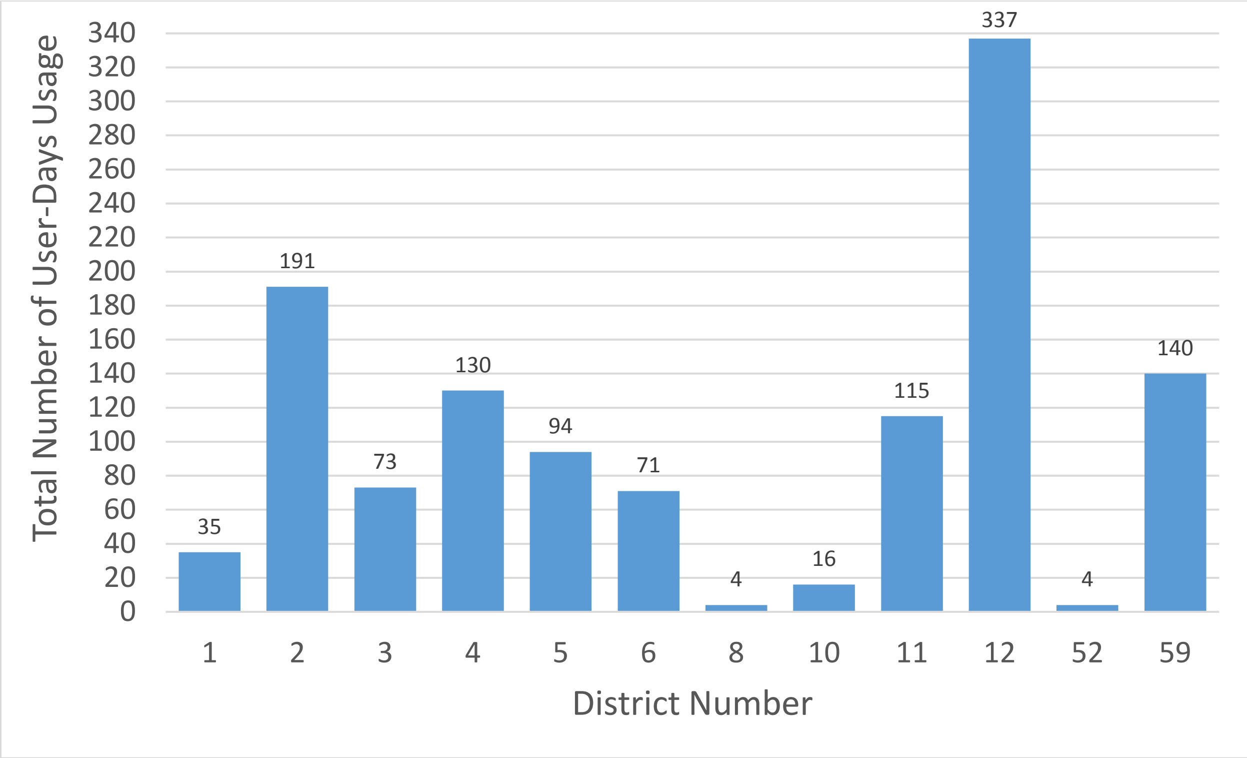

Figure 3.3: TopoDOT usage by districts from Dec. 1, 2015 to Nov. 1, 2016. District 52 is OLS, and District 59 is the Office of Photogrammetry (OoP)

In addition, Caltrans has two PolyWorks network licenses. PolyWorks has a very good edge detection and extraction tool. It is often used for extracting curbs, guardrails, K-rails, and bridge structural features. Because of its limited use, two licenses were found to be adequate for all Caltrans districts. Therefore, no addition licenses were procured for the Central and Southern California MTLS deployments.

CHAPTER 4: TRAINING CALTRANS STAFF ON MTLS OPERATIONS

In order to expand the capacity for MTLS deployment, more personnel must be trained to collect MTLS data, post-process MTLS data, and extract features from the MTLS point cloud. The Caltrans MTLS training has evolved throughout this research project. Initially, an AHMCT researcher conducted MTLS data collection training classes with OLS personnel in the Central and Southern California Caltrans districts. Trimble, Applanix, and Riegl provided training as part of their purchase agreements. After that, an AHMCT researcher working with district surveyors developed MTLS guidelines which included MTLS post-processing training materials in order to maintain institutional knowledge as MTLS surveyors retire or promote. Currently, MX8 MTLS training and support is provided by AHMCT or via peer-to-peer support by district surveyors.

Some districts have set up internal training programs and experienced great success in training new personnel to process MTLS data internally. District 1 has expanded to have two personnel capable of processing MTLS data. The additional personnel available for MTLS projects would increase both capacity and guard against loss of institutional knowledge due to loss of key personnel through retirement or job changes.

This task included:

- An AHMCT researcher updating the MTLS data collection procedure manual for the new version of Trident Capture (Ver. 7.0). The MTLS data collection procedure manual for Trident Capture Ver. 7.0 (TrimbleTridentCapture7_workflow.pdf) is available on the OLS File Transfer Protocol (FTP) site internal to Caltrans' network.

- AHMCT attending an Applanix POSPac MMS software training conducted by Applanix personnel to document POSPac MMS workflow for MTLS.

- AHMCT attending a Trimble Trident software training conducted by Trimble personnel to document Trident workflow for MX8 data.

- AHMCT attending a Riegl RiProcess software training conducted by Riegl personnel to document RiProcess workflow for VMX-1HA data.

- AHMCT conducting and facilitating an MTLS data collection and post-processing peer exchange workshop (April 25 to 27, 2017) to gather best practices from all experienced MTLS district surveyors.

- AHMCT conducting and facilitating a point cloud feature extraction peer exchange workshop (July 11 to 12, 2017) to gather best practices on TopoDOT and feature extraction from all experienced MTLS district surveyors.

- AHMCT providing on-site pilot project, phone, and webinar support on system debugging, GNSS/IMU post-processing, and Trident MTLS data post-processing.

- AHMCT conducting a 3-day MX8 MTLS data post-processing class for Districts 2 and 4 surveyors.

- AHMCT developing (CaltransMTLSguideline2017.docx) a Caltrans MTLS guideline document which includes:

    - MTLS personnel job descriptions, roles, and responsibilities
    - MTLS project planning
    - GNSS/IMU post-processing with POSPac MMS
    - MTLS data post-processing including Quality Assurance/Quality Control (QA/QC) recommendations
    - Point cloud feature extraction
    - MTLS data management plan.

MTLS Data Collection Training

The three-day MTLS data collection training class included:

1. Project planning

    a. GNSS base station location(s) selection and setup best practices

    b. MTLS usage consideration on a project

    c. Control targets setup recommendations and considerations

        i. Target size and placement recommendations

        ii. General steps for painting MTLS targets

        iii. Use of paint templates

    d. Lesson learned and best practices

    e. Path planning

    f. GNSS availability and mission planning

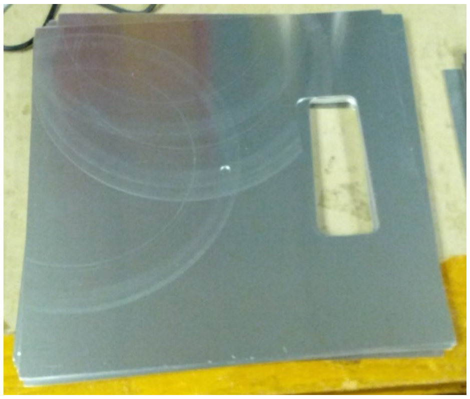

Figure 4.1: 2' x 2' MTLS target template (made by Caltrans DOE)

Figure 4.2: 18" x 2' MTLS target template (made by Caltrans DOE)

2. Personnel roles and responsibilities (details available in "Mobile Terrestrial Laser Scanning Roles, Responsibilities, and System Requirements Capabilities and Capacities").

3. MTLS hardware

Figure 4.3: MTLS system hardware and vehicle training

4. MTLS driver training

    a. Vehicle pre-operation check

    b. DMI removal and installation

    c. Vehicle controls

    d. MTLS power system setup and monitoring

e. Vehicle storage and clearance issues (details available in "Mobile Terrestrial Laser Scanning Roles, Responsibilities, and System Requirements Capabilities and Capacities")

f. Other precautions

5. MTLS operator training

   a. MTLS software setup and data collection steps

   b. GNSS/IMU initialization and dynamic alignment process

   c. Best practices

   d. Individual practice sessions

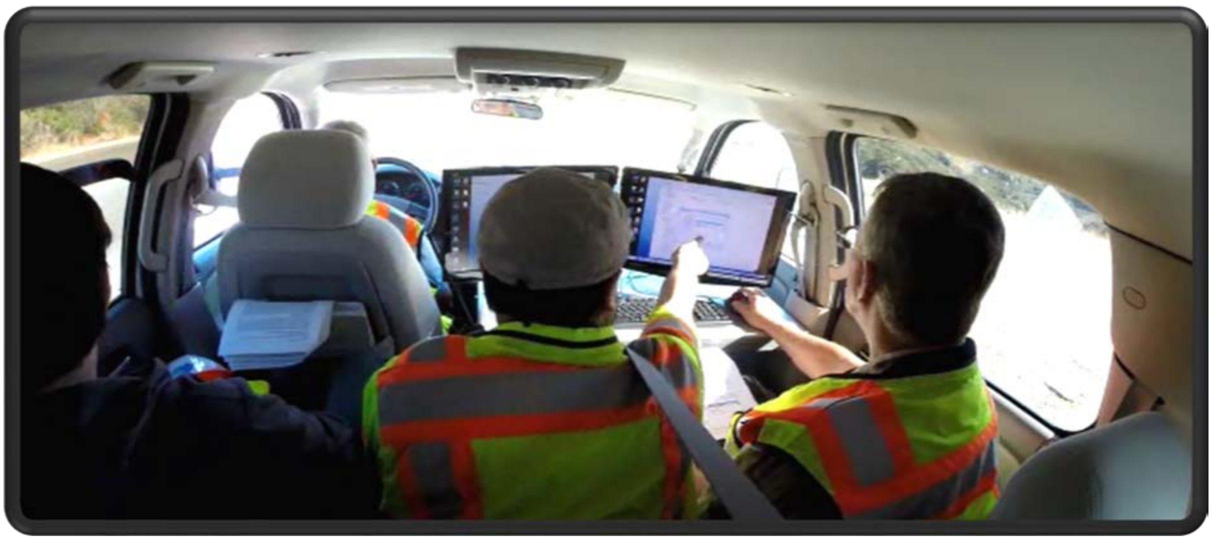

Figure 4.4: MTLS system operator training

6. Use of California Highway Patrol (CHP) and maintenance shadow vehicles for traffic breaks on mainline as well as off-ramps and on-ramps
7. Path planning and shadow vehicles
8. Downloading data from the vehicle computer
9. Data handling/storage, QA/QC, and workflow best practices
10. Pilot projects including coordination of maintenance vehicles for traffic breaks

One training session was held in Caltrans' central region, and one was held in the southern region. An AHMCT researcher and OLS personnel traveled to District 6 and District 8 with the MTLS vehicle for MTLS data collection training. Districts 5, 6, and 10 surveyors attended the

MTLS data collection training in District 6. Districts 8, 11, and 12 surveyors attended the training at District 8.

Support of MTLS Data Post-Processing Training

An AHMCT researcher provided support for an MTLS data post-processing training class (five days). Trimble conducted the training. As part of this task, AHMCT provided MTLS post-processing documentation and workflow using Trimble Applanix POSPac MMS and Trident software.

Figure 4.5: MTLS data post-processing training

MTLS Data Post-Processing Training Class

After Trimble's training classes, new MTLS users required additional MTLS post-processing training. AHMCT developed a three-day MTLS data post-processing training class including:

1. Project planning and GNSS base station setup
2. Applanix POSPac MMS 8.1 data processing
3. Trimble Trident 7.3 data processing
4. QA/QC procedures.

An AHMCT researcher conducted MTLS post-processing training classes in Districts 2 and 4. Each class had three trainees. In addition, the AHMCT researcher conducted refresher training and pilot projects in various Caltrans districts, including 2, 4, and 10.

CHAPTER 5: DEPLOYMENT SUPPORT FOR CENTRAL AND SOUTHERN CALIFORNIA USE OF MTLS

This task provided on-site and remote MTLS deployment support for the Caltrans district surveyors. In addition, an AHMCT researcher gathered feedback for workflow, software, camera field of view, and hardware improvements. District surveyors' feedback was then incorporated into the workflow standards and the documentation that are vital in capturing and maintaining institutional knowledge of MTLS operation. Some feedback was provided to the MTLS system providers along with updating the MTLS specifications.

On-site Support for Pilot Project MTLS Data Collection

After the MTLS data collection training, an AHMCT researcher and OLS personnel provided on-site support for the Central and Southern California districts' first MTLS pilot projects data collection at Districts 5, 6, 10, 11, and 12. Running MTLS pilot projects soon after the training is essential to reinforce learning and retain MTLS operation skills.

On-site pilot project support included:

- Assisting in ground control target setup
- Answering questions raised
- Providing advice on path planning
- Offering counsel on shadow vehicle operations
- Observing the data collection operations and giving feedback to the MTLS operators at the end of the data collection
- Assisting in MTLS post-processing software setup to ensure all MTLS software runs properly.

In addition, the AHMCT researcher traveled to Caltrans district offices (5, 6, 10, and 12) for MTLS deployment support at the request of the districts on an as-needed basis after the first set of MTLS pilot projects.

Figure 5.1: MTLS pilot project/training survey at District 12 on Interstate 405 (I-405) in Orange County

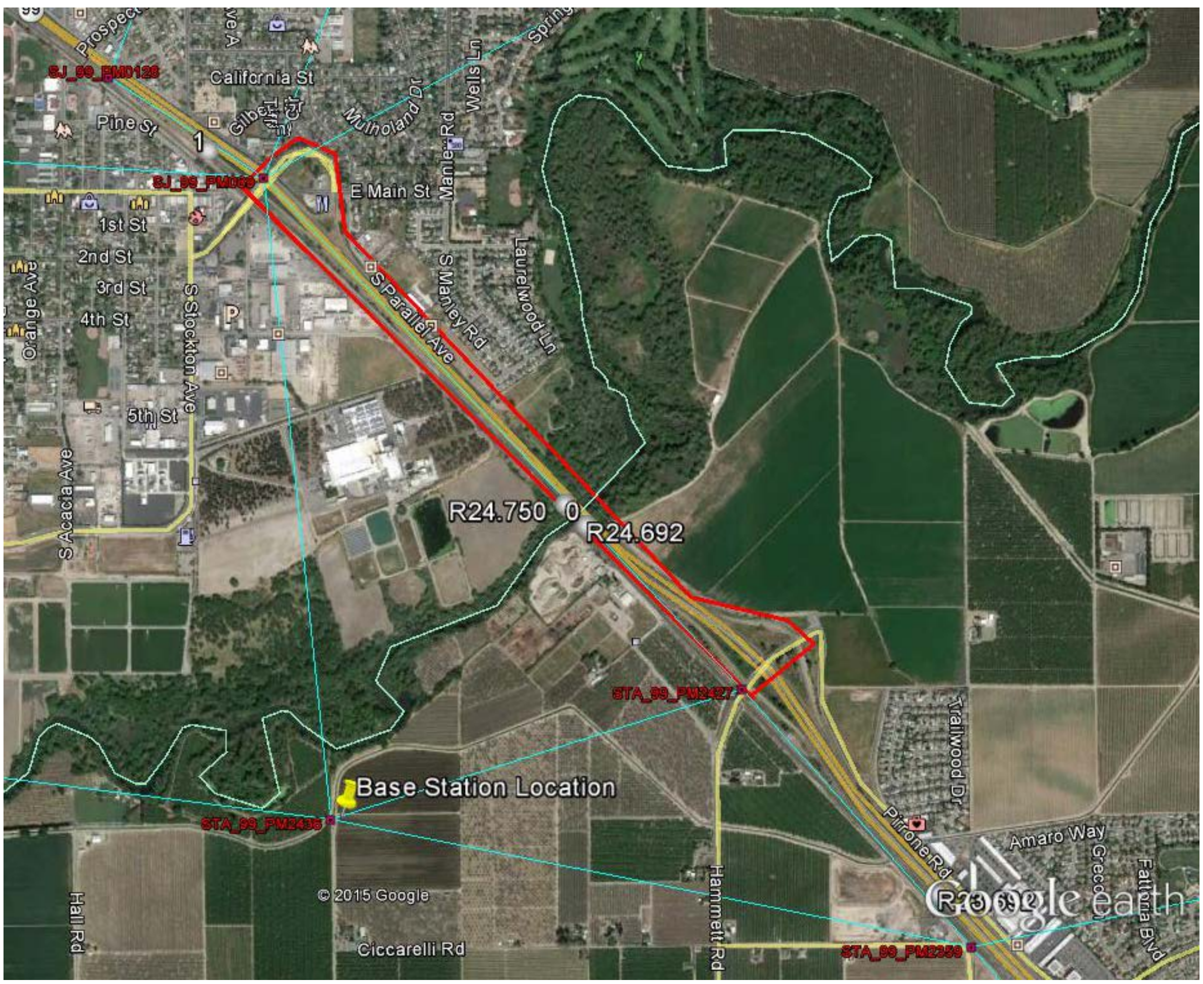

Figure 5.2: Google Earth map of a District 10 MTLS pilot project on State Route 99 (SR 99) near Ripon. The data was collected on May 20, 2015 with CHP and two shadow vehicles from Caltrans Maintenance.

Remote Support for MTLS Data Collection and Data Post-Processing

In this task an AHMCT researcher assisted MTLS users with solving problems encountered in both MTLS data collection and data post-processing. The researcher provided remote technical support via phone, email, and web meetings. Remote technical support problem solving included:

- Helping debug data collection hardware and software issues.
- Resetting MX8 components or the entire system for data collection.
- Reminding users of forgotten or skipped workflow steps pertaining to data collection.
- Solving MTLS software network licensing issues. By default, the McAfee intrusion prevention software interfered with the Trimble Applanix POSPac network license manager on the client computer.
- Assisting users with Applanix POSPac MMS GNSS/IMU data post-processing.
- Assisting users with Trimble Trident data post-processing.
- Creating fly-through point cloud movies for public relation meetings or MTLS promotion opportunities.
- Reviewing and advising on MTLS data collection plans including GNSS base station setup location, layout of ground control targets, and vehicle path planning.

Demonstration of MTLS Technology to District Management

The AHMCT researcher and OLS personnel made several in-person presentations to districts and headquarters management on the possible use of MTLS technology. The objectives were:

- To demonstrate potential applications beyond pavement surveys
- To explore potential additional customers and applications for MTLS
- To solicit district survey managers for their support for MTLS deployment and their assistance on personnel selection
- To inform district survey managers of the MTLS deployment plan and its implementation.

CHAPTER 6: PERFORM CASE STUDIES FOR SPECIAL MTLS PROJECTS

In this task, the AHMCT research team worked with Caltrans districts to identify and perform case studies for special MTLS projects. Throughout every case study, researchers worked together with Caltrans surveyors to refine the workflow and develop a set of best practices and recommendations that would eventually be integrated into the Caltrans Surveys Manual and training materials.

Most MTLS projects are pavement Digital Terrain Model (DTM) surveys. District 4 used MTLS for the OHS project for District 4's Division of Traffic Operation. In addition, there were a few Multidisciplinary Accident Investigation Team (MAIT) projects performed for the CHP for fatal traffic collisions. MTLS was also used to collect data for the Connected Vehicle Smart Intersection Testbed on SR 82 near Stanford.

Overhead Sign (OHS) Mapping Project at District 4

At the time of this research, Caltrans planned to replace its reflective overhead signs with new signs made with ASTM Type XI retroreflective sheeting which does not require external lighting. In addition to reduced electricity costs, Caltrans officials anticipated other savings and safety benefits including reduced maintenance costs, increased worker safety, better sign life-cycle costs, and reduced greenhouse gases.[2] District 4's Division of Traffic Operations requested that District 4 Surveys collect OHS inventory information (location, sign size, catwalk existence, overheard clearance, and sign graphics) on District 4's main highway routes.

The District 4 OHS project was a large-scale, network-wide MTLS project.[3] In the OHS project, District 4 surveyors scanned over 600 highway miles (2061 lane-miles) in six District 4 counties using the MX8 MTLS system. The six OHS project counties scanned by District 4 personnel were Sonoma, Napa, Solano, Marin, Contra Costa, and Alameda. In addition, a District 4 consultant performed the OHS MTLS scan in Santa Clara County. OHS project data collection started on July 22, 2014 and ended in August 2014 (total of six weeks). Some MTLS data collection was carried out during weekends. Data for each county was collected in a separate MTLS project. The CHP provided moving highway closures (at about 50 mph) during the OHS MTLS data collection. The OHS project resulted in a total of 15 TB of post-processed MTLS data. Figure 6.1 shows the coverage of the OHS project, and Table 6.1 provides the MTLS data statistics.

The AHMCT research team developed a specific workflow in conjunction with District 4 surveyors and refined the workflow during the course of the project data post-processing. The OHS extracted feature data is available on the District 4 intranet website managed by District 4 Division of Right of Way, Engineering, Survey & Mapping, Records, Data & GIS (Geographic Information Systems) Applications branch.

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[2] http://www.roadsbridges.com/caltrans-tests-reflective-sheeting-guide-sign-visibility-and-cost-savings
[3] http://www.lidarmag.com/PDF/LiDARNewsMagazine_Boyer-CaltransUsesLiDAR_Vol5No4.pdf

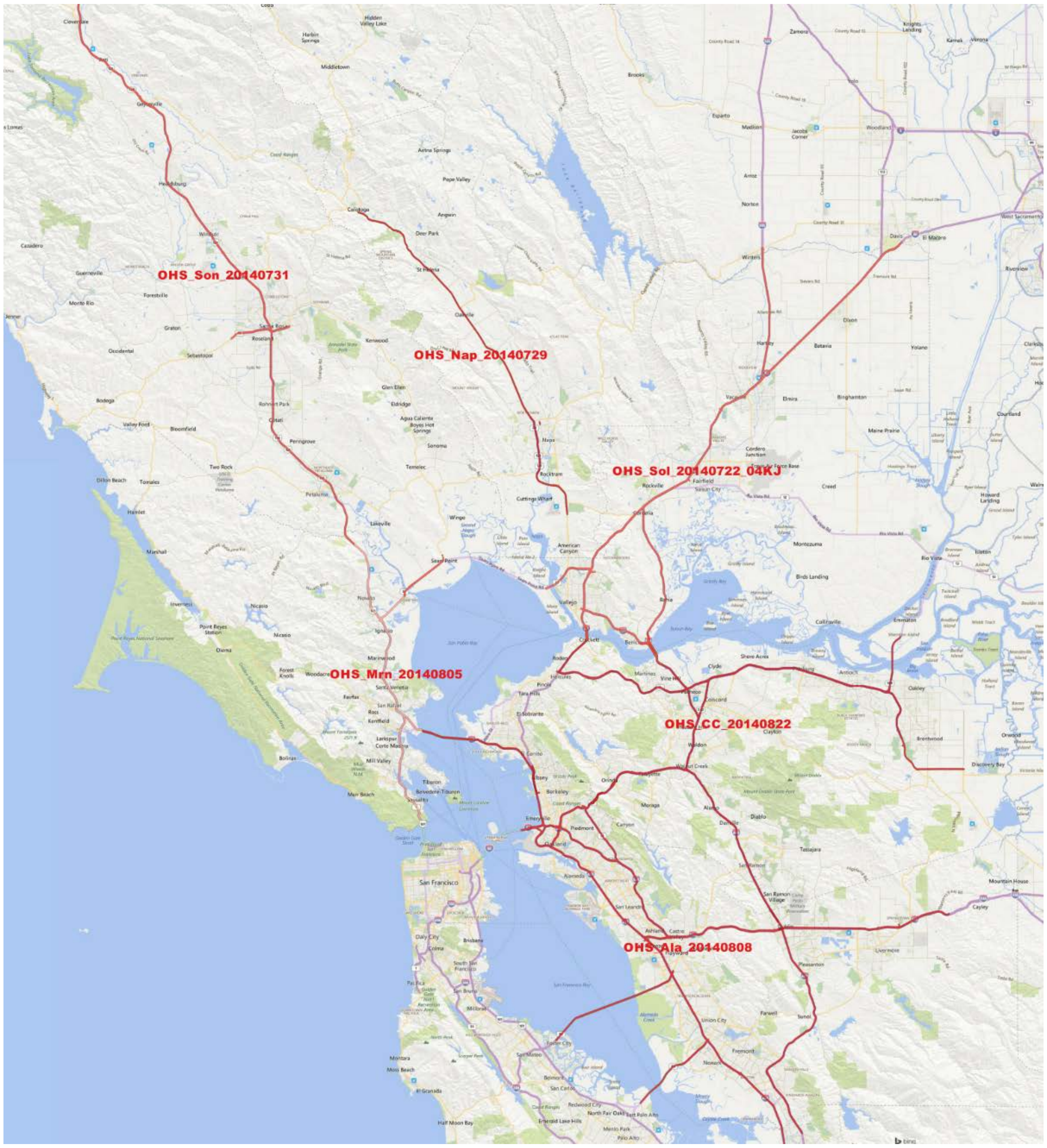

Figure 6.1: Caltrans District 4 OHS project coverage (highlighted in red) map overlaid on Microsoft Bing Map

Table 6.1 Caltrans District 4 OHS project coverage

County	Routes scanned	Lane-miles scanned (miles)	Post-processed MTLS data size (GB)
Alameda	13, 185, 238, 24, 580, 680, 80, 84, 880, 92, & 980	670.0	4,879.4
Contra Costa	160, 24, 242, 4, 580, 680, 780, & 80	438.2	3,378.6
Marin	101,37,580	191.1	1,362.9
Napa	128,29	107.2	924.6
Solano	37,505,680,780,80	348.8	2,432.7
Sonoma	101,12,121,37	305.6	2,192.3

Lessons Learned

- An in-depth understanding of customer requirements—including accuracy, features to be extracted, and deliverable format—is crucial.

- Some MTLS data post-processing requires long computation time. Time and computing resource management are vital in processing MTLS data as quickly as possible.

    - Arrange work so that any data copying is performed overnight.

    - Make sure the external USB 3 drive is plugged into a USB 3 port (*not* a USB 2 port) for data transfer. Slower computers were used in data transfer and data backup in this research.

    - Disable the computer workstation's MS Windows power saving mode.

    - The Trimble Trident "computing XYZ" step requires about one minute of computation time for every minute of data collection time. Assuming the 2,061 lane miles were scanned at 50 mph, 41 hours of computation time would be required to calculate the XYZ coordinates of all the points in the corresponding point cloud.

    - The Trimble Trident "colorizing point-cloud" step requires about three minutes of computation time for every minute of data collection time. Assuming the 2,061 lane-miles were scanned at 50 mph, 123 hours of computation time would be required to colorize all the points in the corresponding point cloud.

    - For pavement surveys, the point cloud is typically exported to LAS file format in the California State Plane Coordinate System. Exporting point cloud LAS files in the Universal Transverse Mercator (UTM) coordinate system is faster when using Trimble Trident since Trident natively stores point cloud data in the UTM coordinate system, and the point coordinates do not require computationally expensive coordinate frame transformation from the UTM to the California State Plane coordinate system.

- Different point cloud feature extraction software tools were tested for sample OHS survey data feature extraction before establishing a new standardized workflow for OHS feature extraction.

- New software features available at the time of this writing would reduce the feature extraction time.

Reuse of OHS Project Data for Other Projects

District 4 (D4) Surveys reused the OHS project data in planning and public hearing meetings for new projects. For example, D4 Surveys used OHS project data to create fly-through animation of the proposed I-680 high-occupancy toll lane project. D4 also used the OHS point cloud at I-680 and the fly-through animation in a public hearing meeting regarding the project. Furthermore, I-80 MTLS data for Solano County was also re-used to fulfil a project survey request. The OHS data may also be used to extract the location of other assets and their metadata in the future. To aid the data management and retrieval, AHMCT worked with District 4 Surveys in related research to develop a Java software tool to automatically extract MTLS project metadata for GIS population and a Web-based GIS data browser [4].

Multidisciplinary Accident Investigation Team (MAIT)

Using MTLS for MAIT can dramatically reduce data collection time on the highway. The MAIT survey project extent may include a long section of roadway approaching and beyond the accident location. A MAIT road survey often requires long complete or partial closure of the highway. An MTLS survey entails a short moving road closure to complete the field data collection. The MX8 MTLS system was used to scan the area surrounding the Orland bus crash for MAIT in April 2014.

The advantages of MTLS for MAIT surveys include:

- Eliminating or reducing road closure for the MAIT survey.
- Improving traffic flow as well as reducing commerce costs and carbon emissions due to traffic jams.
- Improving worker safety by reducing traffic exposure.

The challenges of using MTLS for MAIT surveys include:

- Availability of the MX8 MTLS system may be limited for time-sensitive MAIT surveys due to geographical location of the MTLS system and the planned MTLS project schedule. The additional Riegl VMX-1HA MTLS system (see Chapter 7 for detail) should solve or significantly mitigate the availability problem.
- A standardized survey request from the MAIT to district surveys does not currently exist. MAIT members often rely on their own personal contact to the MTLS surveyors.

Example MAIT MTLS Project

After completing a pilot project at District 12 Ortega Highway (SR 74), I-5 was shut down near the MX8 MTLS vehicle storage area on October 14, 2014. MAIT was doing cross-sections on a small stretch of I-5 where there was a traffic accident with five fatalities. A couple of weeks earlier, a male teenager was driving home with his friends from Knott’s Berry Farm. The vehicle was driven up an embankment where the automobile caught fire. MAIT had been doing their cross-sections for the better part of an hour. District 12 surveyors, OLS personnel, and an AHMCT researcher arrived at the MAIT site with the MX8 MTLS vehicle. The MX8 MTLS vehicle was used to scan the entire accident site in 10 minutes. The closed highway was reopened shortly after the completion of the MTLS survey. Some MAIT members were aware of the existence of the MTLS system. However, MAIT did not know the MX8 MTLS system was available for MAIT survey work.

Figure 6.2: An MX8 MTLS system camera image of the automobile accident embankment site on SR 74

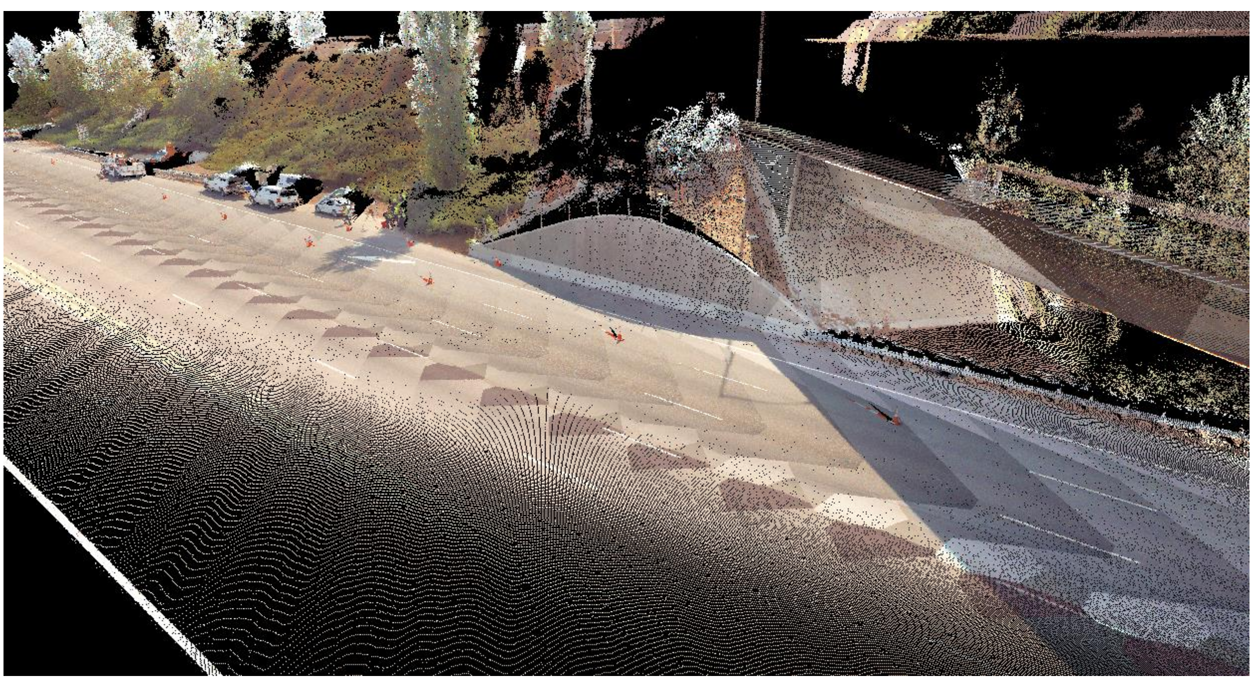

Figure 6.3: Colorized point cloud of the accident site on SR 74 and the surrounding area

Collecting Geospatial Data for Connected Vehicle Smart Intersection Using MTLS

Multi-Modal Intelligent Traffic Signal Systems (MMITSS), also known as “Smart Intersections,” use Dedicated Short Range Communications (DSRC) to communicate with Connected Vehicles. According to the United States Department of Transportation's (USDOT) website:[4]

> The U.S. Department of Transportation's Connected Vehicle program is working with state and local transportation agencies, vehicle and device makers, and the public to test and evaluate technology that will enable cars, buses, trucks, trains, roads and other infrastructure, and our smartphones and other devices to “talk” to one another. Cars on the highway, for example, would use short-range radio signals to communicate with each other so every vehicle on the road would be aware of where other nearby vehicles are. Drivers would receive notifications and alerts of dangerous situations, such as someone about to run a red light as they’re nearing an intersection or an oncoming car, out of sight beyond a curve, swerving into their lane to avoid an object on the road. Connected Vehicles could dramatically reduce the number of fatalities and serious injuries caused by accidents on our roads and highways.

The MMITSS provides the intersection configuration and geospatial data to Connected Vehicles using the Society of Automotive Engineers (SAE) J2735 data format. An example of an SAE J2735 data file on the El Camino Real Boulevard (SR 82) and Ventura Avenue intersection is provided in Appendix A. Figure 6.4 shows the same intersection’s Google Earth aerial image with SAE J2735 intersection configuration and geospatial data overlaid. MTLS technology can be effectively used to collect the required data for MMITSS as demonstrated in the pilot study described below.

[4] http://its.dot.gov/cv_basics/cv_basics_what.htm

Figure 6.4: Smart Intersection required features plotted on Google Earth

Pilot MMITSS MTLS Project

DRISI made a survey request to D4 Surveys to collect MMITSS required data for DRISI's Smart Intersection Testbed location at El Camino Real Boulevard (SR 82). D4 enlisted AHMCT's help since D4 does not have any previous experience dealing with SAE J2753 formatted data. MTLS is the only technology that can collect the required MMITSS data in the minimum amount of time. A D4 surveyor and an AHMCT researcher conducted an MMITSS MTLS pilot project.

<u>Project requirements from DRISI:</u>

1. Eleven intersections on El Camino Real Boulevard. Intersections from north to south: Stanford Avenue, Cambridge Avenue, California Avenue, Page Mill Road, Portage Avenue/Hansen Way, Matadero Avenue, Curtner Avenue, Ventura Avenue, Los Robles Avenue, Maybell Avenue, and West Charleston Road

2. Each intersection requires a unique intersection identifier

3. The location of the "Anchor Point" (the center of the intersection) represented in latitude and longitude

4. Lane center locations in latitude and longitude

5. Number of approaches in the intersection

6. Numbered lanes with each lane assigned a unique number

7. Lane number assigned to each approach
8. Lane widths
9. Lane attributes such as straight, right turn, left turn, etc.; lanes can have multiple attributes (i.e. straight and right turn)
10. Lane offsets in latitude and longitude

Pilot Project Execution

Following the path planned by the AHMCT researcher, D4 surveyors and the AHMCT researcher scanned El Camino Real Boulevard near Palo Alto on December 9, 2014 at night. The MTLS scan was performed at night based on District 4 surveyor's recommendation due to heavy traffic during the day. The color digital roadway images were not critical in extracting the data required by MMITSS.

The total data collection time was about two hours for the eleven intersections, with 250 Gigabyte (GB) of raw MTLS data recorded. The AHMCT researcher processed the GNSS/IMU data using Applanix POSPac MMS software with data from a single GNSS base station. The GNSS base station location was determined using United States National Geodetic Survey Online Positioning User Service.[5] 400 GB of post-processed MTLS was produced. The resulting MTLS data provided better than 6" absolute vertical position accuracy and better than 2" absolute horizontal position accuracy. Moreover, the point-to-point relative measurement accuracy of the MTLS data was better than 0.5". Figure 6.5 shows an aerial view of all eleven intersections' point cloud data. Figure 6.6 and 6.7 display the point cloud rendering of the El Camino Real Boulevard/Page Mill Road intersection and El Camino Real Boulevard/West Charleston Road intersection, respectively.

The pilot MMITSS MTLS project took one day for site reconnaissance, one day for path and project planning, one day for data collection including transporting the MX8 MTLS vehicle to the work site, and three days for post-processing the MTLS data. The GNSS baseline length was less than four miles.

The resulting point clouds were exported in LAS 1.1 format using the World Geodetic System 1984 (WGS84) UTM10N coordinate system with WGS84 ellipsoid height for the elevation (z) coordinate. The LAS 1.1 files were then compressed into LASzip format. The total compressed point cloud files were about 10 GB. In addition, each run's (also known as recording) path was exported as shapefile (SHP) and Keyhole Markup Language (KML) files. The entire vehicle trajectory was also exported as a compressed KML (KMZ) file.

[5] http://www.ngs.noaa.gov/OPUS/

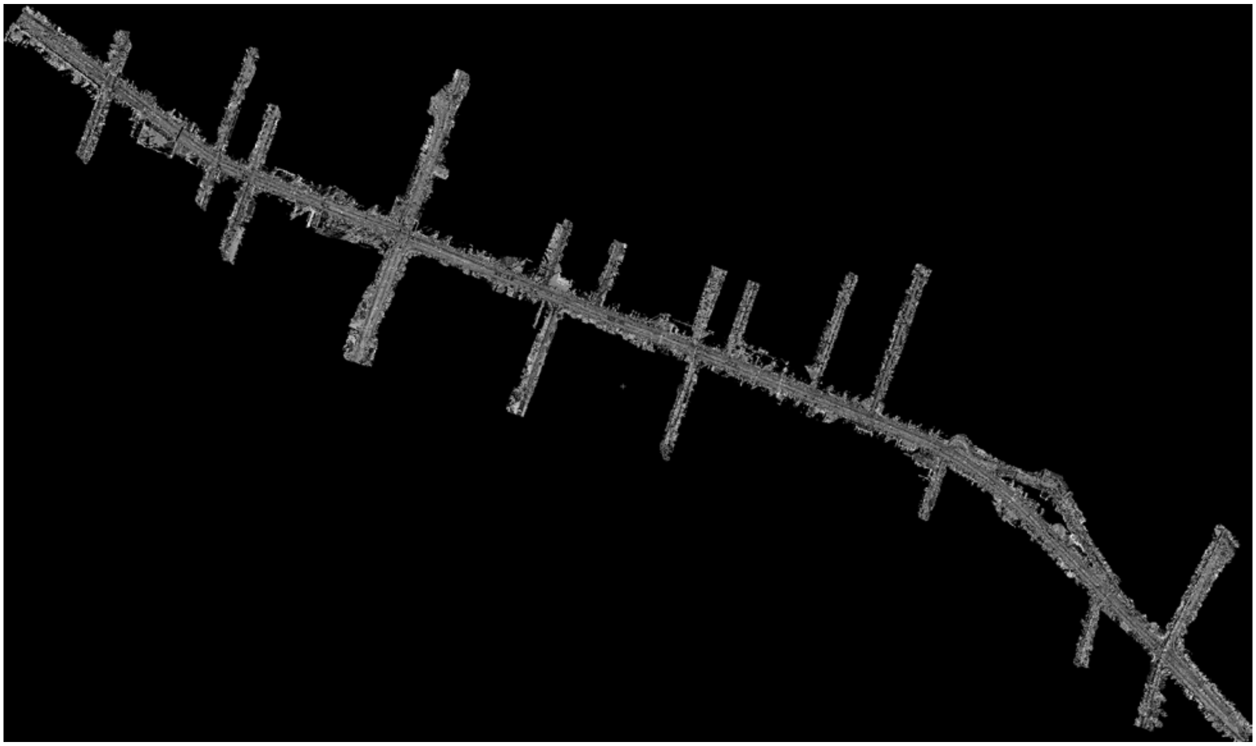

Figure 6.5: Aerial view of all eleven intersections' point cloud data

Figure 6.6: Point cloud rendering of the El Camino Real Boulevard/Page Mill Road intersection

Figure 6.7: Point cloud rendering of the El Camino Real Boulevard/West Charleston Road intersection

Feature Extraction

The DRISI-contracted research team led by Professor Jay A. Farrell, Chair of the Department of Electrical and Computer Engineering at the University of California-Riverside, agreed to do the feature extraction to SAE J2735 format. The AHMCT researcher provided technical guidance and answered questions from Professor Farrell's research team. Professor Farrell indicated that the FHWA would like to provide the eleven intersection point clouds and the trajectory data sets as benchmarking datasets for various research groups working in the Smart Intersections field.

Challenges

The J2735 map data format is not well understood by anyone outside the Connected Vehicle research community. Mapping and survey professionals would have trouble delivering mapping data in J2735 format due to the lack of tools to convert standard map and CAD data formats to the J2735 format. Mapping and survey professional software suites do have excellent tools to extract the MMITSS required data and provide it in other standard map/CAD data formats.

CHAPTER 7:
NEXT-GENERATION MTLS

In this task, an AHMCT researcher, working with OLS personnel, performed the following work:

- Assessed the current usage of the Caltrans MTLS systems
- Updated the MTLS specifications
- Modified the Request for Quotation (RFQ) for the new MTLS system
- Assisted DOE and OLS personnel in the installation of the new MTLS system (a Riegl VMX-1HA)
- Assisted OLS and Riegl personnel in training Caltrans surveyors on the use of the Caltrans VMX-1HA MTLS system.

Caltrans MTLS Systems Usage

OLS gathered Caltrans MTLS systems (MX8 and VMX-1HA) usage data from district MTLS users from March 2016 to February 2018. Table 7.1, Figure 7.1, and Figure 7.2 show the MTLS systems usage statistics (centerline miles scanned).

Table 7.1: Caltrans MTLS deployment statistics

MTLS project statistics from March 2016 to February 2018	
Total number of MTLS projects	100
Total number of Caltrans districts deployed	10
Average number of MTLS projects per month	4.2
Average number of centerline miles scanned per month	26.5
Average number of centerline miles scanned per MTLS project	6.36

Figure 7.1: Total number of MTLS projects per district from March 2016 to February 2018

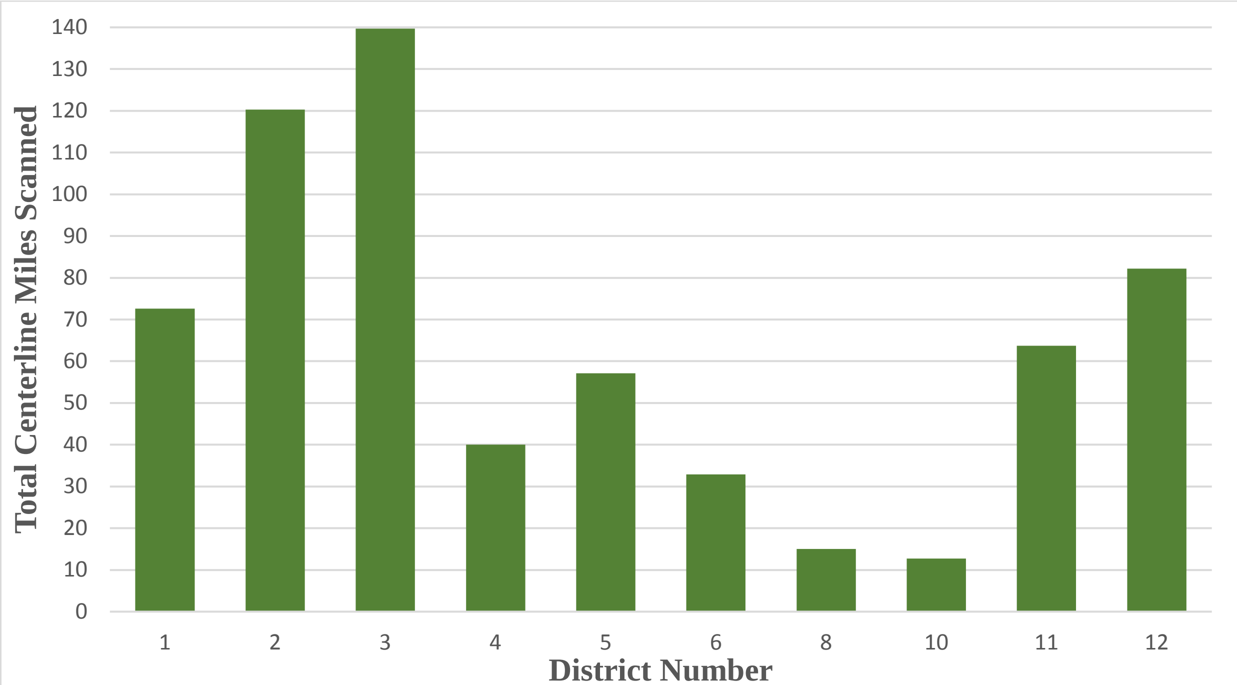

Figure 7.2: Total centerline miles scanned using MTLS from March 2016 to February 2018

Moving the MX8 MTLS vehicle between districts requires one to two days of travel. The MTLS project requires one to two additional days, weather permitting. Due to transport and vehicle maintenance, the MX8 MTLS vehicle was used about three weeks per month. The logistics of the transportation and hand-off of the MX8 MTLS vehicle presented challenges particularly when the vehicle is driven over a long distance, such as traveling from Northern California to San Diego. The long-distance travel from Northern to Southern California also causes higher wear on the DMI bearing, which may be the cause of the DMI failure mentioned in Chapter 2.

Updated MTLS Specifications

Working with OLS personnel, AHMCT researchers enhanced the previously-developed MTLS specifications based on the experience gained during previous acquisition and current field use of the Trimble MX8 MTLS. In addition, the hardware specifications were updated based on current, state-of-the-art MTLS systems' specifications as well as Caltrans and other DOT MTLS user feedback and Caltrans MTLS applications.

The MTLS specifications update included:

- The majority of the updates for the MTLS specifications were in the area of warranty and maintenance services. The maintenance and services cost for MTLS can be rather large. Shipping the laser scanners overseas with proper insurance can cost several thousand dollars. The specification modification concentrates on the total cost of ownership of the MTLS over a six-year service life. The new MTLS specifications require the hardware warranty and all services and license maintenance to provide coverage for four years. The specification also includes component loan during services or repairs.

- The LiDAR scanner's measurement rate, scan rate, and range accuracy specifications were updated based upon the latest LiDAR advancements and available LiDAR scanners.

- The digital camera specifications (frame rate and image resolution) were also updated based on the latest available digital cameras. A 360-degree Field of View (FOV) Ladybug 5 camera was added to the specification to increase image coverage.

MTLS Request for Quotation

Following Caltrans Division of Procurement and Contracts' (DPAC's) advice and recommendation, an RFQ was used for the procurement of the next-generation MTLS system. AHMCT, OLS, and DPAC personnel modified and updated an example RFQ using the updated MTLS specifications. The RFQ was a best-value procurement that features evaluation of the bidders in the following categories: Administrative Requirements, Technical Requirements, and Cost. The Administrative Requirements are mandatory and have no associated points. The maximum number of points available is 150. The Technical Requirements and Cost each represent 50% of the total points. Some of the requirements were mandatory and were scored as pass or fail. Some of the requirements were quantified, with points awarded when the component specification exceeded the base requirement specification.

The RFQ Technical Requirements were divided into following categories:

- Bidder Qualifications and Customer Support
- System Requirements
- LiDAR Requirements
- Digital Camera Requirements
- Position & Orientation System Requirements
- Data Acquisition Software Requirements
- Post-Processing Software Requirements
- Warranty Requirements

The final RFQ for the next-generation MTLS system was approved by DPAC and posted for bidders' responses in March 2016. AHMCT, OLS, and DPAC personnel evaluated all bidders' bid packages, and the Riegl VMX-1HA MTLS system won the award.

Support for Riegl VMX-1HA MTLS Installation

An AHMCT researcher assisted DOE, OLS, and Riegl personnel in the installation of the Riegl VMX-1HA in August 2016 at DOE Shop C. Caltrans and AHMCT leveraged experience gained from the MX8 MTLS vehicle installation that resulted in a superb installation of the VMX-1HA MTLS system. DOE staff designed, fabricated, and installed:

- A custom roof rack for the VMX-1HA sensor pod located on the roof of a 2014 2-wheel drive Chevrolet Tahoe (see Figure 7.3 and 7.4). The custom roof rack also supported the attachment of a Rhino-brand folding ladder as shown in Figure 7.4. The folding ladder provided MTLS users with safe and easy access to the sensor pod and the Ladybug camera cap.

- A power-adjustable table for the Liquid-Crystal Display (LCD) and laptop.

- A rack for the Riegl VMX-1HA control unit housed in a Pelican case (shown in Figure 7.5) mounted at the rear of the Chevrolet Tahoe.

- Diamond plate for mounting the Weather Guard toolbox and Riegl VMX-1HA control unit. The WeatherGuard toolbox stores the camera caps, scanner caps, tools, and cleaning supplies.

In addition, DOE staff installed and wired an additional VMX-1HA backup battery under the Chevrolet Tahoe's hood. Furthermore, they ran and secured all the necessary wiring for the VMX-1HA system for safe vehicle operation. Riegl personnel praised DOE's aesthetically pleasing and professional installation job. *Riegl said this was the best installation of the VMX-1HA system that they have ever seen.*

Figure 7.3: Riegl VMX-1HA sensor pod mounted on a custom roof rack with a Rhino-brand folding ladder on the side of the vehicle

Figure 7.4: Riegl VMX-1HA sensor pod mounted on a custom roof rack

Figure 7.5: Riegl VMX-1HA control unit housed in a black Pelican case next to a white Weather Guard toolbox mounted at the rear of the Chevrolet Tahoe

Figure 7.6: Custom 3D-printed Ladybug camera cap 3D-printed by DOE staff

Upon the completion of the VMX-1HA installation, an AHMCT researcher, OLS, and Riegl personnel performed system performance verification on SR 65 and I-80. In addition, the Caltrans Headquarters building and the DOE shops were scanned. The VMX-1HA MTLS system was demonstrated to potential survey customers' management after the system verification. The Caltrans VMX-1HA vehicle was subsequently driven to San Diego in September 2016 to support training for Caltrans surveys by Riegl personnel.

The Riegl VMX-1HA was initially shipped with older 5-megapixel cameras in order to facilitate earlier deployment. Riegl shipped Caltrans the latest 9-megapixel cameras in October 2016. An AHMCT researcher traveled to District 12 in order to replace the cameras on the Riegl VMX-1HA MTLS system on October 4, 2016. The AHMCT researcher tested the new cameras with D12 surveyors as well as setting all the cameras to optimize their field of view. After the training and the deployment of the VMX-1HA, the AHMCT researcher continued to provide support to District 11 and 12 surveyors for their deployment of the Riegl VMX-1HA MTLS system.

CHAPTER 8: MTLS-RELATED IT INFRASTRUCTURE REQUIREMENT REVIEW AND RECOMMENDATIONS

This task assessed Caltrans-wide MTLS-related high-level IT infrastructure requirements. AHMCT performed preliminary investigation into data storage, data distribution, and data management. In addition, the AHMCT researcher also worked with OLS to develop a new specification of HP Z840 computer workstation for MTLS data post-processing and point cloud feature extraction. The new HP Z840 workstation specification was used in the procurement of ten workstations for district surveyors in 2017. Caltrans District 4 and AHMCT are developing new MTLS workstation specifications for the new HP Z8 workstation. HP obsoleted the HP Z840 in late 2017.

MTLS Data Storage Size Estimate

The MTLS data size is huge compared to most other data. Having sufficient storage for MTLS data can be an IT challenge. This section provides an estimate of current existing post-processed MTLS data size in Caltrans districts and their MTLS data growth rate. The estimate can be used for IT storage requirements for MTLS data. Table 8.1 lists the estimate of existing post-processed MTLS as of November 2017. The estimate at that time for the all post-processed MTLS from all Caltrans districts was about 100 TB. The 100-TB data size estimate does not include the original raw data collected from the MX8 MTLS vehicle. Some districts retain the raw MTLS data. Currently, Caltrans does not have a data retention policy for MTLS data (either raw or post-processed). The earliest MTLS data from the Caltrans MX8 MTLS system is about four years old.

Table 8.1: Current Caltrans post-processed MTLS data size estimate (as of November 2017)

District	Estimated post-processed MTLS data size (TB)
1	~ 6 to 8
2	20
3	8
4	35
5	~ 5 to 7
6	~ 4 to 6
10	1
11	~6 to 10
12	~ 6 to 10
Total	~ 100

Based on historical MTLS project data [1], the average post-processed MTLS data growth rate is about 5 TB per district per year. The 5 TB/district/year growth rate is for DTM survey projects. The number of traditional DTM survey projects may decrease because of the decreasing number of future planned capital projects. Thus, a 5 TB/district/year growth rate may be an overestimate. Nevertheless, it is a good number to use for estimating future storage requirements. District 12 surveyors will be brokering MTLS work for Districts 8 and 11. Therefore, the District 12 MTLS data growth rate may be as high as 15 TB per year. However, District 9 experienced minimal

MTLS work historically with only one MTLS project in District 9 since the deployment of the MX8 MTLS system four years ago. Each district's data growth rate will vary due to district size, trained personnel availability, and available projects. Excluding District 9, the entire Caltrans post-processed MTLS data growth rate is about 5 TB/district/year x 11 districts = 55 TB/year.

If the current MTLS systems are also used to collect data for asset management, the MTLS data growth rate could increase significantly. Survey-grade MTLS data size estimate is 50 GB per mile. Caltrans maintains about 15,000 centerline miles in California. Asset management scanning of the entire Caltrans highway system may generate up to 750 TB for each statewide cycle. Table 8.2 lists the centerline miles and lane miles within each district and the anticipated post-processed MTLS data size for scanning the entire district should Caltrans executive management decide to use the MTLS systems for asset management data collection. Currently, each district will need to work with their district IT to establish data storage needs and plans for capacity expansion.

Table 8.2 Highway miles of each Caltrans district [5]

District	Centerline miles	Lane miles	Estimated MTLS data size for all major highways (TB)
1	925	2,341	46.3
2	1,719	4,001	86.0
3	1,454	4,339	72.7
4	1,346	5,915	67.3
5	1,148	3,189	57.4
6	2,012	5,759	100.6
7	1,078	6,257	53.9
8	1,848	6,570	92.4
9	739	1,787	37.0
10	1,307	3,474	65.4
11	1,019	4,158	51.0
12	268	1,885	13.4
Total	14,863	49,645	743.2

MTLS Data Management Plan

MTLS vehicles produce very large data sets. Currently, these large data sets are primarily stored using portable, external hard drives. This solution is neither sustainable nor efficient and puts project data at risk. Effectively managing MTLS data requires an enterprise-level improvement in network capacity and storage. Caltrans OLS has procured data storage for MTLS data from all districts. Caltrans OLS recognizes the importance of MTLS data management moving forward. AHMCT researchers have been working with OLS to develop an MTLS data management plan that best suits Caltrans' specific requirements. The MTLS data management plan will include:

- Roles and responsibilities
- Data retention policy

- Data access, sharing, and security policy
- Data backup policy
- Metadata requirements

An AHMCT researcher provided OLS with a set of MTLS data and directory structure organization recommendations using previous research results [4]. AHMCT will work with OLS to continue development of the MTLS data management plan as well as long-term and short-term MTLS storage needs. The completed MTLS data management plan will be provided in the Caltrans MTLS guideline document.

CHAPTER 9: CONCLUSIONS AND FUTURE RESEARCH

This final report documents the work performed and the results of the Expanding Mobile Terrestrial Laser Scanning Capability and Capacity throughout Caltrans research project. This research project's deliverables include:

- MTLS training documents
- Statewide MTLS deployment status and usage
- Identification and documentation of best practices and operational recommendations to retain Caltrans institutional knowledge on MTLS deployment and operation
- Special MTLS project case studies
- Updated MTLS system procurement specification and RFQ for a new MTLS system
- Documentation of high-level Caltrans MTLS-related IT infrastructure requirements
- Conclusions including lessons learned and recommendations.

Lessons Learned

- Maintaining spare parts has reduced system down time. A spare DMI was purchased for each of the MTLS systems (MX8 and VMX-1HA) during this project. The spare MX8 DMI has reduced the MX8 DMI failure down time to only one day from one week.
- Trident Version 7.1 or higher (the latest version of MTLS post-processing software) should be used since Caltrans is currently deploying Microsoft Office 2013 statewide (see Chapter 2). All Caltrans MTLS workstations have been upgraded to Trident Version 7.3 during this project and do not experience any conflict with 32-bit Microsoft Office.
- MTLS specifications were updated to ensure that the maintenance and service plan from the vendor covers:
    - Free loaner component should any component fail, and
    - Repair and/or replacement of components.
- MTLS deployment has been successful and yielded accurate data due to the development and rigorous application of good and consistent workflow.
- Automation tools allow efficient extraction of GIS data for MTLS data management.
- The RFQ procurement process works well for purchasing a MTLS system.
- The DOE staff were instrumental in the installation and deployment of both MTLS systems.

- The second MTLS system improved MTLS availability for time-sensitive projects such as MAIT surveys.

Recommendations

- With an accommodating budget, spare parts should be purchased and maintained in order to reduce system down time:
    - Several extra 43 mm Heliopan Digital Ultraviolet/Infrared filters should be purchased and available as spares
    - Other spare parts, such as a computer motherboard, interface board, power supplies, ups, and inverter, should be considered.

- A custom shipping case (e.g. Pelican case with custom-cut foam) should be used to better protect the camera pods for international shipping.

- When shipping the system, screw-on lens caps should be used instead of snap-on lens caps.

- Due to personnel changes via retirement or promotions, ensuring continued availability of trained MTLS surveyors requires continued training or peer-to-peer training.

- MTLS users should provide peer-to-peer support and pass on institutional knowledge to new MTLS surveyors. OLS hosted two three-day-long peer-to-peer workshops to exchange and document MTLS best practices for data post-processing and feature extraction. The peer-to-peer workshops were valuable in gathering the best ideas from all MTLS users. A few districts have used their current MTLS users to train new MTLS users.

Future Work

- Provide deployment support for both the Trimble MX8 and the Riegl VMX-1HA MTLS systems.

- Support MTLS data management and distribution:
    - MTLS data backup policy
    - MTLS data retention policy (raw and post-processed MTLS data)
    - MTLS data sharing policy
    - Visualization for MTLS data availability.

- Assist Caltrans with updating Chapter 15 of the Caltrans Surveys Manual.

- Add new sensors such as 360 camera and 3D GPR to MX8.

- Perform additional registration target spacing research with the Geospatial Technology Proving Ground.
- Update Applanix POS LV520 system's firmware.
- Research and develop a distributed MTLS data storage and processing system.
- Research and develop a unified data storage system and web-based portal for Caltrans GIS data including MTLS, photolog, pavement surveys, and other GIS data.

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5. Caltrans, "2015 State of the Pavement Report," California Department of Transportation, Division of Maintenance, Pavement Program, 2015.

APPENDIX A
EXAMPLE SAE J2735 FILE FOR
EL CAMINO REAL BOULEVARD/VENTURA AVENUE INTERSECTION

```
Map_Name   ElCamino_Ventura.nmap
RSU_ID  ElCamino_Ventura
IntersectionID 8
Intersection_attributes       00110011    /*elevation: Yes, lane width: Yes, Node data 16 bits,
node offset solution: cm, geometry: Yes, navigation: Yes*/
Reference_point 37.416827     -122.130086     126 /*lat, long, elevation(decimeter)*/
No_Approach    8
#updated till above

Approach    1   /*El Camino NB Ingress*/
Approach_type   1  /*1: approach, 2: egress*/
No_lane 1

Lane    1.1     /*WB Left Lane 1 El Camino*/
Lane_ID 1
Lane_type      1        /*1 to 5, for this intersection all 1: motorized vehicle lane */
Lane_attributes       0000000000101010    /*not egress path, straight and right turn permitted,
turn on red, no u-turn */
lane_width 300        /*in cm
No_nodes 6
1.1.1  37.4169866468893      -122.130000210762
1.1.2  37.4170307815634      -122.129962494937
1.1.3  37.4170849305485      -122.129916657523
1.1.4  37.4171300619484      -122.129878848045
1.1.5  37.4171868392503      -122.129828584405
1.1.6  37.4172460932902      -122.129774043178
No_Conn_lane   3
6.1    4     /*Straight ahead */
8.1    3     /*Right Turn */
4.1    2     /*Left turn */
end_lane
end_approach
Approach       2
Approach_type  2                    /*1: approach, 2: egress*/
No_lane 2
Lane   2.1
Lane_ID 2
Lane_type      1        /*1 to 5, for this intersection all 1: motorized vehicle lane */
Lane_attributes       0000000001100011    /*egress path, straight permitted, no turn on red, no
u-turn */
Lane_width     300      /* in cm*/
No_nodes       6
2.1.1       37.41696095334986  -122.1299523422702
2.1.2       37.41700970790048   -122.1299111922852
2.1.3       37.41706013205283   -122.1298685756512
2.1.4       37.41710650048794   -122.1298319282414
2.1.5       37.41716278849669   -122.129784395843
2.1.6       37.41722254267579   -122.129732366792

No_Conn_lane   0     /* no connected lane because it is a egress lane*/
end_lane
end_approach
Approach       3
Approach_type  1                    /*1: approach, 2: egress*/
No_lane 4
Lane   3.1
Lane_ID 3
Lane_type      1        /*1 to 5, for this intersection all 1: motorized vehicle lane */
Lane_attributes       0000000000111000    /*not egress path, right-turn permitted, yield, turn
on red, no u-turn */
Lane_width     500      /* in cm
No_nodes       15
3.1.1  37.4168480870637      -122.129869050664
3.1.2  37.4167945740257      -122.129775207644
3.1.3  37.416752587023       -122.129694655567
```

```
3.1.4   37.4167072578119       -122.129615998308
3.1.5   37.4166654529058       -122.129527585763
3.1.6   37.4166253179026       -122.129450314706
3.1.7   37.4165816223502       -122.129373029699
3.1.8   37.4165420534362       -122.129299646587
3.1.9   37.4164914692832       -122.129194064057
3.1.10  37.4164384584931       -122.129102173236
3.1.11  37.4163897773087       -122.129009933191
3.1.12  37.4163503483793       -122.128932345782
3.1.13  37.4163052204576       -122.128856514608
3.1.14  37.4162602739833       -122.128777576582
3.1.15  37.4162154053831       -122.128697130949
No_Conn_lane   2
2.1     3     /*Right turn */
8.1 4     /*Straight ahead */
end_lane
Lane    3.2
Lane_ID 4
Lane_type      1        /*1 to 5, for this intersection all 1: motorized vehicle lane */
Lane_attributes        0000000001100010    /*not engress path, straight permitted, no turn on
red, no u-turn */
Lane_width     330      /* in cm
No_nodes       15
3.2.1   37.4168085782828       -122.129894993364
3.2.2   37.4167612363993       -122.129803326548
3.2.3   37.41671856613         -122.129723165972
3.2.4   37.4166777567939       -122.129641283509
3.2.5   37.4166324954969       -122.129557674936
3.2.6   37.4165882069033       -122.129477981343
3.2.7   37.4165497784701       -122.129399350525
3.2.8   37.4165127034988       -122.12932698084
3.2.9   37.4164568817556       -122.129227048344
3.2.10  37.4164049246162       -122.129132034479
3.2.11  37.4163578512605       -122.129039125341
3.2.12  37.4163182955449       -122.12896346953
3.2.13  37.4162752939008       -122.128882196374
3.2.14  37.416231580044        -122.128807291442
3.2.15  37.416184685551        -122.128726196491
No_Conn_lane   1
8.1     4     /*Straight ahead*/
end_lane
Lane    3.3
Lane_ID 5
Lane_type      1        /*1 to 5, for this intersection all 1: motorized vehicle lane */
Lane_attributes        0000000001100010    /*not engress path, straight permitted, no turn on
red, no u-turn */
Lane_width     320      /* in cm
No_nodes       15
3.3.1   37.4167828774395       -122.129919763941
3.3.2   37.4167337558151       -122.129823828595
3.3.3   37.4166932705907       -122.129744446435
3.3.4   37.4166515993766       -122.129664377984
3.3.5   37.4166078273512       -122.129576425087
3.3.6   37.4165641805396       -122.129500268396
3.3.7   37.41652626832         -122.129425492268
3.3.8   37.4164842530757       -122.129348222989
3.3.9   37.4164362681913       -122.129248980595
3.3.10  37.4163839793604       -122.12915818556
3.3.11  37.4163325642596       -122.129061838988
3.3.12  37.4162928163662       -122.128987639312
3.3.13  37.416250414411        -122.128907282272
3.3.14  37.4162056323078       -122.128829975817
3.3.15  37.4161572522109       -122.128752841295
No_Conn_lane   1
8.1     4     /*Straight ahead*/
end_lane
Lane    3.4
Lane_ID 6
Lane_type      1        /*1 to 5, for this intersection all 1: motorized vehicle lane */
Lane_attributes        0000000001110100    /*not engress path, left permitted, no turn on red, no
u-turn */
```

```
Lane_width     300      /* in cm
No_nodes       10
3.4.1  37.4167542957233       -122.129940919943
3.4.2  37.4167188133126       -122.129873395987
3.4.3  37.416685898609        -122.129814519242
3.4.4  37.4166575304934       -122.129757467598
3.4.5  37.4166329437434       -122.129707781475
3.4.6  37.4166093125726       -122.129661619431
3.4.7  37.4165886688114       -122.12962113307
3.4.8  37.4165675253101       -122.12958123555
3.4.9  37.4165490711042       -122.12954507991
3.4.10 37.4165364525146       -122.129518469369
No_Conn_lane   1
6.1 2    /*Left turn */
end_lane
end_approach
Approach       4
Approach_type  2                    /*1: approach, 2: egress*/
No_lane 3
Lane    4.1
Lane_ID 7
Lane_type      1        /*1 to 5, for this intersection all 1: motorized vehicle lane */
Lane_attributes        0000000001100011    /*egress path, straight permitted, no turn on red, no
u-turn */
Lane_width     320      /* in cm
No_nodes       7
4.1.1  37.41671818331718     -122.1299790370869
4.1.2  37.4166674160099      -122.1298838770647
4.1.3  37.41662171804333     -122.1297954413551
4.1.4  37.41657905667823     -122.1297162102326
4.1.5  37.41653485239063     -122.1296384561613
4.1.6  37.41650503545573     -122.1295717022707
4.1.7  37.41647246351928     -122.129505460882
No_Conn_lane   0    /* no connected lane because it is a egress lane*/
end_lane
Lane    4.2
Lane_ID 8
Lane_type      1        /*1 to 5, for this intersection all 1: motorized vehicle lane */
Lane_attributes        0000000001100011    /*egress path, straight permitted, no turn on red, no
u-turn */
Lane_width     350      /* in cm
No_nodes       7
4.2.1     37.41668971979865      -122.1299977528803
4.2.2     37.41664009948519      -122.1299071420392
4.2.3     37.4165924868289       -122.1298186168547
4.2.4     37.41655623484152      -122.1297444676824
4.2.5     37.41651131259039      -122.1296570668022
4.2.6     37.41647744599954      -122.1295946627315
4.2.7     37.41644553347895      -122.1295327893084
No_Conn_lane   0    /* no connected lane because it is a egress lane*/
end_lane
Lane    4.3
Lane_ID 9
Lane_type      1        /*1 to 5, for this intersection all 1: motorized vehicle lane */
Lane_attributes        0000000001100011    /*egress path, straight permitted, no turn on red, no
u-turn */
Lane_width     500      /* in cm
No_nodes       7
4.3.1  37.41665650402286    -122.130024909075
4.3.2  37.41660740261181    -122.1299352771995
4.3.3  37.41656154830789    -122.1298485051693
4.3.4  37.41647874367495    -122.1296811072763
4.3.5  37.41652570048112    -122.1297771398576
4.3.6  37.41644635605765    -122.1296211745271
4.3.7  37.41641382120163    -122.1295579328486
No_Conn_lane   0    /* no connected lane because it is a egress lane*/
end_lane
end_approach
Approach       5
Approach_type  1                    /*1: approach, 2: egress*/
No_lane 1
```

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Lane    5.1
Lane_ID 10
Lane_type      1        /*1 to 5, for this intersection all 1: motorized vehicle lane */
Lane_attributes        0000000001100100    /*not egress path, left permitted, no turn on red, no
u-turn */
Lane_width     600      /* in cm
No_nodes       2
5.1.1  37.4166805576826      -122.130196784375
5.1.2  37.4166610045652      -122.130214517263

No_Conn_lane   3
8.3 2    /*Left turn */
4.3 3    /*Right turn*/
2.1 4    /*Straight ahead*/
end_lane
end_approach
Approach       6
Approach_type  2                    /*1: approach, 2: egress*/
No_lane 1
Lane    6.1
Lane_ID 11
Lane_type      1        /*1 to 5, for this intersection all 1: motorized vehicle lane */
Lane_attributes        0000000001100011    /*egress path, straight permitted, no turn on red, no
u-turn */
Lane_width     365      /* in cm
No_nodes       2
6.1.1    37.41670823973271     -122.130247713306
6.1.2    37.41669141468812    -122.1302620010036

No_Conn_lane   0    /* no connected lane because it is a egress lane*/
end_lane
end_approach
Approach       7
Approach_type  1                    /*1: approach, 2: egress*/
No_lane 4
Lane    7.1
Lane_ID 12
Lane_type      1        /*1 to 5, for this intersection all 1: motorized vehicle lane */
Lane_attributes        0000000001110100    /*not egress path, left-turn permitted, yield, no turn
on red, no u-turn */
Lane_width     300      /* in cm
No_nodes       9
7.1.1  37.4168860924956      -122.130224851502
7.1.2  37.4169267553284      -122.130298088773
7.1.3  37.4169654343165      -122.13036603265
7.1.4  37.4170005683         -122.130436689151
7.1.5  37.4170426855377      -122.130512121982
7.1.6  37.4170760272553      -122.130579238831
7.1.7  37.4171055288253      -122.130635389872
7.1.8  37.4171346483101      -122.130686154465
7.1.9  37.4171548691911      -122.130727814425
No_Conn_lane   1
2.1    2     /*Left turn */
end_lane
Lane    7.2
Lane_ID 13
Lane_type      1        /*1 to 5, for this intersection all 1: motorized vehicle lane */
Lane_attributes        0000000001100010    /*not egress path, straight permitted, no turn on red,
no u-turn */
Lane_width     300      /* in cm``
No_nodes       14
7.2.1  37.4168601733727      -122.130249924204
7.2.2  37.4169272689098      -122.130369478131
7.2.3  37.416983020142       -122.130480187431
7.2.4  37.4170313300606      -122.130568611237
7.2.5  37.4170779383489      -122.130653921526
7.2.6  37.4171280148642      -122.130750723564
7.2.7  37.4171844645941      -122.130851772612
7.2.8  37.4172517455689      -122.130988481799
7.2.9  37.417315588047       -122.131114878602
7.2.10 37.4173797021789      -122.131236925363
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7.2.11  37.4174372832197       -122.131344423421
7.2.12  37.4174883869364       -122.131444802312
7.2.13  37.4175398541223       -122.131540271136
7.2.14  37.4175709277513       -122.131596778432
No_Conn_lane   1
4.1    4     /*Straight ahead*/
end_lane
Lane   7.3
Lane_ID 14
Lane_type      1        /*1 to 5, for this intersection all 1: motorized vehicle lane */
Lane_attributes       0000000001100010    /*not egress path, straight permitted, no turn on red,
no u-turn */
Lane_width     300      /* in cm
No_nodes       14
7.3.1   37.4168353722198       -122.130278087594
7.3.2   37.4168992754557       -122.130394563832
7.3.3   37.4169599305509       -122.13050381567
7.3.4   37.4170110358304       -122.130600967752
7.3.5   37.4170538819355       -122.130679156555
7.3.6   37.4170999049248       -122.130775396004
7.3.7   37.4171536150626       -122.130879090654
7.3.8   37.4172254334351       -122.131006334894
7.3.9   37.4172907601317       -122.131136790603
7.3.10  37.4173592423859       -122.131262071411
7.3.11  37.4174103457281       -122.131369508015
7.3.12  37.4174675616061       -122.13147229542
7.3.13  37.4175182028492       -122.131566538141
7.3.14  37.4175435594928       -122.131619243036
No_Conn_lane   1
4.2    4     /*Straight ahead*/
end_lane
Lane   7.4
Lane_ID 15
Lane_type      1        /*1 to 5, for this intersection all 1: motorized vehicle lane */
Lane_attributes       0000000001100010    /*not egress path, straight permitted, no turn on red,
no u-turn */
Lane_width     500      /* in cm
No_nodes       15
7.4.1   37.4168053771414       -122.130303792863
7.4.2   37.4168705574988       -122.130419765344
7.4.3   37.4169339936173       -122.130530299544
7.4.4   37.4169787512213       -122.130627843697
7.4.5   37.4170251321128       -122.130705299909
7.4.6   37.4170710884292       -122.130799286074
7.4.7   37.4171224013777       -122.130910600156
7.4.8   37.417189376809        -122.131038051008
7.4.9   37.4172595400253       -122.131168052007
7.4.10  37.417324122927        -122.131291982088
7.4.11  37.4173829447374       -122.131396631709
7.4.12  37.4174383438703       -122.131502303361
7.4.13  37.417483283692        -122.13158679392
7.4.14  37.4175151040482       -122.13164481331
No_Conn_lane   1
4.3    4     /*Straight ahead*/
6.1    3     /*Right turn*/
end_lane
end_approach
Approach       8
Approach_type  2                    /*1: approach, 2: egress*/
No_lane 3
Lane   8.1
Lane_ID 16
Lane_type      1        /*1 to 5, for this intersection all 1: motorized vehicle lane */
Lane_attributes       0000000001100011    /*egress path, straight permitted, no turn on red, no
u-turn */
Lane_width     500      /* in cm
No_nodes       7
8.1.1    37.41698999613381   -122.1301487685417
8.1.2    37.41703092627824   -122.130232766276
8.1.3    37.41708310110117   -122.1303344493398
8.1.4    37.41714589126958   -122.1304401705027
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8.1.5    37.41721002952112   -122.1305543959672
8.1.6    37.41727348471503   -122.1306893439825
8.1.7    37.41734802732613   -122.1308197665664
No_Conn_lane   0    /* no connected lane because it is a egress lane*/
end_lane
Lane   8.2
Lane_ID 17
Lane_type      1        /*1 to 5, for this intersection all 1: motorized vehicle lane */
Lane_attributes       0000000001100011    /*egress path, straight permitted, no turn on red, no u-turn */
Lane_width     330      /* in cm
No_nodes       7
8.2.1  37.41695988328576   -122.1301760265833
8.2.2  37.41700210639135   -122.1302565966703
8.2.3  37.41705529342506   -122.1303549071552
8.2.4  37.41711435649771   -122.1304651339681
8.2.5  37.41717157898459   -122.1305777219551
8.2.6  37.41724331422332   -122.1307125253804
8.2.7  37.41731608677779   -122.130846484155
No_Conn_lane   0    /* no connected lane because it is a egress lane*/
end_lane
Lane   8.3
Lane_ID 18
Lane_type      1        /*1 to 5, for this intersection all 1: motorized vehicle lane */
Lane_attributes       0000000001100011    /*egress path, straight permitted, no turn on red, no u-turn */
Lane_width     330      /* in cm
No_nodes       7
8.3.1    37.41693012392327     -122.1301991068885
8.3.2    37.41697332123947     -122.1302827458411
8.3.3    37.41702753956477     -122.1303801398179
8.3.4    37.41708465565918     -122.1304865748143
8.3.5    37.41714568540198     -122.1306041053189
8.3.6    37.41721402968123     -122.1307398148387
8.3.7    37.41728075340647     -122.1308723842856
No_Conn_lane   0    /* no connected lane because it is a egress lane*/
end_lane
end_approach
end_map
```