Best Practices for Surveying and Mapping Roadways and Intersections for Connected Vehicle Applications

Task 1 Report: Mapping Methodology Assessment

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I. Introduction

This project focuses on best practices for sensor-based surveying and mapping of roadways and intersections relative to the needs of Connected Vehicle (CV) applications. Connected vehicle applications will put new demands on transportation surveying and mapping given that detailed roadway feature maps will need to be developed, maintained, and communicated consistently to connected vehicles. To enable these applications, within the U.S. alone, hundreds of thousands of intersections and other roadway locations will need to be surveyed, with application-relevant roadway features mapped to application-specific accuracies. This Task 1 interim report documents the results of a sensor-based mapping methodology assessment. The assessment methodology included interviews with persons listed in the Appendix and a literature survey of the documents in the Bibliography.

There are several alternative methodologies for roadway mapping. For CV applications, the methods must be capable of creating and maintaining maps of detailed roadway features such as lane edges, road edges, and stop bars. Maps could be extracted from design and as-built construction documents. The advantage is that these documents are often already available in computer-aided design files. The disadvantage is that the current reality on the ground, especially regarding lane and stop bar striping, may diverge significantly from the design documents over time, necessitating map updating by other means. Other methods include photogrammetry, laser scanning, probe vehicles, and crowd sourcing, all of which will be referred to as sensor-based.

This interim report focuses on sensor-based mapping and is organized as follows. Section II provides an introduction to sensor-based mapping, introduces stationary, mobile and aerial laser scanning approaches, and discusses related tradeoffs. Section III discusses the mobile terrestrial laser scanning (MTLS) map production process. The discussion includes current practices, expected improvements, and issues affecting attainable accuracy. Section IV discusses selected CV applications (based on the Connected Vehicle Reference Implementation Architecture or CVRIA, version 1, see http://www.iteris.com/cvria/) along with necessary feature and required mapping accuracy. It also discusses the effect that the map accuracy specification has on real-time vehicle position estimation specifications. Section V discusses various map production business models.

II. Sensor Based Mapping

For existing CV testbeds, the surveying/mapping work has been accomplished using whatever means were readily available. Manual surveying can achieve high accuracy, but with a high cost per intersection. Manual extraction of roadway features from satellite (e.g., Google Earth)[1] imagery yields relative accuracy at the decimeter level with absolute accuracy at the meter level, but is a slow human-involved process. Such non-automated processes have been feasible to date, because the number of locations to be mapped has been small. In the future, however, many more locations will need to be completed. Some examples of map information required by connected vehicle applications include; lane edges, road edges, location of intersection center, number of approaches, number of lanes on each approach, lane widths, location of stop bars, and length of storage space in left turn lanes.

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[1] Manual CV testbed data feature extraction from DOT geo-rectified photo logs should also be feasible, but to the authors' knowledge, this has not been implemented.

Commercial success of CV applications requires buy-in from automobile manufacturers. Auto manufacturers become interested when there is a global scale solution, as numerous local solutions are infeasible from their production, marketing, and maintenance perspectives. In the future, when maps for roadways and intersections across a variety of nations must be developed maintained, and distributed, in addition to cost and accuracy, several technical issues become important:

- Initialization of the map;
- Detection of changes to or obsolescence of regions within existing maps;
- Adaptation or replacement of regions within existing maps; and
- Continuity of maps across jurisdictional or geographic boundaries.

The following sections discuss the use of various sensor technologies to automate such processes. The required sensors are currently available. Both the sensors and the processes discussed below are being used at present in manual and semi-automated processes. Due to the vast quantities of data that are involved, further automation of the mapping construction and updating processes are required for these technologies to move from testbeds to global realities.

A. Sensor Based Mapping Overview

The high-level steps of the sensor based mapping process are illustrated in Figure 1 [Vu, Farrell & Barth 2015; Yen, Ravani & Lasky 2014].

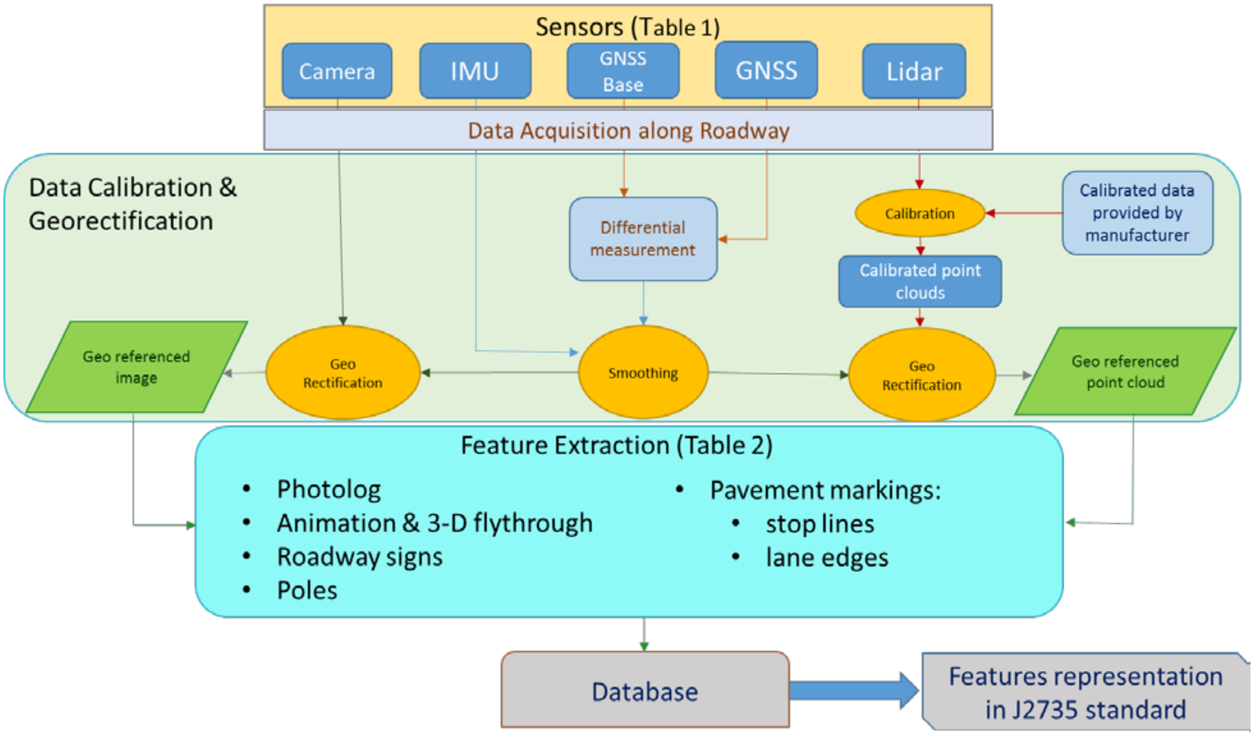

Figure 1. Sensor Based Mapping Process

A rigid platform containing a suite of sensors is placed in or moved through an environment for which a digital map is to be constructed. Sensor data are acquired and processed (see Section III) to produce a map of roadway features.

A variety of databases may be involved in the above steps:

1. The raw uncalibrated sensor data that are the output of the upper gray box, prior to the georectification process, are usually not distributed publicly, except by special request. Instead, it is maintained in a variety of formats within the databases of the entity that acquires the data. The database formats may be proprietary to the instrument manufacturer or converted to standard formats such as Rinex for Global Navigation Satellite System (GNSS) [IGS 2013] or LAS for LIDAR (Light Detection and Ranging) [ASPRS 2008].
2. The calibrated and georectified imagery and point cloud data are the output of the green box and is potentially available for distribution. Photologs and LIDAR calibrated photologs (colorized point clouds) are two of the most common types of mapping database distributions at the present time. State Departments of Transportation (DOT's) use photologs for a variety of purposes, such as for roadway assessment, roadway inventory management, accident analysis, and safety analysis. Software products are available that allow the user to "fly through" and make position related calculations using the calibrated imagery.
3. After manual or automated processing of the calibrated imagery and point cloud data, certain roadway features will have been extracted along with their locations and metadata descriptors. These are the output of the Cyan box. Distribution of such feature maps is still in its infancy, especially over large regions. Effective distribution and use will require specifications for feature descriptors. One example is the Navigation Data Standard (NDS) [NDS 2015].

To enable CV applications, within the limited communication constraints, subsets of the roadway feature database are communicated to the end-users (connected vehicles and infrastructure) using communication standards such as SAE J2735 [SAE 2009].

B. Typical Sensor Packages

Typical sensors include Global Navigation Satellite System (GNSS) receivers, an inertial measurement unit (IMU), cameras, and LIDARs [Vu, Farrell & Barth 2013; Vu & Farrell 2013; Yen, Ravani & Lasky 2014]. The purpose of the cameras and LiDAR sensors is to sense the roadway environment to enable analysis of that environment, including feature detection and mapping. The camera and LIDAR sense the roadway feature locations relative to the sensor platform. The georectification process requires knowledge of the platform orientation and location (i.e. the platform pose) to compute the feature locations in an Earth Centered Earth Fixed reference frame suitable for a map. The purpose of the GNSS and IMU data is to compute the sensor platform pose with high accuracy at a high rate.

A few examples of sensor packages that are currently available are summarized in Table 1. Each contains at least 6 cameras, providing a nearly 360 degree field-of-view, and at least two LIDAR sensors. Each contains at least one dual frequency GNSS receiver and an IMU. Multiple cameras are useful to help ensure that visual imagery is available of the roadway, features, and overhead structures in spite of occlusions. Multiple LIDAR sensors help to ensure a sufficiently dense set of reflections from features to enable feature detection. Also, multiple views of features from different locations and aspect angles facilitates accurate estimation of feature location. One GNSS receiver is sufficient for determining platform location. The GNSS combined with the IMU allows accurate estimation of the time history of the pose at the high sampling rate of the IMU [Vu, Farrell & Barth 2013]. Sometimes two GNSS antennae are used to directly measure platform attitude [Cohen, McNally & Parkinson].

Table 1. Examples of commercially available Mobile Terrestrial Laser Scanners (MTLS).

Product Features	Product Name			
	Trimble MX2	Trimble MX8	Topcon	Mandli
360° LIDAR	72 K pps	1 M pps	120 K pps	1.4 M pps
Number of LIDARs	2	2	5	2
LIDAR name	SLM-251 Class 1	VQ-250	Velodyne HDL-32E	Velodyne HDL-64E
Number/Resolution of digital cameras	6/12 MP	8/5 MP	6/30 MP	8/8 MP
Dual frequency GNSS receiver	Yes	Yes	Yes	Yes
IMU Positioning & orientation rate		200 Hz	100 Hz	200 Hz
IMU/GNSS Brand	Applanix POSPac MMS	Applanix POS LV 220	Honeywell HG1700	Applanix POS LV 220
Wheel Encoder DMI		Yes	Yes	Yes

An example of sensor data rates are summarized in Table 2. For different sensor combinations, the specific amounts of data will change, but the overall conclusion is the same. The database containing the raw sensor data grows very quickly. Due to the size of the data sets and the time varying nature of the roadway infrastructure, the database must be managed and curated with care.

Table 2. Example rates of data accumulation for an MTLS.

Sensor	Bytes/Msg.	Msgs./sec	Bytes/Sec	GB/Hr	GB/Hr (with timestamp overhead)
IMU	19	200	3800	0.013	0.232
LIDAR	1206	3473	4,188,438	15.08	15.278
Camera	35,836,416	7.5	268,773,120	967.583232	967.583
GPS measurement data	612	1	612	0.002	0.0374
GPS Ephemeris data	256	.002	.512	1.8432e-6	3.13344e-5
DGPS data	1071	1	1071	0.0038	0.0039
Total:			273 MB /sec	982 GB/Hr	983 GB/Hr
Hrs. of collection per TB:					≈1 Hr.
Miles of coverage per TB (assuming a speed of 30 mph):					≈30 miles

C. Georectification

Figure 2 illustrates the *GeoRectification* process. The goal is to estimate and store the position of feature points within a specified world frame of reference. In this figure, the desired feature is the center of the left hand turn sign. The frame of reference has its origin at the center of the intersection. This feature position is depicted by the green arrow, which is indicated by the symbol P_F^W for the position of the feature F relative to the World. There is no single sensor that can efficiently provide P_F^W, so the vector is instead measured indirectly through the various quantities shown in the right

$$P_F^W = R_{WP}\left(R_{PL}P_F^L + T_{PL}^P\right) + T_{WP}^W$$

Figure 2. Georectification Process

hand side of the equation at the bottom of the figure. GNSS and IMU data can be processed to determine the position and rotation (i.e., the pose) of the sensor platform relative to the world. This vector is represented by the purple arrow in the figure. The position and orientation are represented by the purple symbols T_{WP}^{W} and R_{WP} in the equation at the bottom of the figure. The translation and orientation of the LIDAR and Camera frames relative to the IMU are known and fixed when the platform is designed. These quantities a represented by the red arrow and the red symbols T_{PL}^{P} and R_{PL} in the equation at the bottom of the figure. Finally, the yellow arrow represents the LIDAR measurement of the feature location relative to the LIDAR frame, which is represented by P_F^L. Because all the quantities on the right hand side of the equation can be computed from the sensor data, the desired position of the feature in the world frame P_F^W, as necessary for a map, can be computed.

Various factors affect the accuracy and success of sensor based mapping. The right-hand side of the georectification equation in Figure 2 contains five quantities that are estimated from the data. Any inaccuracies in the determination of these five quantities accumulates into the overall inaccuracy of P_F^W. The quality of the IMU, GNSS and processing algorithms determine the accuracy of T_{WP}^{W} and R_{WP}, which are computed at high-rates. Processing algorithms typically smooth IMU and GNSS data optimally in a post-processing mode [Triggs, Mclauchlan, Hartley 2010; Vu, J. A. Farrell & M. Barth 2013; Eustice, Singh, & Leonard 2006; Dellaert & Kaess 2006]. While the quantities T_{PL}^{P} and R_{PL} are accurately initialized based on design calculations, their values may also be refined in the post-processing optimization process. The reliability of detecting features and the accuracy of estimation of P_F^L are determined by various LIDAR and operational issues, predominantly the distribution and density of LIDAR reflections from the feature's surface. Various articles discuss the processing of LIDAR point clouds to detect roadway relative features [Ibrahim & Lichti, 2012; Yang, Fang, Li & Li 2012; Yang, Fang, Li & Li 2012; Yang, Wei, Li, Li 2012; Yang, Fang, Li 2013; Guan, Li, Yu, Chapman & Wang 2014; Kumar, Conor, McElhinney, Lewis & McCarthy 2014; Guan, Li, Yu, Wang, Chapman & Yang 2014; Guan, et al. 2014; Guan, Li, Yu, Ji & Wang 2015; Yu, Li, Guan, Jia, Wang 2015].

D. Laser Scanning and Photogrammetry: STLS, MTLS, ALS

The principles underlying Laser Scanning and Photogrammetry are similar and will be treated together in three different scenarios [Kieval 2015]: Stationary Terrestrial Laser Scanning (STLS), Mobile Terrestrial Laser Scanning (MTLS), and Aerial Laser Scanning (ALS).

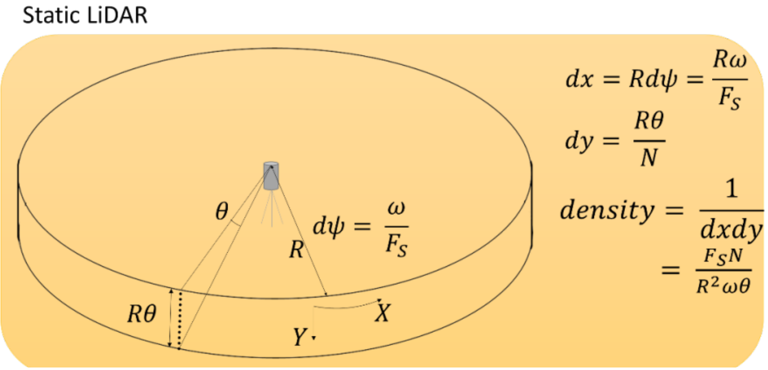

Figure 3. Stationary Terrestrial Laser Scanner Performance Analysis

The georectification process for STLS is simplified by the fact that the stationary instrument location serves as the reference point and is stable throughout the data collection procedure. This enables all measurements in a single survey to be referenced relative to a single point. The georectification transformation procedure from the LIDAR instrument relative measurement to the earth frame (e.g., latitude, longitude, elevation) is greatly simplified.

The relative spatial errors generated in the measurement process are solely attributed to the accuracy of the LIDAR measurements. An inaccuracy of the resulting georectified survey is a combination of the LIDAR measurement error and instrument location error (usually via GNSS). The GNSS survey of the instrument location is greatly enhanced due to extended GNSS measurement duration at a single stationary location.

Figure 3 depicts a typical STLS configuration wherein a LIDAR rotates at an angular rate ω, emitting a vertical line containing *N* laser pulses distributed across a field-of-view (FOV) with angle θ. For each pulse, the return intensity and round-trip time-of-flight are measured at a rate F_S. When the LIDAR reflects from an object at a distance *R*, the density of reflected points is approximately $\frac{F_S N}{R^2 \omega \theta}$ points per square meter. For example, if an STLS rotates at 15 Hz with 1000 vertical scans per second ($F_S = 15kHz$), each containing *N*=64 laser pulses with a 30 degree FOV, then a reflecting surface *R*=20 meters from the LIDAR would reflect approximately 49 points per meter (PPM) squared per second. The number of points per stationary reflecting object accumulates as the STLS remains running at a fixed location. The STLS includes a GNSS receiver so that its location can be precisely determined. Knowledge of the LIDAR frame cylindrical coordinates (R, θ, ψ) together with the STLS pose allows estimation of the ECEF position of each reflected LIDAR point. The main drawback of the STLS is that the region that is mapped is small, as determined by the LIDAR range. The STLS could be moved to multiple (stationary) locations to extend its range.

The migration from stationary surveys to mobile surveys has allowed an increased rate of data collection with the development of new methods to manage the accuracy of the resulting survey in spite of the motion of the instruments. Each individual LIDAR measurement must be time aligned with a specific *pose* of instrumentation. Each pose describes both the position and attitude (i.e., orientation) of the LIDAR at a specific time. While STLS only requires accurate determination of one pose, MTLS and ALS require determination of a time history (or trajectory) of poses. This trajectory estimation process can be solved by various methods [Triggs, Mclauchlan, Hartley & Fitzgibbon 2010; Vu, J. A. Farrell & M. Barth 2013; Eustice, Singh, & Leonard 2006; Dellaert & Kaess 2006] and introduces various opportunities for estimation errors that are not relevant in a static survey. The trajectory estimation methods may incorporate GNSS receivers, Inertial Measurement Units (IMU), and cameras. Time alignment associated with integrating measurements from various sensors introduces errors that become more significant as the speed of the moving platform increases. The speed of the survey platform transitioning through the environment also affects the quantity of data collected for a specific region. The point density in a mobile survey will become more sparse as the velocity of the measurement platform increases.

ALS mounts the sensor platform on either a piloted or autonomous aerial vehicles (UAVs). The mapping error in an ALS approach is strongly influenced by two factors: the speed of the platform and the distance of the LIDAR reflections. Traditional ALS vehicles are fixed wing vehicles that move at high speeds and cannot hover. The high speed lowers the point density per pass over a given area and makes time alignment more critical. Long range due to high altitude makes platform attitude estimation more critical. Imaging of surveyed control points on the ground or incorporating an IMU provides additional measurements to calibrate these error sources.

For fixed wing aircraft the ALS survey accuracy is typically reduced relative to MTLS and STLS. This issue is overcome in some ALS implementations where the aerial vehicle (e.g., a quadrotor) is capable of travelling at slow speeds, hovering, and flight at low altitudes.

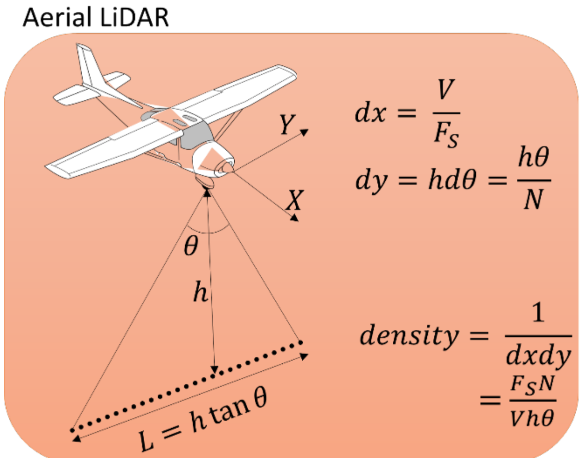

Figure 4. Aerial Laser Scanner Performance Analysis

Figure 4 depicts a traditional ALS configuration wherein a LIDAR emits a line containing *N* laser pulses distributed across a FOV with angle θ. The LIDAR line scanner is rigidly mounted so that straight and level flight results in a scan on the Earth surface, below the plane, perpendicular to the direction of travel. The lines are generated and the return intensity and round-trip time-of-flight are measured at a rate F_S. When the LIDAR reflects from an object at a vertical distance h, the density of reflected points is approximately $\frac{F_S}{Vh\tan\left(\frac{\theta}{N}\right)}$ points per square meter. For example, if an ALS at traveling at *V*=100 m/s emits pulses at a line rate of F_S =15 kHz, with *N*=64 laser pulses per line over a 30 degree FOV, then a reflecting surface *h*=5000m below the LIDAR would reflect approximately 4 PPM. The number of points per reflecting object does not accumulate, unless the aircraft traverses the airspace above the reflecting object multiple times. Because the aircraft is moving, it typically is instrumented with at least one GNSS antenna and receiver and an IMU. These instruments allow accurate determination of the LIDAR attitude and position at the high LIDAR sampling rate. The aircraft is typically also instrumented with cameras allowing the detection of known survey points on the earth for calibration and cross-checking. A main advantage of ALS is that it can cover a large geographic area much faster that is possible with an STLS. The main disadvantages are the lower density and position accuracy of the reflected points.

An MTLS mounts one or more rotating LIDARs onboard a land vehicle that can be driven through the environment to be mapped. The MTLS is more mobile than an STLS allowing it to acquire data more rapidly for mapping a roadway network. However, reflecting objects may be occluded from the LIDAR by interfering entities such as other vehicles. The density of the point cloud along the roadway is approximately $\frac{F_S N}{R^2\omega\theta}$ points per meter. The number of points reflected per object does accumulate as the MTLS drives by, but only over a short time-window determined by the speed of travel of the vehicle. Multiple transits within a given section of roadway, although not required, may have several benefits: increased point cloud density, decreasing the likelihood of occluded sections, and acquiring surface reflections from various aspect angles.

Tables 3 and 4 compare the accuracy, collection speed and range of STLS, MTLS, and ALS. Table 3 is qualitative, while Table 4 gives example numbers based on assumed experimental conditions [Kieval 2015]. The point density is critical to the performance of automated feature (e.g., lane stripe) detection.

Table 3. Qualitative comparison of STLS, MTLS, and ALS.

Laser Scanner	**Stationary**	**Mobile**	**Aerial**
Collection Range/ Speed	Small	Large	Very Large
Point Density	High	Medium	Low

Table 4. Example quantitative comparison of MTLS and ALS [Kieval 2015].

Laser Scanner	**Mobile**	**Aerial**
Point Density (ppm)	100 - 3000	10-50
Field of View (degree)	360	45-60
Measurement Rate (pps)	160,000 – 400,000	200,000
Relative Accuracy (ft)	0.023	0.065
Absolute Accuracy (ft)	Submeter	0.25 – 0.5

The ALS and MTLS instrument suite includes GNSS and IMU to enhance the accuracy of the platform trajectory (pose history) estimation. The IMU also enhances that ability to accurately time align the instrument measurements with the appropriate vehicle pose. Commercial trajectory estimation approaches reliably achieve meter level trajectory estimation with the MTLS system moving at highway speeds. Use of advanced estimation methods has demonstrated decimeter level (or better) automated survey results [Vu, J. A. Farrell & M. Barth 2013]. When accuracies equivalent to a stationary survey are required with a mobile application, individual control points can be surveyed and used to improve the accuracy of the MTLS survey.

E. Crowd Sourced Data

Crowd sourced data involves ordinary drivers reporting anonymized travel logs to mapping companies. Many drivers have navigation software running either through their cell phone or through on-board devices typically used for general navigational purposes. These anonymized trajectories provide very large datasets that explicitly contain potentially useful information about traffic conditions. The datasets do not contain explicit information about roadway features such as stop bars or lane edges; however, bundles of closely spaced trajectories provide useful information about number of lanes, lane centerlines, lane and route connectivity, road conditions, and other items. The data are not highly accurate, because the location of the data recording device in the vehicle is typically not known and cellphone or on-vehicle position determination is currently not accurate to more than a few meters. Enhanced processing algorithms may be able to improve accuracy. Most importantly, the data is timely and low cost, and can serve complementary purposes to accurate surveyed data sets. The data can, for example, detect accidents, pot holes, obstacles, road closures, or newly opened streets or roadway connections, which could trigger a request for mapping by more accurate means.

F. Summary

The capabilities of STLS, MTLS, ALS, and crowd sourcing have been evaluated relative to the requirements for Connected Vehicle application mapping requirements. While the accuracy obtained through STLS implementations is sufficient for CV applications, the time investment involved in widespread STLS surveys is prohibitive. ALS currently is the best option for regional surveys, but currently lacks the accuracy and road surface reflection point density needed for reliable roadway feature detection, especially those requiring sub-meter mapping accuracy. The most suitable mapping approach for Connected Vehicle applications is MTLS followed by optimal sensor integration and data processing for trajectory estimation, georectification, and feature extraction and mapping. At present, feature extraction is largely a manual process. Over the next several years, these processes are expected to migrate through human-assisted toward automatic processing. Crowd sourced data is expected to be useful for detecting changes to the roadway infrastructure that will later be surveyed by more accurate methods. Further details associated with MTLS hardware, software, configuration, and methodology are discussed below.

III. MTLS Process, Instruments, Software

Mobile Terrestrial LIDAR Systems are comprised of numerous individual sensors mounted upon a single platform. The common sensors and components comprising an MTLS include:

- LIDAR(s) – either planar or rotating LIDAR sensor(s)
- Camera(s) – one or more cameras
- GNSS – Real Time Kinematic (RTK) capable GNSS receiver
- IMU – Inertial measurement
- Processors – Data logging with precisely time aligned data streams
- Data Storage – repository for partially processed data onboard the vehicle
- Power support – energy storage and/or generation to handle additional power loads

The physical construction of the MTLS requires significant consideration to physical layout, occlusions, signal processing, calibration, and configuration. Each individual sensor possesses specific operational constraints and considerations. When properly integrated and configured the system provides accurate and robust system for mapping roadway infrastructure effectively and efficiently [Berber, Mills & Smith-Voysey 2008; Yen, Ravani & Lasky 2014]. The overall process is depicted in Figure 1.

The physical layout attempts to provide a rigid structure, so that the pose variables T_{PL}^{P} and R_{PL} defined relative to Figure 2 are constant. The camera(s) and LIDAR(s) are mounted to not be occluded by the mounting structure and the other instruments, while also having a clear view of the roadway and its environment. It is critical that the LIDAR(s) are able to acquire a high density of roadway reflections to allow detection and recognition of roadway features.

While the sensor data may be processed in real-time for quality assurance, all the data is saved to the disk with precise time stamps for post-processing. Accurate time alignment is necessary because the platform is moving. The georectification process sums three vectors to construct the desired vector P_{F}^{W}. Three of the quantities in the georectification formula change with the pose of the vehicle. Accurate time alignment ensures that the correct set of quantities is estimated and summed.

The first step of the georectification process is determination of the platform trajectory by use of the GNSS and IMU data. The (differential) GNSS measurements provide constraints on the vehicle location at the measurement time instants at a low rate (i.e., 1 Hz). The IMU measurements provide constraints on the platform motion between the GNSS measurement epochs at very high rates (i.e., >200 Hz). Optimal nonlinear smoothing algorithms [Triggs, Mclauchlan, Hartley & Fitzgibbon 2010; Vu, J. A. Farrell & M. Barth 2013; Eustice, Singh, & Leonard 2006] combine these data in a post-processing operation to estimate the platform trajectory. These algorithms can also incorporate the LIDAR and Camera measurements. For example reflectors easily detectable by either the LIDAR or Camera may be placed at surveyed locations to serve as control points. This GNSS/IMU smoothed result provides the time history of the platform pose at the IMU sample rate which is necessary to perform LIDAR and camera georectification.

The LIDAR data and camera data are stored onboard. The translation of camera data and LIDAR data into a georectified point cloud and photolog requires extensive post processing, filtering, and manipulation. The photolog and colorized point cloud are direct outputs of the georectification process. Commercial companies (e.g., HERE) will soon stitch the photolog images together into a continuous panoramic image. In either case, the user can fly though this database seeing and analyzing the roadway environment.

The georectified LIDAR point cloud data are useful for feature detection and mapping. After data reduction to a small specific region, the first task is to identify the individual points within the point cloud subset that are expected to belong to the same surface (e.g., high intensity points lying on a near horizontal surface). These individual points are processed to remove outliers and used to estimate the desired characteristics to describe the feature (e.g., location).

The designated features such as lane markings, road edges, stop bars, and intersections can be identified, characterized and defined. This feature extraction process is specific to the attribute and requires very specific programming. A high density of LIDAR reflections on the surface of interest greatly facilitates feature detection and mapping.

The process of creating a georectified photolog is similar to processing the LIDAR data but entails special image processing steps when transitioning from one survey frame to the next. Each image will possess a small amount of location measurement error. When two or more images are being merged the images must be processed and aligned to avoid visual blurring and distortion. This process is well-documented (see, e.g., [Forsyth & Ponce, 2011]) but requires significant processing power as the size of the images increase. Due to the extensive processing requirements the integrated and georectified photolog (or panoramic image) is created as a post-processing step.

IV. Applications: Features and accuracy requirements

Numerous ITS applications have been identified with the potential to improve mobility, safety, and the environment [ED-MAP 2004; MTA 2012; Spear, Vandervalk & Snyder 2010]. Connected vehicle technology has been identified as an enabling technology for many of the identified applications. The V2V and V2I connected vehicle implementations often require accurate positional information relative to a reference map. The reference map contains road features, such as, lane markings, stop bars, road edges, turn pockets and intersection geometry. The goal of this section is to discuss mapping and real-time positioning tradeoffs and to characterize the accuracy requirements of a variety of connected vehicle applications. For a common list of connected vehicle applications, we reference the CVRIA (http://www.iteris.com/cvria/). The CVRIA CV application list is based on the results of an extensive connected vehicle research program carried out by the USDOT over the last decade.

G. Mapping and Real-time Positioning Tradeoffs

The Figure 5 illustrates a connected vehicle maneuvering within a lane near an intersection. Various quantities of interest for the application – forward distance s_F, left distance s_L, and right distance s_R – are illustrated. Each of these quantities is computed in real-time at a high rate by differencing the vehicle position p_V with a quantity computed from the map information: p_L, p_F, or p_R. For example, $s_F = p_F - p_V$, each of which is uncertain, with uncertainty indicated in the figure by the size of the concentric circles around the point. Therefore, the uncertainty in the computed quantity is related to the uncertainty in the positions. If we characterize the uncertainty by a standard deviation, then the equation is

$$\sigma_{s_F} = \sqrt{(\sigma_{p_V})^2 + (\sigma_{p_F})^2}.$$

This equation is important as it shows the tradeoff between the accuracy specifications of the map features denoted by σ_{p_F} and the implied accuracy requirements for real-time positioning (i.e., navigation) denoted by σ_{p_V}.

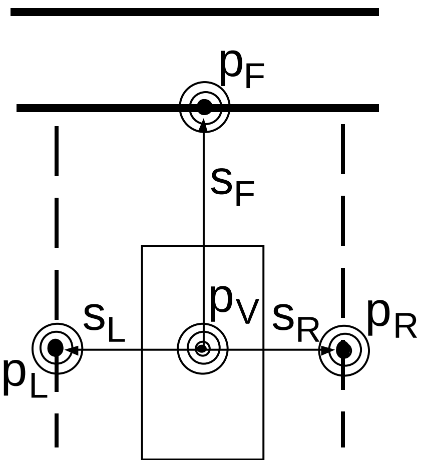

Figure 5. CV application variable definitions

Figure 6 illustrates this tradeoff. Assume that for a given application, the distance to the stop bar $||s_F||$ must be computed with a standard deviation of less than one meter. The outermost curve in the figure shows the locus of points that satisfy this specification. If for example, the map is accurate to 10 cm, then real-time vehicle position estimated to 0.99 meter accuracy is sufficient. However, if the map is only accurate to 0.9m, then the vehicle position must be estimated in real-time to an accuracy of approximately 40 cm.

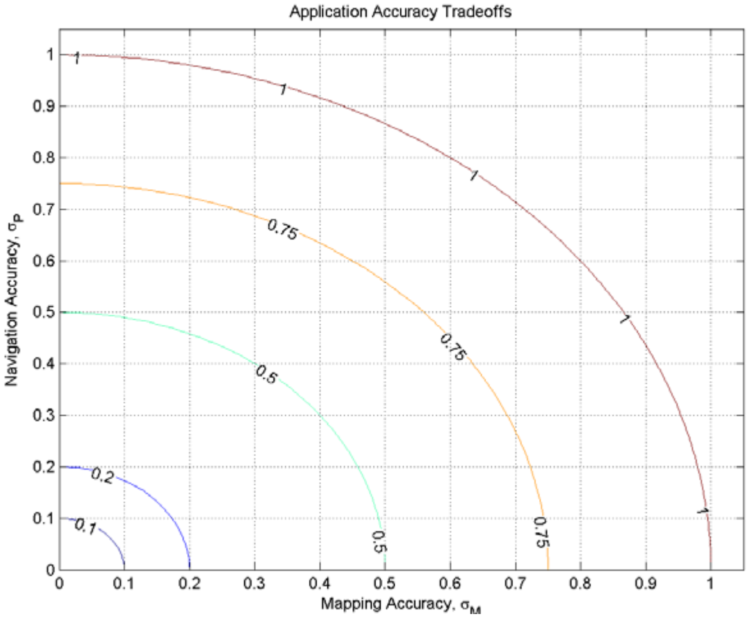

Figure 6. CV Mapping and positioning tradeoffs.

H. Connected Vehicle (CV) Application Accuracy Requirements

The CV applications from the CVRIA version 1 are presented in three tables segregated as either a mobility, environmental, or safety application[2]. Vehicles possessing Connected Vehicle technology will typically possess a GNSS receiver capable of 2 to 3 meters accuracy in many road environments. This level of GNSS technology will likely provide sufficient accuracy for applications requiring “Coarse Positioning” in the following tables. The mobility applications requiring “Lane Level Positioning” or “Where in Lane Positioning” will require improved positioning technology (e.g., a GNSS receiver capable of receiving differential corrections, perhaps processing the carrier phase information) and likely require an accurate reference map of the roadway. These applications requiring improved accuracy and a detailed map will be reviewed in greater detail in a subsequent report.

The CV safety applications, as shown in Table 1a, identify numerous applications requiring positioning better than 3 meters. The pure V2V applications that are independent of lane arrangement do not require a detailed map representation. Alternately the V2V applications such as Intersection Movement Assist requires detailed knowledge of the intersection geometry and the position of vehicles within the intersection. This example clearly requires a detailed intersection reference map as well as accurate vehicle positioning. Rather than report explicitly on each application in the table, we cite a single example below to provide background on the positioning and mapping needs.

Safety Application Example – Emergency Electronic Brake Light (EEBL)
The EEBL application enables a vehicle to broadcast a self-generated emergency brake event to surrounding vehicles. The receiving vehicle determines the relevance of the event and if appropriate provides a warning to the driver in order to avoid a crash. This application improves driver safety for both the host vehicle and the remote vehicle as seen in Figure 7. The EEBL equipped braking vehicle (RV) and the EEBL vehicle receiving the message (HV) can interact in numerous beneficial scenarios. The most beneficial situation in Figure 7 is scenario 4 when a heavy braking event occurs and the equipped HV can not only avoid impacting the RV but can moderate is own deceleration rate. The moderation of deceleration by the HV reduces the risk of additional collisions of non-equipped vehicle following the HV. Many potential scenarios exist for the potential deployment of EEBL with varying levels of technology implementation.

At the simplest EEBL technology level a vehicle can be equipped to sense the distance and deceleration rate of a vehicle directly in front of a host vehicle. This can be accomplished without the need of absolute vehicle position and only requires proximity (e.g. radar, LIDAR, stereo vision camera) sensing. EEBL applications which only utilize on-board proximity sensors will be limited to responding only to vehicles directly in front of a host vehicle. Any obstructions will reduce the effectiveness of the application.

EEBL applications utilizing Connected Vehicle technology will integrate the equipped vehicles’ absolute position into the EEBL algorithm. When a vehicle’s positional accuracy is “coarse positioning”, the benefits are limited by approximation relative vehicle positioning between equipped vehicles. A hard braking event

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[2] Please note that the initial mapping and positioning accuracy analysis was carried out on CVRIA version 1; as of August 3, 2015 CVRIA version 2 has been released, describing an expanded list of CV applications. This section of the report will be expanded for the final report.

can be broadcast to nearby vehicle as a warning, but countermeasures cannot be fully deployed since vehicle proximity is unknown and the vehicle may be in different lanes.

EEBL applications utilizing "lane level positioning" can improve the fidelity of the application by limiting warnings to vehicles in the same lane. This greatly improves the effectiveness of the application. Finally, "where in lane" positioning provides the greatest benefit to equipped vehicles. The scenarios shown in Figure 7 can be fully optimized with where in lane positioning. The relative position between equipped vehicles will be accurately determined even when line-of-sight doesn't exist. The EEBL application is particularly useful when there is line of sight obstruction by other vehicles or poor weather conditions (e.g., fog, heavy rain). Various automotive OEMs have experimented with the EEBL concept.

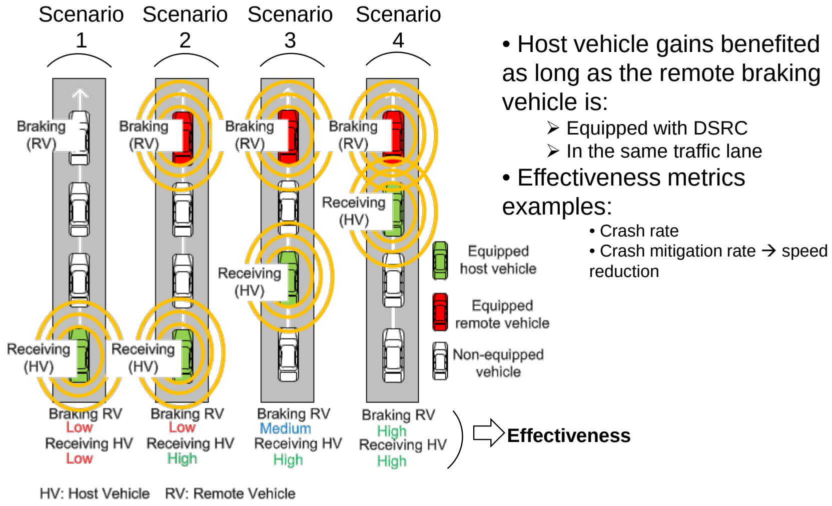


Figure 7. EEBL Safety CVRIA application as envisioned by OEM (Honda).

The CV mobility applications, as outlined in Table 1b, have several V2I implementations that required accurate knowledge of a vehicle's position within the roadway, both from a lateral point-of-view (e.g., lane markings) and a longitudinal point-of-view (e.g., stop bars at intersections). Examples include: Traffic Signal Priority, Speed Harmonization, and Intermittent Bus Lanes. These applications must coordinate specific vehicle movements within a lane and require detailed reference maps in conjunction with accurate vehicle positioning. We describe a single mobility application example below to highlight the mapping needs.

Mobility Application Example – Cooperative Adaptive Cruise Control (CACC)

The goal of CACC is through partial automation to coordinate the longitudinal motion of a string of vehicles by utilizing V2V communications in addition to traditional adaptive cruise control (ACC) systems. There are a wide variety of CACC implementations, but in general CACC implementations employ the following conditions:

- V2V messages are communicated between leading and following vehicles, and the application performs calculations to determine how and if a string can be formed;
- The CACC system provides speed and lane information of surrounding vehicles in order to efficiently and safely form or decouple platoons of vehicles; and,
- the "groups" of vehicles that are formed are referred to as "strings" rather than "platoons" of vehicles (strings are sometimes called loosely coupled platoons).

The simplest CACC technology can be deployed with only proximity (e.g. radar, LIDAR, stereo vision camera) sensing and with significant gaps between the vehicles. This "no-positioning" version would not be able to coordinate platoon formation or decoupling. The application would only be able to loosely keep a group of vehicles traveling a constant speed. More meaningful implementations of CACC require some level of absolute vehicle positioning.

When a vehicle's positional accuracy is at "coarse positioning", the benefits are limited by approximating relative vehicle positions between equipped vehicles. Lateral maneuvers would not be feasible without the addition of on-board sensors to determine lane markings and nearby vehicle proximity. When at "Lane Level" positioning accuracy, it is possible to have the application coordinate vehicle strings with formation and de-coupling maneuvers. But to maximize CACC potential, "where in lane" accuracy is required to manage complex merge and split maneuvers and minimize headway within a string. The additional integration of lane keeping can be assisted by on-board proximity sensing and sub-meter relative position accuracy. Figure 8 depicts a CACC application with relevant gap, headway, and vehicle roles.

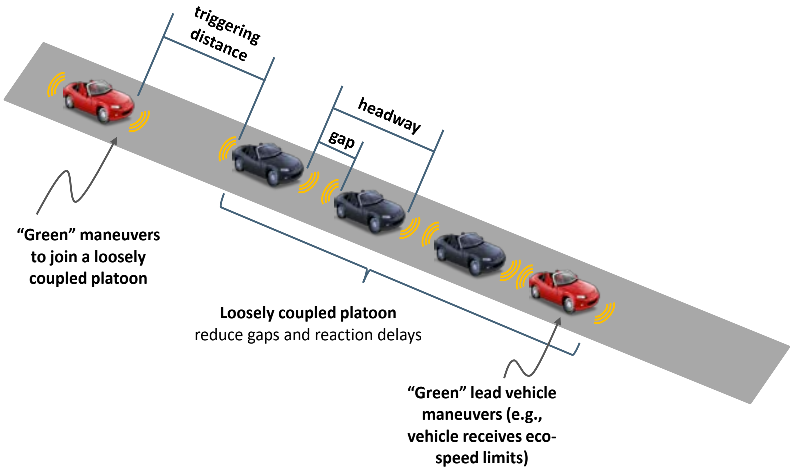


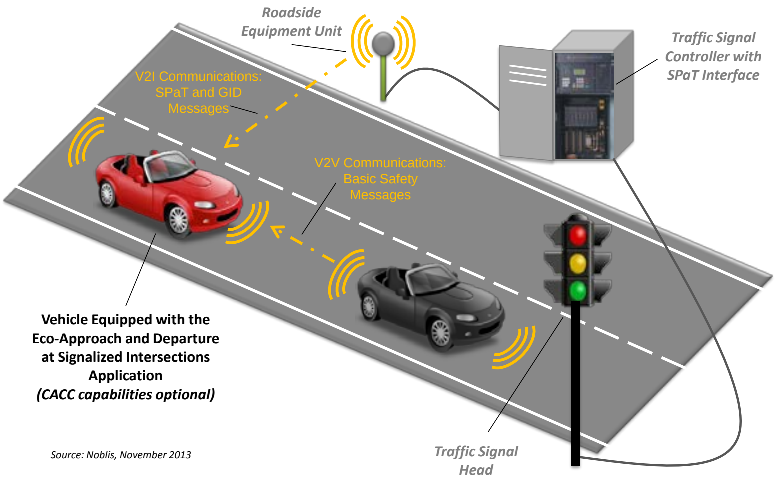
Figure 8. CACC Mobility CVRIA application as deployed in pilot demonstrations.

Several CV environmental applications, as shown in Table 1c, also require accurate map relative positioning. Eco Approach and Departure, Eco Speed Harmonization, and Eco Transit Signal Priority all require detailed knowledge of vehicle position within the roadway. It is important to note that the required positional accuracy for a specific application must consider the additive errors of vehicle positioning error and map errors. A two meter vehicle positioning error and two meter map error leads to a potential four meter error in the CV application deployment. Since errors are more easily controlled during a mapping survey it is important to reduce map errors whenever feasible. A single environmental application is described below.

Environmental Application Example – Eco Approach and Departure (EAD)

An EAD implementation at signalized intersections provides speed advice to the driver of the vehicle traveling through the intersection. Longitudinal control can be carried out by driver using driver vehicle interface or the longitudinal control can be automated (e.g., see the GlidePath program). The speed of the vehicle is managed to pass the next traffic signal on green or to decelerate to a stop in the most ecofriendly manner. The application also considers a vehicle's acceleration as it departs from a signalized intersection. An EAD equipped vehicle will be advised to follow a speed trajectory based on: SPaT data sent from a roadside equipment (RSE) unit to connected vehicles via V2I communications; Intersection geometry information; signal phase movement information; and, potential data from nearby vehicles can also be utilized using V2V communications. Figure 9 shows the current pilot deployment architecture of EAD at signalized intersections.

At the simplest EAD technology can be deployed with “coarse positioning” and serve as a loose advisory to the driver. The coarse positioning application would lack precision and only provide limited environmental or fuel improvements. To improve the potential for EAD, a minimum of “Lane-level” positioning is required with some level of on-board proximity sensors. The proximity sensors determine the presence of forward vehicles relative to the equipped vehicle. To fully maximize the EAD application potential, “where in lane” accuracy is required to manage maneuvers during congestion and brief signal opportunities. Careful coordination of SPaT, vehicle position, vehicle speed, and frontal vehicle’s provide the greatest environmental improvements. Figure 10 depicts a EAD application with signal timing scenarios.



Source: Noblis, November 2013

Figure 9. EAD Environmental CVRIA application as deployed in pilot demonstrations.

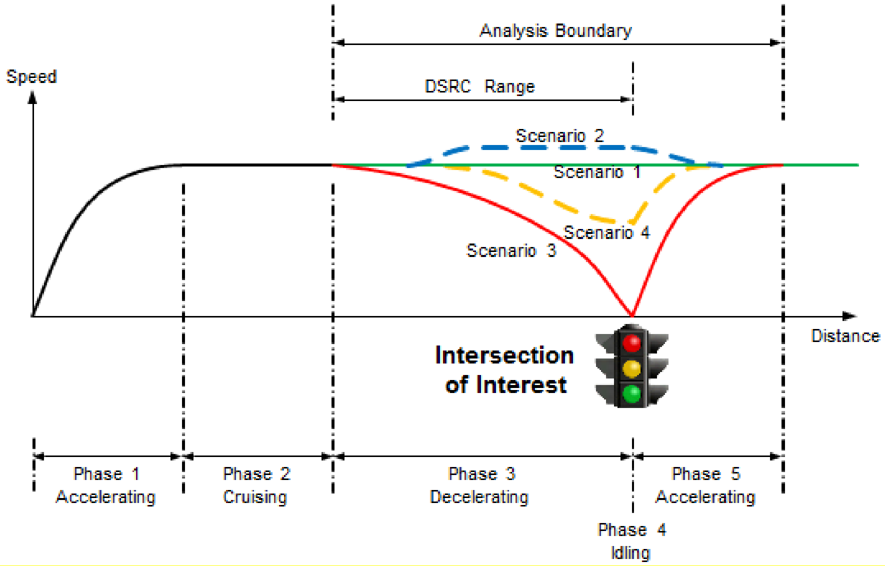


Figure 10. EAD signalized intersection timing scenarios.

			No Positioning	**Coarse Positioning** $\sigma_S > 10m$	**Lane Level Positioning** $3m > \sigma_S > 1m$	**where in Lane Positioning** $0.5m > \sigma_S$
Safety	**Transit Safety**	Transit Pedestrian Indication		Coarse positioning is sufficient to inform the pedestrians about the (future) presence of a transit vehicle		
		Transit vehicle at Station/Stop/Stop Warnings		Coarse positioning is sufficient to inform nearby vehicles of the presence of a transit vehicle in near future	Enhanced accuracy and bandwidth will enable prediction of vehicle motion	
		Vehicle Turning Right in Front of a Transit Vehicle			Lane-level positioning is sufficient to activate driver warnings	Better positioning accuracy and bandwidth will help to predict the vehicle trajectory motion
	V2I Safety	Curve Speed Warning		Coarse positioning is sufficient for general speed warnings	Lane-level positioning allows warnings specific to vehicles about a curve as well as recommended speed	
		In-Vehicle Signage		Coarse positioning is sufficient to provide all the regulatory warning and informational signs and signals(stop, curve warning, guide signs, service signs, and directional signs)	Lane-level positioning will improve the selectivity of vehicle for the presented information	
		Oversize Vehicle Warning		Coarse positioning will help unequipped vehicles to display warnings or reroute information when the vehicle does not have adequate height or width clearance	Lane-level positioning will allow lane specific vehicle warnings and guidance	
		Pedestrian in Signalized Crosswalk Warning		Coarse positioning is sufficient to warn local vehicles regarding presence of known pedestrians in the crosswalk and also inform the pedestrians about potential vehicle in the area	Lane-level positioning will enable prediction of vehicle crosswalk infringement.	
		Railroad Crossing Warning		Coarse positioning is sufficient to provide selected vehicles with warning about approaching train	Lane-level positioning will enable prediction of unsafe situations	
		Red Light Violation Warning		Coarse positioning is sufficient to provide selected vehicles with signal information	Lane-level positioning is the least requirement to predict the likelihood of vehicle signal violation	Better positioning efficacy will provide warning about possible signal violation beforehand and also give instructions to prevent the situation

Table 1a: Safety Connected Vehicle Applications (part 1 of 3)

		Red Light Violation Warning		Coarse positioning is sufficient to provide selected vehicles with signal information	Lane-level positioning is the least requirement to predict the likelihood of vehicle signal violation	Better positioning efficacy will provide warning about possible signal violation beforehand and also give instructions to prevent the situation
		Reduced Speed Zone Warning		Coarse positioning is sufficient	Lane-level positioning allows per lane guidance	
		Restricted Lane Warnings		Coarse positioning allow identical communication to all vehicles	Lane-level positioning allows vehicle specific restriction warnings and alternative route advice specific to each lane	
		Spot Weather Impact Warning		Coarse positioning is necessary to alert drivers about unsafe and blocked road conditions	Lane specific warning is possible along with substitute route advice	Automated driver assistance is feasible for local road conditions
		Stop Sign Gap Assist			Lane-level positioning enables warning drivers on minor roads about unsafe gaps on the major road	Enhance accuracy improves prediction about possible collision, especially for multiple vehicles on minor roads
		Stop Sign Violation Warning			Lane-level positioning is sufficient to warn drivers about predicted stop sign violations	Enhanced accuracy enables automated assistance for better prediction or prevention
		Warnings about Hazards in a Work Zone		Coarse positioning enables warnings about general hazards (vehicle approaching at high speed) to maintenance personnel within a work zone	Lane-level accuracy significantly enhances accuracy of predictions (giving warnings to more specific vehicles), reducing false alarms.	
		Warnings about Upcoming Work Zone		Coarse positioning is sufficient to provide information about an approaching work zone condition	Lane-level allows per vehicle alternate routing suggestions.	
	V2V Safety	Blind Spot Warning	Relative vehicle position is sufficient for applying currently			Where in lane positioning is necessary when absolute positioning is used in both vehicles
		Control Loss Warning	Internal vehicle detection of loss of traction control enables broadcast to all vehicles within range	Absolute positioning allows far away vehicles to ignore the message	Allows nearby vehicles to display driver warnings	Allows automatic vehicle reaction
		Do Not Pass Warning			Lane level positioning is necessary to warn about passing zone which is occupied by vehicles in the opposite direction of travel	Where in lane will assist drivers regarding when to pass

Table 1a: Safety Connected Vehicle Applications (part 2 of3)

		Emergency Vehicle Alert	No positioning is necessary to alert the driver about the location of and the movement of public safety vehicles responding to an incident	Absolute positioning allows far away vehicles to ignore the message	Allows nearby vehicles to display driver warnings	
		Forward Collision Warning	Relative positioning is sufficient to implement in current technology			Where in lane positioning is necessary when absolute positioning is used on both vehicles, plus V2V communications
		Motorcycle Approaching Indication	Relative positioning can be implemented in today's technology to give warnings	Coarse positioning is sufficient for providing warnings to all the vehicles in specific region	More accurate positioning will provide more vehicle specific warnings	More accurate positioning will help vehicles to predict any future collision or accident
		Intersection Movement Assist			Lane level positioning is necessary to warn about potential conflicts	Where in lane positioning will improve prediction
		Pre-crash Actions			Lane level positioning is necessary to mitigate the injuries in a crash by activating pre-crash actions	Where in lane positioning enables faster predictions with more warning time
		Situational Awareness		Coarse positioning is sufficient to broadcast a general warning to all vehicles about road conditions measured by other vehicles	Lane level positioning allows more lane specific warnings, plus vehicles can determine warning relevance	
		Slow Vehicle Warning		Coarse positioning is sufficient to warn the driver about approaching a slow vehicle	Lane level positioning will help providing warnings to vehicles in specified lane	
		Stationary Vehicle Warning		Coarse positioning is sufficient to warn the driver about an approaching stationary vehicle	Lane specific warnings can be implemented	
		Tailgating Advisory	Relative positioning can be used to provide tailgating warning with no positioning requirement		Lane level positioning on both vehicles is necessary in case of absolute positioning	Where in lane will help provide more accurate warnings and discard the false alarms
		Vehicle Emergency Response		Coarse positioning is needed for public safety vehicles to get information from connected vehicles involved in a crash	Improved positioning will help to gather more information	Allows diagnosis of how the accident happened

Table 1a: Safety Connected Vehicle Applications (part 3 of 3)

			No Positioning	**Coarse Positioning** $\sigma_S > 10m$	**Lane Level Positioning** $3m > \sigma_S > 1m$	**where in Lane Positioning** $0.5m > \sigma_S$
Mobility	**Border**	Border Management Systems	No positioning is necessary for electronic interactions if RF transponder is used		Lane level positioning is necessary when the use of RF transponder is limited or absent	
	Commercial Vehicle Fleet Operations	Container Security	No positioning is necessary for container security operation			
		Container/Chassis Operating Data	No positioning is necessary for this application	Coarse positioning can include more operating data like route log		
		Electronic Work Diaries		Coarse positioning is necessary to collect information relevant to the activity of a commercial vehicle	Better positioning will collect more detailed work information(routing, log activity, driving pattern etc.) in future	
		Intelligent Access Program		Coarse positioning is necessary for remote compliance monitoring	Better positioning will enable more detailed monitoring	
		Intelligent Access Program – Mass Monitoring				
	Commercial Vehicle Roadside Operations	Intelligent Speed Compliance		Coarse positioning is necessary for monitoring speed	Lane level positioning will provide more information about the driving pattern	
		Smart Roadside Initiative		Coarse positioning is necessary to activate the application	Lane level positioning will provide more detailed information	
	Electronic Payment	Electronic Toll Collection	No positioning is required when RF transponder is used to collect tolls electronically and detect and process violation		Lane level positioning of vehicle is necessary when the use of RF transponder is limited or absent	
		Road Use Charging				
	Freight Advanced Traveler Information Systems	Freight Drayage Optimization		Coarse positioning of the vehicle is necessary for information exchanges		
		Freight Specific Dynamic Travel Planning		Coarse positioning is necessary to have pre-trip and enroute travel planning, routing, and other traveler information such as truck parking locations and current status	Better positioning will help by providing more detailed route and nearby facility information in future	
	Planning and Performance Monitoring	Performance Monitoring and Planning		Coarse positioning is necessary to monitor and collect data including transportation planning, condition monitoring, safety analyses, and research and predict speed and travel times	Lane level positioning will predict lane level speed and travel times and thus improve the application efficiency	

Table 1b: Mobility Connected Vehicle Applications (part 1 of 3)

	Planning and Performance Monitoring	Performance Monitoring and Planning		Coarse positioning is necessary to monitor and collect data including transportation planning, condition monitoring, safety analyses, and research and predict speed and travel times	Lane level positioning will predict lane level speed and travel times and thus improve the application efficiency	
	Public Safety	Advanced Automatic Crash Notification Relay		Coarse positioning is necessary to automatically transmit an emergency message in times of crash or other distress situation	Lane level positioning will enable the vehicle to broadcast messages to nearby vehicles only	
		Emergency Communications and Evacuation		Coarse positioning is sufficient to activate the application		
		Incident Scene Pre-Arrival Staging Guidance for Emergency Responders		Coarse positioning is necessary to activate the application		
		Incident Scene Work Zone Alerts for Drivers and Workers		Coarse positioning is necessary to activate the application		
	Traffic Network	Cooperative Adaptive Cruise Control			Lane level positioning is sufficient for automatically synchronizing the movements of many vehicles within a platoon	Where in lane positioning will improve the applications efficiency and reduce the occurrences of wanted circumstance
		Queue Warning			Lane level positioning is sufficient to broadcast the queued status information (rapid deceleration, disabled status, lane location) give warnings to vehicles in times of potential crash situation	
		Speed Harmonization		Coarse positioning is necessary speed recommendations based on weather information	Lane level positioning is suitable for speed recommendations based on traffic conditions	
		Vehicle Data for Traffic Operations		Coarse positioning helps pointing out the changes in vehicle speeds indicating the disruption of traffic flow as well as the location of potential incidents	Lane level positioning will help detecting the incident location more efficiently and accurately	
	Traffic Signals	Emergency Vehicle Preemption		Coarse positioning is necessary to activate the application	Lane level positioning is necessary to plan travelling route and facilitate safe and efficient movement through intersections for high priority emergency vehicle	

Table 1b: Mobility Connected Vehicle Applications (part 2 of 3)

		Freight Signal Priority			Lane level positioning of freight and commercial vehicles is necessary to provide traffic signal priority for traveling in a signalized network	
		Intelligent Traffic Signal System			Lane level positioning of vehicle is necessary to get vehicle location and movement information to improve the operations of traffic signal control systems	
		Transit Signal Priority				Where in lane positioning of transit vehicle is necessary to respond to a transit vehicle request for a priority at one or a series of intersection
	Transit	Dynamic Ridesharing		Coarse positioning is a necessity to gather information from both passengers and drivers to provide them with convenient route by arranging carpool trips	Better positioning will improve the dynamic ridesharing application	
		Dynamic Transit Operations		Coarse positioning is necessary to plan, schedule, modify and dispatch users trips and itinerary by using automated vehicle location	Better positioning will improve the efficiency of the application in future	
		Integrated Multi-Modal Electronic Payment	No positioning is necessary for electronic interactions if RF transponder is used		Lane level positioning is necessary when the use of RF transponder is limited or absent	
		Intermittent Bus Lanes	No positioning is necessary to create and remove a bus lane during peak demand times to enhance transit operation mobility		Lane level positioning will help maintaining the lanes	
		Road ID for the Visually Impaired		Coarse positioning is necessary to assist visibly impaired travelers to identify the appropriate bus and route options to their intended destination.	Better positioning will help the traveler in times of distress (road accident, weather hazard etc.)	
		Smart Park and Ride System		Coarse positioning is sufficient to provide travelers with real-time information on Park and Ride capacity	Lane level positioning will provide travelers with the location of the park and ride capacity	
		Transit Connection Protection		Coarse positioning is necessary to help the passenger with the	Better positioning will improve the applications efficiency	

Table 1b: Mobility Connected Vehicle Applications (part 3 of 3)

			No Positioning	**Coarse Positioning** $\sigma_S > 10m$	**Lane Level Positioning** $3m > \sigma_S > 1m$	**where in Lane Positioning** $0.5m > \sigma_S$
Environmental	AERIS/ Sustainable Travel	Connected Eco-Driving		Coarse positioning is required for longitudinal actions such as following speed advice	Could be necessary to differentiate between lane-based eco-driving advice	
		Dynamic Eco-Routing		Coarse positioning is necessary to enable the application		
		Eco- Approach and Departure at Signalized Intersections		Required for longitudinal speed trajectory planning	Required for differentiating lane-based SPaT	Required when vehicle has to stop precisely at stop bar
		Eco-Cooperative Adaptive Cruise Control	Sensor-based relative positioning is required		Required for lateral and longitudinal control, with sensor assist	
		Eco-Freight Signal Priority		Required for longitudinal speed trajectory planning	Required for differentiating lane-based SPaT	
		Eco-Integrated Corridor Management Decision Support System	No positioning is necessary to enable the application	Coarse positioning provides advanced functions		
		Eco-lanes Management		Coarse positioning is necessary to enable the application	Lane level positioning will improve the application's efficiency in future	
		Eco-Multimodal Real-Time Traveler Information	No positioning is necessary to enable the application	Coarse positioning provides advanced functions		
		Eco-Ramp Metering			Lane Level positioning is necessary to differentiate lane speeds	
		Eco-Smart Parking		Coarse positioning is necessary to enable the application		
		Eco-Speed Harmonization		Coarse positioning is necessary to enable the application	Lane level positioning is necessary to differentiate lane-based speed advice	
		Eco-Traffic Signal Timing	No positioning is necessary to enable the application			
		Eco-Transit Signal Priority		Required for longitudinal speed trajectory planning	Required for differentiating lane-based SPaT	
		Electric Charging Stations Management		Coarse positioning is necessary to enable the application		
		Low Emissions Zone Management		Coarse positioning is necessary to enable the application		

Table 1c: Environmental Connected Vehicle Applications (part 1 of 2)

		Roadside Lighting		Coarse positioning is necessary to enable the application		
	Road Weather	Enhanced Maintenance Decision Support System		Coarse positioning is necessary to enable the application		
		Road Weather Advisories and Warning for Motorists		Coarse positioning is necessary to enable the application	Possible lane differentiation required for hazards	
		Road Weather Information and Routing Support for Emergency Responders		Coarse positioning is necessary to enable the application		
		Road Weather Information for Freight Carriers		Coarse positioning is necessary to enable the application		
		Road Weather Information for Maintenance and Fleet Management Systems		Coarse positioning is necessary to enable the application		
		Variable Speed Limits for Weather-Responsive Traffic Management		Coarse positioning is necessary to enable the application		

Table 1c: Environmental Connected Vehicle Applications (part 2 of 2)

V. Business Models

The main focus of this Task 1 effort was sensor based mapping approaches and requirements related to CV applications. Accurate roadway digital databases are also important to other roadway applications, for example: roadway planning, construction documentation, accident investigation, roadway inventory assessment, pavement characterization, and vertical clearances. Numerous sources and methodologies exist to acquire digital roadway infrastructure maps and representations. The focus thus far has been to explain and analyze the existing technologies, requirements, and applications. Telephone interviews make clear that the FHWA, state DOT's and commercial enterprises are all at various stages of constructing roadway digital data bases.

Before summarizing existing business models, it is useful to consider the issues, tradeoffs, and desired characteristics related to digital roadway data bases:

- **Huge data sets:** The raw data produced by the instruments is huge. To illustrate the order of magnitude of data consider the data in Table 2: given 4.1 million miles of US public roads, driven at 50 mph, with 1 TB/hr of data generation, yields about $82\text{x}10^3$ TB of raw data. Much of the data may be irrelevant or redundant. Which raw data should be stored? How and where should it be stored? Who should have access to it?
- **Time variation:** The roadways, the plates on which they sit, the roadway environment, and the coordinate systems in which they are defined are all time varying. How often should the data sets be reacquired? How can obsolete data be detected and removed or replaced?
- **Database spatial continuity:** Connected vehicle commercial success will require uniformity of database contents, accuracy, and behavior across geographic boundaries.
- **Automaker uniformity:** Market success will require uniform vehicle behavioral expectations across auto manufacturers.

State DOTs are required to perform maintenance, management, construction, and oversight of a state owned roads and highways. This responsibility requires detailed knowledge of the road network, features, attributes, condition, and geometry. The traditional survey methods and photologs are rapidly being updated with georeferenced GIS databases. When the DOT desires data along an extensive network, GIS databases are frequently created with data collected through STLS, MTLS, and ALS. Since the primary interest of state DOTs is the road network, the predominate method of georeferenced data collection is transitioning toward MTLS mounted on a vehicle and driven on the state owned roads. The MTLS data collection for state DOTs is either contracted to third party service providers of MTLS data or state DOTS purchase MTLS equipment and perform their own georeferenced data collection.

State DOTs that purchase their own hardware and software have the upfront cost for hardware, software, training, and integration. Once the equipment and methods have been integrated within the institution there is the incremental cost of performing MTLS based surveys. Software packages are available to help with data management, georectification, and construction of photologs. This approach requires highly trained data processing personnel within the DOT are available as consultants. An advantage is that the DOT has complete control of the MTLS equipment and its schedule, plus direct access to the raw and processed to use as is needed. A disadvantage is that the high quantities of data must be managed and curated. Also, in states where MTLS is performed separately by each district, special attention must be paid to combining maps across district boundaries.

Other states contract to third parties (e.g., Mandli) to collect and process the MTLS data. This shifts the costs of equipment purchase and maintenance, data curation and management, and training of data processing personnel from the states to the third parties; however, the DOT may be limited in its access to some forms of data. The third parties try may be able to present the state DOT's with a cost savings by more fully utilizing their equipment and expertise, so that their fixed costs are spread over more projects. Some third parties are working towards automated feature detection. While the third party is responsible for managing and curating all data from a given contract period, it may be difficult to combine map information if the state DOT switches between third party vendors at the end of a contract.

The MTLS generated data is most useful if it can be accessed and used by all knowledgeable employees of the DOT. Some states and third party providers have developed the expertise to make this possible through web interfaces.

Finally, if the state DOT's will be generating the maps for CV applications, those states would need to specify methods at an early stage to ensure full coverage of all roads, nationwide (or global) coverage, uniform accuracy, and common interface standards. Without these characteristics, the automobile manufacturers will not be able to utilize the resulting map databases.

Certain corporate entities are also developing maps intended to have global coverage. Certain corporations (e.g., Apple, Bing, Google) are developing maps intended to be used in consumer applications (routing, advertising, context based search, autonomous taxi service). Such maps do not require high-accuracy and do not contain roadway relative features.

Other corporations (HERE) are developing highly accurate maps with global coverage, intending to use a "data as a service" business model. HERE will have a fleet of over 300 MTLS vehicle allowing them to guarantee a maximum time between surveys of three years for any road in the U.S., with higher frequency surveys in urban areas, or surveys on demand in areas that are thought to have changed. Changes are detected using crowd sourced data or through authorized persons (e.g., DOT employees). They are developing at least two products of interest:

- HERE Reality Lens provides calibrated street-level panoramic views. The user can fly thorough the roadway environment and perform various types of measurements to support analysis. This product builds on the EarthMine technology. The database can be accessed via an internet user interface or downloaded (regionally) to the user computer.
- HERE HD Live Map provides a lane-level map with lane edges and centerline. This product is intended for connected vehicle and autonomous vehicle type of applications. Point features can be stored along the lanes. Both real-time and historical traffic information is expected to be included on a per lane basis.

Both of these products are still under development. HERE is open to discussions about map content and features, along with contracting options. If they succeed, it would be the first global roadway map.

There have also been discussions on how the federal government could assist in organizing datasets. Several discussions have been carried out as part of the CVRIA development, and the role it should play in terms of defining map features and databases.

VI. Concluding Statement

Connected vehicle applications will continue to improve in performance and feasibility as roadway feature maps become more accurate and available. The methods and procedures implemented in the early stages will help define the future needs and requirements. This review and analysis has characterized the current and existing methods utilized by state DOTs, vendors, and corporations for collecting and mapping relevant road features and attributes. While most feature extraction and mapping is currently performed manually, globally applicable feature maps will necessitate that the processes progress toward human-assisted and eventually to automated processes.

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IX. Appendix: Acronym Definitions:

ALS – Aerial Laser Scanner
CV – Connected Vehicles
DOT – Department of Transportation
GNSS – Global Navigation Satellite Systems
IMU – Inertial Measurement Unit
LAS – American Society for Photogrammetry and Remote Sensing laser file format
LIDAR – Light Detection and Ranging
MIRE – Model Inventory of Roadway Elements
MMITSS – Multi-Modal Intelligent Traffic Signal System
MMSTS – Manufacturing Major Subsystem Technical Specification
MTLS – Mobile Terrestrial Laser Scanner
NCHRP – National Cooperative Highway Research Program
PPM – Points per square meter
RINEX – Receiver Independent Exchange Format
STLS – Stationary Terrestrial Laser Scanner
UAV – Autonomous Aerial Vehicle

X. Appendix: Contacts

This report was written in part using notes from many interviews with the people noted below. We greatly appreciate their enthusiasm in discussing the related topics. The report has not yet been distributed for comment. All statements and any errors are the responsibility of the authors.

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