Title

A Qualitative Analysis of Vehicle Positioning Requirements for Connected Vehicle Applications

Permalink

https://escholarship.org/uc/item/0tc2n9jc

Authors

Williams, Nigel
Barth, Matthew

Publication Date

2020

DOI

10.1109/MITS.2019.2953521

A Qualitative Analysis of Vehicle Positioning Requirements for Connected Vehicle Applications

Nigel Williams* and Matthew Barth
University of California, Riverside, Riverside, CA 92521.
E-mail: nwill005@ucr.edu

xxxxxxx

Abstract—Many Connected Vehicle (CV) applications, including safety-critical ones such as collision warning, require lane-level positioning accuracy to function correctly. However, differential GNSS, the primary positioning method used by CVs in current deployments across the U.S., cannot always provide this level of accuracy. This is particularly true in urban environments. Alternative positioning methods or strategies must be developed to fill this gap. To determine what strategies are appropriate, we first identify the positioning requirements of each CV application listed in the USDOT's Connected Vehicle Reference Implementation Architecture (CVRIA). These requirements include accuracy, integrity, update rate, and type of positioning (relative or absolute). Based on our overall analysis, we recommend two general positioning strategies: 1) utilize other sources of positioning information whenever possible (particularly at intersections), and 2) estimate the uncertainty of the positioning solution and use this uncertainty as an input to CV applications themselves.

Digital Object Identifier 10.1109/MITS.2019.2953521
Date of current version: 20 March 2020

---

*Corresponding author

I. Introduction

The U.S. Department of Transportation (USDOT) and other government agencies around the world are committed to using Connected Vehicle (CV) technology to improve the safety, mobility, and environmental impacts of transportation (see, e.g., [1], [2]). CV technology features the sharing of information between vehicles (V2V), between the vehicle and infrastructure (V2I/I2V), and among other related entities (V2X). Information is shared via different media, including wireless communication such as Dedicated Short Range Communications (DSRC) and cellular communications.

Many Connected Vehicle applications have already been defined and developed around the world. A list of CV applications is maintained at the USDOT's Connected Vehicle Reference Implementation Architecture (CVRIA) website [3]. The list contains 88 applications as of March 2018. Each application is accompanied by a text description, system architecture diagram, and further information. Some applications are rigorously defined, others are already being implemented, and still others need significant development. A number of these applications are being tested in pilot deployments of CV technology across the U.S., such as the Connected Vehicle Pilot Deployment [4].

Most CV applications require some level of knowledge about the vehicle's position. In current deployments [4], vehicle position is typically provided by a differential Global Navigation Satellite Systems (GNSS) receiver sometimes coupled with an Inertial Navigation System (INS). This method of positioning can provide consistent lane-level accuracy in open-sky regions [5]. However, if the GNSS receiver's view of the sky is blocked (by objects such as buildings, foliage, and terrain), the positional accuracy may be degraded. Errors of ten meters or more are not uncommon in the so-called "urban canyons" of large cities (see, e.g., [6]), and are hard to predict. Such large errors are unacceptable for some applications (e.g., cooperative adaptive cruise control).

Therefore, the first objective of this paper is to qualitatively identify the positioning requirements of CV applications, namely the required accuracy, integrity, positioning type (relative or absolute), and update rate. All of these are explained below. For the purposes of our analysis, we separate accuracy into four levels, which are described below.

1) *None*: No positioning required.
2) *Coarse* ("Where-on-road"): Accuracy sufficient to determine which roadway segment the vehicle is traveling on, and approximate location on it. Positioning accuracy is typically 5-10 meters. If the position error exceeds 10 meters, that location may be discarded (i.e., the accuracy drops to "None").
3) *Lane-level*: Which lane the vehicle is in (the "absolute positioning" case, explained below) or the number of lanes between vehicles ("relative positioning" case, explained below). Given that a typical passenger car is 1.8 m wide, the position error must be less than 0.9 m. This way, the measured position will fall within the correct lane, even if one side of the vehicle is on the lane edge. Submeter accuracy is also declared necessary for correct lane assignment in [37].
4) *Where-in-lane*: Where-in-lane accuracy is important for automated driving functions such as stopping at a stop bar and lane keeping. While 0.9 m accuracy may be sufficient for lane placement, it is not sufficient for these tasks. Therefore, we define 0.1 m as the required accuracy. This is also the required accuracy for collision avoidance applications in [38].

Many Connected Vehicle (CV) applications, including safety-critical ones such as collision warning, require lane-level positioning accuracy in order to function correctly. However, the GNSS receiver's sky view cannot be assumed clear in many environments where vehicles operate, such as in urban canyons common in many large cities [13]; therefore, lane-level accuracy cannot be guaranteed. There are at least two ways to deal with insufficiently accurate position information: 1) monitor the integrity of the GNSS position [32] and if the positioning accuracy does not meet the needs of the application, then gracefully exit the application; and 2) use alternative positioning method(s) in order to achieve consistent lane-level accuracy. Method 2, however, generally does not provide the same information as GNSS. For example, vehicle-mounted radar can measure the position of one vehicle relative to another (relative position), but by itself cannot determine the vehicle's position on the map (absolute position). Therefore, another objective of this paper is to identify what *type* of positioning—relative or absolute—is required by each application.

Different applications also require position updates (of sufficient accuracy) at different rates. Applications such as collision warning require the most frequent updates (on the order of 10 Hz), whereas an application like Eco-Speed Harmonization, which uses vehicle data to calculate the average speed on a roadway section, may only need position updates every 10 seconds or so. Thus, another positioning requirement we identify is the maximum allowable time between position updates. For the purpose of our analysis, we separate this value into three levels: tenths of seconds, seconds, and tens of seconds.

To summarize, the first main objective of this paper is to identify the positioning requirements (in terms of accuracy, integrity, type, and update rate) of the Connected Vehicle applications listed in the CVRIA [3]. The second main objective is to identify positioning methods and/or strategies that could help CVs meet their application positioning requirements, without substantially increasing vehicle cost. In the Connected Vehicle Pilot Deployment, only a subset of the CV applications are tested at each pilot site. Therefore, the contributions of this paper may help planners decide what CV applications and associated positioning technology is required.

The rest of this paper is organized as follows. Section II reviews GNSS-based and other positioning methods which may be used for Connected Vehicles. Section III describes the methodology used to determine the positioning requirements of each application. Section IV provides the analysis results. Given those and the expected operating conditions for the applications, Section V discusses what positioning methods/strategies might be appropriate for improving CV application performance without substantially increasing vehicle cost. The paper ends with concluding remarks and suggestions for future work.

II. Background on Positioning Technologies

A. Global Navigation Satellite Systems

A GNSS receiver calculates its three-dimensional position based on the pseudoranges (measured ranges) to at least four satellites. Each pseudorange is derived from the (measured) time for the satellite signal to travel from satellite to receiver. Consumer-grade GNSS receiver accuracy is usually about 10 meters [19]. This level of accuracy is generally sufficient to determine which road segment a vehicle is on, but not which lane it is in. Therefore, we say standalone consumer-grade GNSS has "coarse" accuracy.

Differential GNSS (DGNSS) allows consistent meters-level accuracy. DGNSS may be differential pseudorange or differential phase, though it usually refers to differential pseudorange. Differential pseudorange enables accuracy of 1 to 3 m, while differential phase improves it further to a few centimeters (where-in-lane accuracy) [7], [44]. The basic mechanism by which accuracy is improved in each case is explained below.

Differential pseudorange utilizes the fact that GNSS receivers operating in close proximity experience similar "common mode" errors, such as ionospheric and tropospheric delay. A base station with known coordinates can determine these time-varying errors and broadcast corrections to nearby Differential GNSS receivers. Differential phase builds on the accuracy improvement of differential pseudorange. Once the common mode errors are eliminated, it is possible to use the carrier phase information of the GNSS signal, yielding accuracy approximately 100 times better than differential pseudorange [7]. This technique is commonly known as Real Time Kinematic (RTK).

Recent advances in RTK have improved its performance and made it more affordable. In the past, it was typically in the domain of expensive dual frequency receivers. Single-frequency receivers are less expensive, but require a longer time to obtain an RTK fixed-integers solution. However, this time is shorter if using multiple GNSS constellations, as compared to using a single constellation [45].

The drawback of DGNSS is that it requires a separate "correction" signal, using a known set of local base stations. These corrections can be received by various means, including information on the Internet (e.g., NTRIP [8]), satellite signal (e.g., WAAS [9]), or a separate DSRC broadcast. Comparable accuracy to differential pseudorange GNSS may be achieved without the need for a base station by directly sharing pseudorange signals among vehicles [10]–[12]. However, since there is no reference point with known coordinates, the improved accuracy applies only to *relative* positioning.

Unfortunately, all GNSS positioning methods are vulnerable to Non-Line of Sight (NLOS) error [13]. This can occur when the receiver's view of one or more satellites is blocked by terrain, vegetation, buildings (the "urban canyon" effect), or other objects. Furthermore, signals may be reflected or even reach the receiver via two or more paths (multipath), resulting in an erroneous position estimate. NLOS errors on the order of ten meters are easily possible (see, e.g., [6]).

Various methods have been developed to reduce the negative impact of NLOS error [46]. One type of method uses three-dimensional (3D) building information together with satellite ephemeris (orbit) data. For example, a 3D map may be used to calculate the number of satellites that should be visible at a particular time and place. This technique has been used to improve GNSS-based services such as navigation [47], [48], by routing road users through areas with better satellite visibility. 3D building models may also be used to calculate which GNSS signals should be LOS, and which ones should not, at a particular time and location. When using this technique to reduce the GNSS position error, it is referred to as 3DMA (3D map-aided) GNSS [6], [13], [49].

B. Complementary Positioning Methods to GNSS

Techniques to enhance the absolute positioning accuracy of GNSS include: integration with sensors that measure vehicle motion ("ego motion sensors"), and map-matching of the vehicle position. Ego motion sensors typically part of Inertial Navigation Systems (see, e.g., [14], [15]) and Encoder Navigation Systems (these might use wheel speed sensors and steering angle encoders [16], wheel turn sensors [33], etc.). While these sensors can be used in conjunction with GNSS to provide long term stable accuracy, inertial navigation systems (e.g., dead reckoning) by themselves accumulate error over time and therefore are not dependable during long periods of time without accurate position updates from other sources such as GNSS.

Another technique used to improve positional accuracy is map-matching with sufficiently accurate maps. Map-matching (see, e.g., [17]) constrains the vehicle position to the roadway, eliminating or partially correcting erroneous position estimates that appear to fall outside the roadway.

However, this technique requires a map database, and cannot guarantee lane-level accuracy.

Ranging sensors can be used for positioning independently of GNSS. Vehicle-based ranging sensors detect other vehicles and measure their position and speed relative to the sensor-equipped vehicle. Such sensors include camera, radar, and LiDAR (Light Detection And Ranging); in order of increasing cost and accuracy. These sensors are typically capable of lane-level or higher accuracy within a range of about 50 m [18].

Ranging sensors may also be used for *absolute* positioning when combined with a feature-based map. LiDAR is probably the most prominent example [19], although radar and vision may be used too. A vehicle equipped with multiple radar sensors may traverse a route, building a map of radar-detected features that can later be used for localization [20]. Computer vision may be used for absolute positioning by, for instance, determining distance and orientation to a landmark with known coordinates [21].

III. Analysis Methodology

In the literature, the positioning requirements of vehicular applications have been investigated both: 1) in general for a wide range of applications ([19], [38]–[40]); and 2) in detail for a small number of applications (e.g., [37], [41]). In [38]–[40], groups of applications were examined in terms of the Required Navigation Performance (RNP) parameters: accuracy, integrity, continuity, and availability. Farrell et al. [19] evaluated the accuracy requirement of individual CV applications, and showed how application functionality changes with the level of position accuracy. We evaluate accuracy in a similar manner, providing statistics on this and other positioning requirements: positioning type (relative or absolute), update rate, and RNP parameters. All of these are explained below.

The positioning attributes of each CV application listed in the CVRIA [3] were identified using the information accompanying the application (as described in Section I). These positioning attributes are explained below:

- Required accuracy: The minimum level of accuracy required for basic functionality of the application. The four levels are described in Section I. In the literature, accuracy is often given in terms of two standard deviations [39] or 2 drms (distance root-mean-squared) [38]. This is equivalent to the 95th percentile (i.e., 95% of the time), for the two-dimensional case [42].
- The "maximum benefit" accuracy: As noted by [19], many applications gain significant benefits (additional knowledge or functionality) at a higher-than-required level of positioning accuracy. If so, the highest such level is considered the "maximum benefit" accuracy, and the benefit(s) are listed under that level. Sometimes these benefits, such as "automatic vehicle reaction" for the Control Loss Warning application, require some level of vehicle automation, which may not be featured on all Connected Vehicles.
- Required type of positioning: Whether absolute or relative positioning is needed. If both are required, "absolute" is indicated. This is because relative position can be derived from absolute positions, but not vice versa. Absolute positioning also requires map information of sufficient accuracy [19]. Note that the positioning type may change at a higher accuracy level than required.
- Update interval: The maximum time that may elapse between position updates of the required accuracy, in order for the application to function properly. We classify this interval into three levels: tenths of seconds, seconds, and tens of seconds.

Table 1 connects each accuracy level to its accuracy and integrity requirements. Key integrity parameters are "Alert Limit", the error level above which an alarm should be raised, and "Time to Alert" (TTA), the maximum time that can elapse between the occurrence of such a fault and the corresponding alarm being raised. In accordance with the "Highway User Requirements" table in the Federal Radionavigation Plan [38], we set the alert limit at 3 m for 1 m accuracy, and at 0.2 m for 0.1 m accuracy. We also set the TTA at 5 seconds since it is generally the lowest TTA for the applications listed in [38] (including the "Collision avoidance" group). The reason for having such a short TTA even for applications requiring only "coarse" accuracy is as follows. For example, the Eco-Approach and Departure application can provide misleading information if the position error exceeds 20 meters for over 5 seconds. Future work could examine each application in detail and determine the appropriate time-to-alert for each application. Another RNP specification, availability, is typically set at 95% or higher in the literature [38], [39]). However, it is more complicated in the case of Connected Vehicles because the availability of position data depends on the penetration rate of CV technology.

Table 2 shows the analysis results (positioning attributes) for example Safety applications. A checkmark indicates the required positioning accuracy. The required positioning type is absolute unless "relative" appears in parentheses. Text written under a higher level of accuracy indicates significant benefits (additional knowledge/functionality) gained at that level.

Table 1. Accuracy and integrity requirements at each accuracy level.

Accuracy Level	Accuracy (95th Percentile)	Alert Limit	Time to Alert
Coarse	10 m	20 m	5 s
Lane-level	1 m	3 m	5 s
Where-in-lane	0.1 m	0.2 m	5 s

Table 2. Positioning attributes of sample safety applications.

		No Positioning	Coarse Positioning	Lane-Level Positioning	Where-in-Lane Positioning	Max. Time Between Position Updates (s)
Transit safety	Transit pedestrian indication		✓	Pedestrian-bus collision warning (relative)	More accurate collision warning (relative)	1
	Transit vehicle at station/stop warnings		✓	Detection of transit vehicle pulling in or out		1
V2I safety	Curve speed warning		✓	Additional warning if speed within curve is likely to exceed recommendation		1
	Oversize vehicle warning		✓	Accurate distance to low-clearance zone		1
V2V safety	Blind spot warning + lane change warning			✓ (relative)	More accurate warning (relative)	0.1
	Control loss warning		✓ (relative)	Distance/direction to out-of-control vehicle (relative)		0.1

Table 2 was generated as follows. According to the application description in the CVRIA [3], the first application (Transit Pedestrian Indication) informs pedestrians at a transit stop about the presence of a transit vehicle, and vice versa. Since the information needed is whether the pedestrian or transit vehicle is in the vicinity of a stop, coarse, absolute positioning is required. An update time of 1 s is required, because 10 s may be too long of a delay. Increasing the accuracy (in relative positioning, at least) to "lane-level" enables usage of vehicle/pedestrian trajectory data for collision warning. Increasing the accuracy further to "where-in-lane" provides more accurate trajectories and hence more accurate collision warnings. Therefore, where-in-lane accuracy is considered the "maximum benefit" level.

The second application, "Transit vehicle at Station/Stop Warnings" informs nearby *vehicles* about the presence of a transit vehicle. Thus, its required level of positioning accuracy is also "coarse", and lane-level accuracy is the "maximum benefit" level because this allows detection of the transit vehicle pulling into or out of the stop. The third application, "Curve Speed Warning", warns the vehicle of an upcoming curve in the road and provides a recommended speed. To know whether the vehicle is nearing a curve, coarse, absolute positioning is needed. However, if lane-level absolute positioning is available, the vehicle's distance from the curve start may be used to determine whether the vehicle's speed is unsafely high. For timely warnings, the update interval should not exceed 1 s.

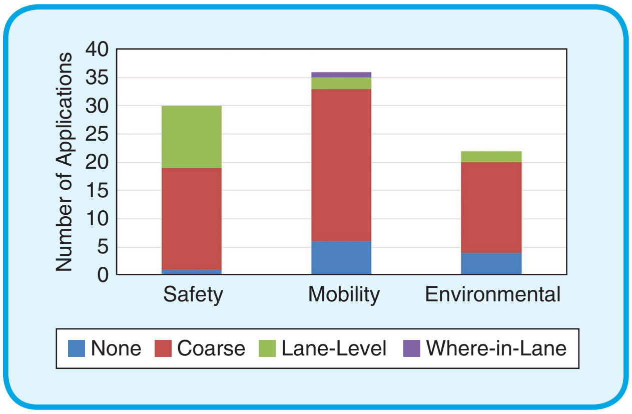

FIG 1 Required positioning accuracy (by application type).

IV. Analysis Results

This section presents statistics on the positioning attributes of the Connected Vehicle applications. Subsection A provides an overview of all applications and examines the statistics for each application type (Safety, Mobility, and Environmental). The following subsections, one for each application type, do a more detailed discussion of the application groups within that type. For the positioning attributes of all applications, please see the complete table in the Appendix.

A. All Applications

82% of all applications require either no or "coarse" positioning for basic functionality; the remainder require lane-level positioning. Of the applications which require positioning, about three-quarters require absolute positioning, and the rest need only relative positioning.

Figures 1 and 2 break down these statistics by application type. Regarding the position accuracy (Fig. 1), most of the applications requiring lane-level accuracy are in Safety; 90% of the Mobility and Environmental applications require either no or coarse positioning. Regarding the positioning type (Fig. 2), Safety contains most of the relative positioning applications. When positioning is required by a Mobility or Environmental application, it is usually absolute.

Despite the fact that lane-level accuracy enables nearly all applications, 15% of all applications benefit from where-in-lane accuracy, and many more benefit from a higher level of accuracy than is required. The "maximum benefit" accuracy is lane-level or higher for 80% of the applications. Figure 3 shows the distribution of required vs. "maximum benefit" accuracy. Notably, while about 10 of the applications do not *require* positioning, nearly all applications *benefit* from some form of positioning.

Figure 4 examines the distribution of the "maximum benefit" accuracy for each application type. It can be seen that the "maximum benefit" accuracy is lane-level or higher for all Safety applications, and for over 60% of the Mobility and Environmental applications.

B. Safety Applications

The 30 Safety applications provide information that is intended to reduce the risk of an accident. The applications address collisions with transit vehicles (Transit Safety), location-based hazards (V2I, or vehicle-to-infrastructure, Safety), and collisions with other vehicles (V2V, or vehicle-to-vehicle, Safety). Table 2 shows two applications from each of these groups, along with their positioning attributes. Table 2 was generated using the method described in Section III. Transit Safety contains only three applications. Following is a discussion of the other two groups of Safety applications, which are larger.

The 13 V2I Safety applications provide safety information based on vehicle location along the roadway. Therefore, 12 of the 13 require absolute positioning. For those applications which warn of something ahead (e.g., Curve Speed Warning), coarse positioning is sufficient. Approximately two-thirds of the applications fall into this category. The other one-third deal with collisions between vehicles and therefore require lane-level positioning. However, all applications in this group benefit from lane-level accuracy, as can be seen in the Appendix.

Updates every 0.1 s are necessary for some of the collision prediction applications; an update interval on the order of 1 s is sufficient for the rest of the V2I Safety applications, which display information inside the vehicle once it reaches a certain area of the roadway. The positioning requirements are summarized below:

- Type: Absolute (12), Relative (1)
- Required Accuracy: Lane-level (4), Coarse (9)
- Update Interval: 0.1 s (3), 1 s (10)

The 14 V2V Safety applications are intended to prevent vehicle-vehicle crashes. Hence, they nearly all require relative positioning. Similar to the V2I Safety applications, only a portion of applications require lane-level accuracy, but all benefit from it. For most of these applications, the interval between accurate position updates must be on the order of 0.1 s, because vehicle dynamics must be closely tracked (and warnings given) in a timely manner.

- Type: Absolute (1), Relative (12), None (1)
- Required Accuracy: Lane-level (6), Coarse (7), None (1)
- Update Interval: 0.1 s (9), 1 s (4), 10 s (1)

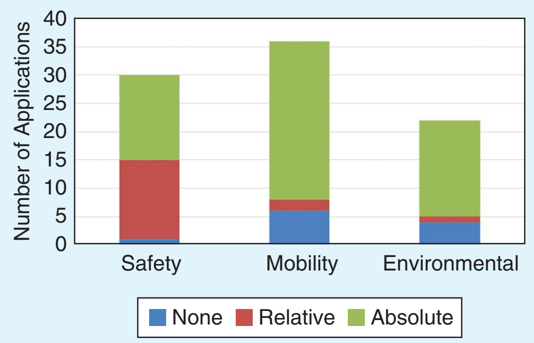

FIG 2 Required positioning type (by application type).

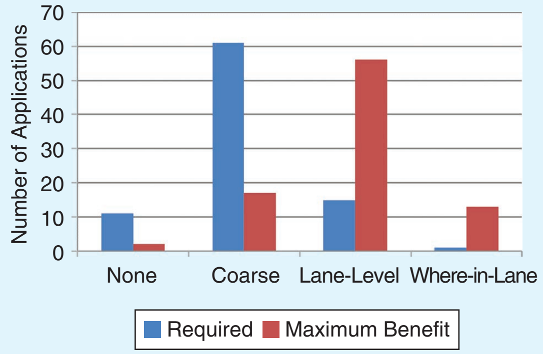

FIG 3 Required vs. "maximum benefit" accuracy.

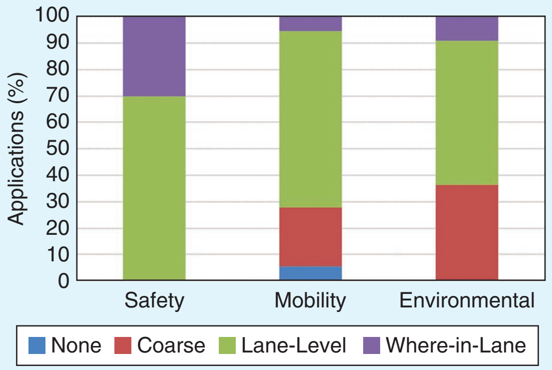

FIG 4 "maximum benefit" positioning accuracy by application type.

C. Mobility Applications

The 36 Mobility applications are intended to facilitate the movement of goods and vehicles. As such, they include applications to improve emergency response, ease traffic congestion, facilitate ridesharing, etc. There are 11 groups of Mobility applications. Table 3 shows the positioning attributes of sample applications from four of the larger groups.

Table 3. Positioning attributes of sample Mobility applications.

		No Positioning	Coarse Positioning	Lane-Level Positioning	Where-in-Lane Positioning	Max. Time Between Position Updates (s)
Public safety	Advanced automatic crash notification relay		✓	Lane of crashed vehicle		1
	Emergency communications and evacuation		✓			10
Traffic network	Cooperative adaptive cruise control (CACC)			✓ (relative)	Tighter vehicle spacings and maneuvers possible (relative)	0.1
	Queue warning		✓ (relative)	Lane of queue (relative)		1
Traffic signals	Emergency vehicle preemption		✓	Can plan route through traffic and direct other vehicles to make way (relative)		1
	Freight signal priority		✓	Whether vehicle is in left-turn bay (requiring left-turn green)		1
Transit	Dynamic ridesharing		✓	High-occupancy lane usage data		10
	Intermittent bus lanes		✓	Whether vehicle is in bus lane		1

While coarse positioning enables nearly all Mobility applications (see Figure 1), the "maximum benefit" accuracy is generally lane-level. Figure 5 shows how the "maximum benefit" accuracy varies from group to group. The first 6 groups are mostly small (1-2 applications each), so they are consolidated into the first bar. We see that lane-level accuracy is the dominant "maximum benefit" in every bar. Also, the Traffic Network and Traffic Signals groups benefit from higher accuracy levels than the Public Safety and Transit groups.

D. Environmental Applications

The 22 Environmental applications deal with the environmental aspects of traffic: reducing energy use and emissions (the AERIS/Sustainable Travel group) and providing road weather information (the Road Weather group). Example applications from each of these groups are shown in Table 4.

The 16 AERIS/Sustainable Travel applications range from Eco-CACC and other applications involving partial automation, to applications giving advice upon request (e.g., Dynamic Eco-Routing). In the former case, a short interval (about 0.1 s) between lane-level positioning updates is necessary, whereas in the latter case, a longer interval (on the order of 10 s) between coarse positioning updates can suffice. Therefore, the positioning requirements of this group are quite diverse. They are summarized below:

- Type: Absolute (11), Relative (1), None (4)
- Required Accuracy: Lane-level (2), Coarse (10), None (4)
- Update Interval: 0.1 s (1), 1 s (9), 10 s (5)

Table 4. Positioning attributes of sample Environmental applications.

		No Positioning	Coarse Positioning	Lane-Level Positioning	Where-in-Lane Positioning	Max. Time Between Position Updates (s)
AERIS/ sustainable travel	Connected eco-driving	✓	Eco-driving advice based on local traffic/road grade	Advice based on surrounding vehicle data (relative)		10
	Dynamic eco-routing		✓			10
	Eco-approach and departure at signalized intersections		✓	Length of queue at intersection	Automatically stop at stop bar	1
	Eco-cooperative adaptive cruise control			✓ (relative)	Tighter spacings in car-following and maneuvers (relative)	0.1
Road weather	Road weather information and routing support for emergency responders		✓			1

Approximately half of the AERIS/Sustainable Travel applications have a Mobility counterpart (for example, Speed Harmonization is the Mobility version of Eco-Speed Harmonization), in which case the positioning requirements are almost identical. The difference between the applications arises from the objective: Environmental applications primarily seek to reduce energy use and/or emissions, while Mobility applications primarily aim to lower overall travel time.

The Road Weather applications deal with weather conditions such as high winds, standing water, and flooding along the roadway. All require coarse, absolute positioning and do not gain any obvious benefits at higher levels of positioning accuracy. Though, to use probe vehicle data to accurately determine which areas of the roadway are impacted by weather conditions, position updates every second are preferable.

E. Summary

Table 5 shows the dominant trends in the large (4 or more applications) groups. While V2I and V2V Safety are the only groups in which a significant number of applications actually require lane-level positioning, it can be seen that most groups still benefit from lane-level positioning. The time interval between accurate position updates must be on the order of seconds for most application groups; V2V Safety's requirement is even stricter, 0.1 second. Finally, absolute positioning is required by most groups. The exceptions are V2V Safety and some of the Traffic Network applications.

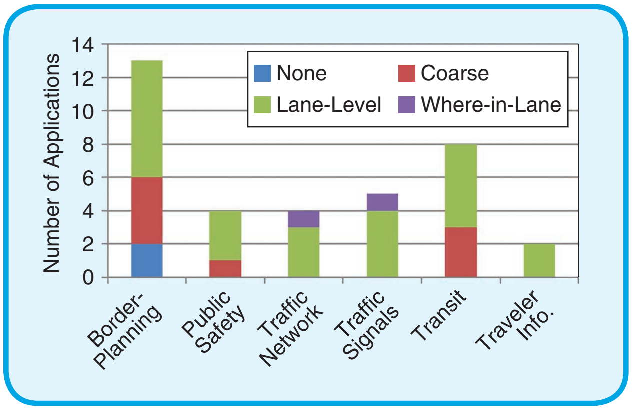

FIG 5 "maximum benefit" positioning accuracy by group (Mobility applications).

V. Improving Position Accuracy and Availability for CV Applications

From the above analysis of CV application positioning requirements, it is clear that lane-level accuracy plays an important role in application performance: 80% of applications (including virtually all Safety applications) either require or benefit from it. However, as mentioned earlier, the currently used positioning method of CVs (GNSS+INS) cannot be relied on to provide this level of accuracy in environments where terrain or buildings significantly block the GNSS receiver's view of the sky. While adding positioning technology to the vehicle to achieve lane-level accuracy in these environments may be cost-prohibitive, application performance could still be improved at low cost by: 1) tracking the accuracy of the position solution and adjusting the applications accordingly; and 2) using the infrastructure to aid in the positioning task.

A. Integrity Monitoring and Application Adjustment

Part (1) of this strategy—estimating the accuracy of the GNSS position solution—is commonly referred to as "integrity monitoring" in the literature. Perhaps the most prominent example of this is Receiver Autonomous Integrity Monitoring (RAIM), which utilizes redundant (i.e., more than four, the required number) satellite measurements to detect faults [30]. However, such additional satellites may not be available in urban environments. Other integrity monitoring schemes

Table 5. Summary table of application groups.

		Accuracy					
Application Type	Group	No Positioning	Coarse Positioning	Lane-Level Positioning	Where-in-Lane Positioning	Max. Time Between Position Updates (s)	Positioning Type
Safety	V2I safety		✓	✓+		1	Abs
	V2V safety		✓	✓+	+	0.1	Rel
Mobility	Public safety		✓	+		1	Abs
	Traffic network		✓	+		1	Rel/Abs
	Traffic signals		✓	+		1	Abs
	Transit		✓	+		10/1	Abs
Environmental	Sustainable travel		✓	+		10/1	Abs
	Road weather		✓			1	Abs

✓ required + gains significant benefits.

Table 6. Summary of positioning configurations.

Configuration Symbol	Configuration Name	Example Hardware		Expected Benefits/Functionality
		Infrastructure Side	Vehicle	
			Ego-motion sensors (EMS)	When GNSS error occurs: • Detect GNSS error → adjust applications/communication • Maintain accuracy temporarily via dead reckoning (DR)
I	Infrastructure sensing	Ranging sensors (e.g. camera, radar)		Applications marked with "I": • More vehicles' positions are available (especially when DSRC penetration rate is low) • Increased positional accuracy in urban areas
I + C	Infrastructure sensing + communication	Same as "I", plus: DSRC	DSRC	Same as above, plus: • More vehicles' positions are available for the "I + C" applications
I + ID	Infrastructure sensing + communication + vehicle "identification" of infra. position	Same as "I + C", plus: (example) RFID tags embedded in roadway	DSRC RFID reader (example)	Same as above, plus: • Increased positional accuracy in urban areas for "I + C" applications
			Same as above, plus: EMS	• Infrastructure position can be used to determine whether GNSS position is lane-level accurate (even if EMS have drifted) • Use infrastructure-provided position as starting point for DR

use information furnished by GNSS receivers, such as dilution of precision, a measure of satellite geometry which may be used to infer approximate accuracy [25]; or non-GNSS sources of position information, such as ego-motion sensors [23, 31] and maps [24]. Of the above options, ego-motion sensors have the added benefit that they can be used to temporarily take over the positioning task in case of GNSS error. Also, they may be relatively inexpensive: [23] uses wheel speed sensors which are built into the vehicle and an inexpensive MEMS gyroscope to detect when GNSS error occurs, and when the GNSS position solution is accurate again.

The next part of the strategy, application adjustment, is illustrated by the following example. If a vehicle's positioning accuracy drops below "lane-level", the following measures are taken: 1) The applications which require lane-level accuracy (e.g., Forward Collision Warning) are disabled, and those which do not (but were originally operating at a level which relies on lane-level accuracy) are "downgraded" to use a coarser position estimate as input. 2) The vehicle attaches its accuracy information to its broadcasted positions, so that other Connected entities (vehicles, pedestrians, infrastructure) know how to use its position in *their* applications. For example, Connected Vehicles in the U.S. broadcast their position in the Basic Safety Message (BSM) specified in the SAE J2735 standard [43]. Also included in the message is the vehicle's estimated positional accuracy, in terms of one standard deviation, along two axes. Using positional accuracy to adjust application and communication should reduce the usage of inaccurate position data and its consequences (false positives/negatives and incorrect information).

B. Infrastructure Sensing and Broadcasting

Another way to enhance CV application performance, at low additional cost to the vehicle consumer, is to use the infrastructure to aid in the positioning task. The infrastructure may do so by sensing vehicles and possibly also broadcasting their positional data. Fixed ranging sensors such as cameras (e.g., [26], [36]) or radar (e.g., [27]) may be used. In [27], vehicle positions measured by a roadside radar unit were shown to have less than 1-meter error in both the lateral and longitudinal directions (95% of the time), suggesting lane-level accuracy. Even if the accuracy of the infrastructure sensor is worse, it can be characterized by a similar test before it begins use.

Sensing, even without communication of vehicles' positions, is useful for applications which require only the *infrastructure* to know vehicles' positions. An example is the "Intelligent Traffic Signal System" application, which adjusts signal timing based on real-time counts of vehicles approaching the intersection. This and other applications which benefit from infrastructure sensing are marked with code "I" in the Appendix. An added benefit of infrastructure sensing is that even non DSRC-equipped vehicles may be detected. This is especially useful in the early deployment phase of Connected Vehicles (when the percentage of DSRC-equipped vehicles is low) since many applications require a minimum vehicle detection rate of 10% or more to show benefits [34].

If the intersection is also capable of *broadcasting* vehicle positions (e.g., [26], [28]), the benefits of infrastructure sensing extend to a larger set of applications (applications marked with code "I + C" in the Appendix). This is because if a Connected Vehicle (the "host vehicle") knows its position with lane-level accuracy, then it can determine which of the lane-level, infrastructure-broadcasted positions is its own. Consequently, it can also use the infrastructure-broadcasted positions of other vehicles in its applications. This increases the availability of position data for *onboard* applications near intersections. Since about 40 percent of crashes that occurred in the United States in 2008 were intersection-related [35], augmenting the position information this way is particularly useful for the V2V Safety applications.

However, in urban areas, the host vehicle's position may only have coarse accuracy due to NLOS error in the GNSS position. If this is insufficient to distinguish it from its neighbors, how does it determine which infrastructure-broadcasted position is its own? A possible solution is to use radio-frequency identification (RFID) to "synchronize" the vehicle-estimated and infrastructure-estimated positions. Two possible ways to accomplish this task are described below: 1) The vehicle is equipped with an on-board RFID reader, which obtains its lane-level, absolute position when the vehicle passes over an RFID tag embedded in the road [29]. The vehicle uses this position to determine which infrastructure-broadcasted position (each associated with an ID) is its own, and then uses positions broadcasted with that ID while within range of the infrastructure unit. 2) The *vehicle* contains an RFID tag, which is read by an RFID reader near the intersection. If the RFID tag contains a unique ID (which is known to the vehicle), the infrastructure can attach this ID to messages that contain that vehicle's position.

C. Summary and Recommendations

One question that naturally arises from the proposed integrity monitoring scheme is: If a GNSS outage lasts long enough for the ego motion sensors' position estimate to drift significantly, how does the vehicle determine when the GNSS position is lane-level accurate again? This reveals another benefit of infrastructure positioning combined with communication: it can be used to "anchor" a vehicle's position estimate. The infrastructure-provided position, which presumably has lane-level accuracy, can be used to estimate whether the vehicle's GNSS position is lane-level accurate as the vehicle leaves the infrastructure's sensing/communication range. If not, the vehicle can use ego-motion sensors to perform dead reckoning, using the last infrastructure-provided position as a starting point. Two consecutive infrastructure positions can be used to calculate heading, if the time interval between them is sufficiently small (e.g., 1 second). This may then be used as the initial heading for dead reckoning.

All of the strategies discussed in Section V are summarized in Table 6 and the bulleted list below. Table 6 could be considered a first step toward a cost-benefit analysis of the strategies.

- Ego-motion sensors onboard CVs could benefit CV applications in several ways. First, they can be used to detect a drop in GNSS positional accuracy. At this point: 1) this accuracy information could be used to adjust CV applications onboard the vehicle and on other Connected entities (by transmitting this accuracy information along with the vehicle's position) to prevent the use of inaccurate position data for CV applications; 2) the positioning system could switch from using GNSS to using ego-motion sensors, so that the positional accuracy does not degrade so quickly.
- In current deployments of CV technology in the U.S. [4], some intersections are outfitted with equipment for communicating with vehicles. It is worth exploring the possibility of equipping these communication-capable intersections with systems for tracking vehicles in real-time (e.g., ranging sensors). This would greatly increase the number of vehicles whose positions are broadcasted, which is useful for all applications, notably the collision warning applications.
- Providing a way for a vehicle to identify its infrastructure-estimated position would allow vehicles to benefit from the "I + C" (see Table 6) capability even in areas with poor GNSS reception. This identification would also benefit CVs in the following ways: 1) the infrastructure-provided position could be used to estimate whether the GNSS position is lane-level accurate; 2) if not, the infrastructure position could serve as a starting point for dead reckoning once the CV is out-of-range of infrastructure positioning.

VI. Conclusions and Future Work

One objective of this paper was to characterize the positioning requirements of Connected Vehicle (CV) applications. In this study, we used the 88 applications listed in USDOT's Connected Vehicle Reference Implementation Architecture (CVRIA). The positioning attributes examined were the required positioning accuracy, integrity, type, update rate, and the "maximum benefit" positioning accuracy. It is hoped that this analysis can provide guidance to fleet managers and transportation professionals who plan to deploy certain applications on their vehicles/infrastructure and need to know the positioning attributes of those applications (e.g., how functionality changes with accuracy level).

A key finding of this paper is that 80% of the CV applications (including all Safety applications) either require or benefit from lane-level positioning accuracy. While the Differential GNSS that CVs currently use for positioning should be sufficient for this level of accuracy under open-sky conditions, it is not dependable in areas where the GNSS receiver's view of the sky may be partially blocked.

Therefore, another contribution of this paper was to suggest various methods to improve application performance with respect to positioning (without adding expensive equipment to the vehicle). In brief, there are two main suggestions. The first is to use other sources of positioning information (both on-board and infrastructure sensors)

Appendix: Positioning Attributes of the Connected Vehicle Applications listed at the CVRIA

This appendix contains the positioning attributes for *all* of the Connected Vehicle applications listed at [3]. The applications are organized into three tables, one each for Safety, Mobility, and Environmental applications.

In the tables below, a checkmark indicates the required positioning accuracy. The positioning type is absolute unless "relative" appears in parentheses. Text written under a higher level of accuracy indicates significant benefits (additional knowledge or functionality) gained at that level.

For more information on a given application, please see its description at [3].

Codes – These are used to indicate non-GNSS positioning methods that may be used for the application. Following is a guide:

- "R" indicates that vehicle-mounted ranging sensors can fulfill application needs
- "I" indicates applications for which infrastructure-based positioning could potentially fulfill application needs
- "I+C" indicates that infrastructure positioning (with communication) could potentially fulfill application needs
- A "(U)" following "I" or "I+C" indicates that the application does not operate only near intersections. Therefore, infrastructure positioning (if only available at intersections) may not fulfill application needs all the time.

Safety Connected Vehicle Applications

			No Positioning	Coarse Positioning	Lane-Level Positioning	Where-in-Lane Positioning	Max. Time between Position Updates (s)	Codes
Safety	Transit safety	Transit pedestrian indication		✓	Pedestrian-bus proximity warning (relative)	Pedestrian-bus collision warning (relative)	1	
		Transit vehicle at station/stop warnings		✓	Detection of transit vehicle pulling in or out		1	
		Vehicle turning right in front of a transit vehicle			✓ (relative)		0.1	R I+C (U)
	V2I safety	Curve speed warning		✓	Whether speed within curve is likely to exceed recommendation		1	
		In-vehicle signage		✓	More accurate "virtual sign" location		1	
		Oversize vehicle warning		✓	Accurate distance to low-clearance zone		1	
		Pedestrian in signalized crosswalk warning		✓	Detection of vehicle/pedestrian in crosswalk		0.1	I+C
		Railroad crossing violation warning		✓ (relative)	Better collision prediction (relative)		1	
		Red light violation warning			✓		1	I+C
		Reduced speed zone warning / lane closure		✓	Whether current lane will be closed ahead		1	
		Restricted lane warnings		✓	Whether vehicle is in restricted lane		1	
		Spot weather impact warning		✓	Lane-specific weather impacts (e.g., ice)		1	
		Stop sign gap assist			✓		0.1	I+C
		Stop sign violation warning			✓		1	I+C
		Warnings about hazards in a work zone			✓		0.1	
		Warnings about upcoming work zone		✓	Whether current lane will be obstructed, etc.		1	

Safety Connected Vehicle Applications

		No Positioning	Coarse Positioning	Lane-Level Positioning	Where-in-Lane Positioning	Max. Time between Position Updates (s)	Codes
V2V safety	Blind spot warning + lane change warning			✓ (relative)	More accurate warning (relative)	0.1	R I+C (U)
	Control loss warning		✓ (relative)	Distance/direction to out-of-control vehicle (relative)	Automatic vehicle reaction	0.1	
	Do not pass warning			✓ (relative)		0.1	
	Emergency electronic brake light		✓ (relative)	Lane of braking vehicle (relative)		0.1	
	Emergency vehicle alert		✓ (relative)	Lane of emergency vehicle (relative)		1	
	Forward collision warning			✓ (relative)	Fewer false positives/ negatives (relative)	0.1	R I+C (U)
	Intersection movement assist			✓	Improved collision prediction (relative)	0.1	I+C
	Motorcycle approaching indication		✓ (relative)	Lane of motorcycle (relative)	Collision prediction (relative)	1	I+C (U)
	Pre-crash actions			✓ (relative)	Improved collision prediction (relative)	0.1	R I+C (U)
	Situational awareness		✓ (relative)	Lane-specific warnings (relative)		1	
	Slow vehicle warning		✓ (relative)	Lane of slow vehicle (relative)		1	I+C (U)
	Stationary vehicle warning		✓ (relative)	Lane of stationary vehicle (relative)		0.1	I+C (U)
	Tailgating advisory			✓ (relative)	Fewer false positives/ negatives (relative)	0.1	R I+C (U)
	Vehicle emergency response	✓	Approximate crash location	Lane of crash	Diagnosis of how accident happened	10	I+C (U)

(*Continued*)

Mobility Connected Vehicle Applications

			No Positioning	Coarse Positioning	Lane-Level Positioning	Where-in-Lane Positioning	Max. Time between Position Updates (s)	Codes
Mobility	Border	Border management systems	✓					
	Commercial vehicle fleet operations	Container security	✓					
		Container/chassis operating data	✓	Container locations				
		Electronic work diaries		✓	Driving pattern and other detailed information		10	
		Intelligent access program		✓	More detailed monitoring		10	
		Intelligent access program – mass monitoring		✓	More detailed monitoring		10	
	Commercial vehicle roadside operations	Intelligent speed compliance		✓	Speed may be derived from position		1	
		Smart roadside initiative		✓	More accurate geofence		1	
	Electronic payment	Electronic toll collection	✓		Required in the absence of an RF transponder		1	
		Road use charging		✓			10	
	Freight advanced traveler information systems	Freight drayage optimization		✓			1	
		Freight specific dynamic travel planning		✓			1	
	Planning and performance monitoring	Performance monitoring and planning		✓	Lane-level speed and travel time data		10	I(U)
	Public safety	Advanced automatic crash notification relay		✓	Lane of crashed vehicle		1	I(U)
		Emergency communications and evacuation		✓			10	
		Incident scene pre-arrival staging guidance for emergency responders		✓	Better information for staging of assets		1	I(U)
		Incident scene work zone alerts for drivers and workers		✓	Lane information for guidance around incident		1	I(U)

Mobility Connected Vehicle Applications

		No Positioning	Coarse Positioning	Lane-Level Positioning	Where-in-Lane Positioning	Max. Time between Position Updates (s)	Codes
Traffic network	Cooperative adaptive cruise control (CACC)			✓ (relative)	Smaller gaps possible for car-following, lane changes (relative) Lane keeping (absolute)	0.1	
	Queue warning		✓ (relative)	Lane of queue (relative)		1	
	Speed harmonization		✓	Can use lane-level vehicle trajectories to calculate recommended speed		1	
	Vehicle data for traffic operations		✓	Better incident detection		1	
Traffic signals	Emergency vehicle preemption		✓	Can plan route through traffic and direct other vehicles to make way (relative)		1	
	Freight signal priority		✓	Whether vehicle is in left-turn bay (and hence requires left-turn green)		1	I*
	Intelligent traffic signal system		✓	Number of vehicles arriving in each lane/direction of travel		1	I
	Pedestrian mobility				✓	1	I
	Transit signal priority		✓	Whether vehicle is in left-turn bay (and hence requires left-turn green)		1	I*
Transit	Dynamic ridesharing		✓	High-occupancy lane usage data		10	
	Dynamic transit operations		✓			10	
	Integrated multi-modal electronic payment	✓		Required in the absence of RF transponder		1	
	Intermittent bus lanes		✓	Whether vehicle is in bus lane		1	
	Road id for the visually impaired		✓	Location of appropriate bus		1	

(*Continued*)

Mobility Connected Vehicle Applications

			No Positioning	Coarse Positioning	Lane-Level Positioning	Where-in-Lane Positioning	Max. Time between Position Updates (s)	Codes
		Smart park and ride system			✓		10	
		Transit connection protection		✓			10	
		Transit stop requested		✓			1	
	Traveler information	Advanced traveler information systems	✓	Allows use of probe vehicles for collection of traffic and other data	Lane-level data from probe vehicles			I(U)
		Traveler information-smart parking		✓	Location of empty parking spaces			

*Also requires identification of vehicle as freight/transit vehicle.

Environmental Connected Vehicle Applications

			No Positioning	Coarse Positioning	Lane-Level Positioning	Where-in-Lane Positioning	Max. Time between Position Updates (s)	Codes
Environmental	AERIS/ sustainable travel	Connected eco-driving	✓	Eco-driving advice based on road grade, local traffic speeds…	Interactions with nearby vehicles (relative)		10	
		Dynamic eco-routing		✓			10	
		Eco-approach and departure at signalized intersections		✓	Can stop behind queue at intersection	Automatically stop at stop bar	1	
		Eco-cooperative adaptive cruise control			✓ (relative)	Smaller gaps possible for car-following, lane changes (relative) Lane keeping (absolute)	0.1	
		Eco-freight signal priority		✓	Whether vehicle is in left-turn lane (requires left-turn green)		1	I*
		Eco-integrated corridor management decision support system	✓	Link-level emissions data			10	
		Eco-lanes management		✓	Whether vehicle is in eco-lane		10	

Environmental Connected Vehicle Applications

			No Positioning	Coarse Positioning	Lane-Level Positioning	Where-in-Lane Positioning	Max. Time between Position Updates (s)	Codes
Environmental	AERIS/ sustainable travel	Eco-multimodal real-time traveler information	✓	Allows use of probe vehicles for collection of traffic and other data	Lane-level data from probe vehicles		10	I(U)
		Eco-ramp metering			✓		1	
		Eco-smart parking		✓	Parking space locations		1	
		Eco-speed harmonization		✓	Lane-level recommended speeds		1	
		Eco-traffic signal timing		✓	Number of vehicles in each lane/ direction of travel		1	I
		Eco-transit signal priority		✓	Whether vehicle is in left-turn lane (requires left-turn green)		1	I*
		Electric charging stations management	✓		Wireless charging at parking space			
		Low emissions zone management		✓	Whether vehicle is crossing zone boundary		1	
		Roadside lighting		✓			1	
	Road weather	Enhanced maintenance decision support system		✓			1	
		Road weather information and routing support for emergency responders		✓			1	
		Road weather information for freight carriers		✓			1	
		Road weather information for maintenance and fleet management systems		✓			1	
		Road weather motorist alert and warning		✓			1	
		Variable speed limits for weather-responsive traffic management		✓			1	

*Also requires identification of vehicle as freight/transit vehicle.

whenever possible, especially at intersections. The second is estimate the position uncertainty and use this as an input to CV applications.

A large amount of additional research is still needed to verify whether the various parts of the proposed positioning scheme will work. Example research topics are: 1) Is the RFID scheme feasible from a cost-benefit perspective? 2) If the infrastructure takes over the task of broadcasting a vehicle's position information, ideally the vehicle can still continue broadcasting other useful state information (e.g., brake status). However, will this cause communication channel congestion? Also, more detailed cost-benefit analysis is needed to determine whether to equip intersections as proposed. To estimate the benefits of each progressive level of infrastructure equipment (I, I+C, I+ID), traffic simulation of the affected applications (e.g., Intelligent Traffic Signal system) may be used.

Acknowledgment

This work was supported in part by the National Center for Sustainable Transportation.

About the Authors

Nigel Williams is a Ph.D. candidate at the University of California, Riverside. He received a B.S. with Highest Honors in Mechanical Engineering from the University of California, Riverside in 2014, and received the National Center for Sustainable Transportation (NCST) Fellowship in 2015. His research interests in intelligent transportation systems include GNSS positioning in urban canyons, the effect of position uncertainty on Connected and Automated Vehicle (CAV) applications, and control of automated vehicles.

Matthew Barth (Member 1990, Senior Member 2000, Fellow 2014) is the Yeager Families Professor at the College of Engineering, University of California-Riverside. He is part of the intelligent systems faculty in Electrical and Computer Engineering and is also serving as the Director for the Center for Environmental Research and Technology (CE-CERT), UCR's largest multi-disciplinary research center. Dr. Barth's research focuses on applying engineering system concepts and automation technology to Transportation Systems, and in particular how it relates to energy and air quality issues. His current research interests include ITS and the Environment, Transportation/Emissions Modeling, Vehicle Activity Analysis, Advanced Navigation Techniques, Electric Vehicle Technology, and Advanced Sensing and Control.

References

[1] J. Harding et al., *Vehicle-to-Vehicle Communications: Readiness of V2V Technology for Application*. Washington, D.C.: National Highway Traffic Safety Administration, 2014.

[2] Car 2 Car Communication Consortium, "Memorandum of understanding for OEMs within the Car 2 Car Communication Consortium on deployment strategy for cooperative ITS in Europe," 2011.

[3] [Online]. Available: http://local.iteris.com/cvria/html/applications/applications.html

[4] [Online]. Available: http://www.its.dot.gov/pilots/

[5] J. Du and M. Barth, "Next-generation automated vehicle location systems: Positioning at the lane level," *IEEE Trans. Intell. Transp. Syst.*, vol. 9, no. 1, pp. 48–57, 2008. doi: 10.1109/TITS.2007.908141.

[6] Y. Gu, L. Hsu, and S. Kamijo, "Passive sensor integration for vehicle self-localization in urban traffic environment," *Sensors*, vol. 15, no. 12, pp. 30,199–30,220, 2015. doi: 10.3390/s151229795.

[7] J. Farrell, Ed., *Aided Navigation: GPS with High Rate Sensors*. New York: McGraw-Hill, 2008.

[8] G. Weber, D. Dettmering, and H. Gebhard, "Networked transport of RTCM via internet protocol (NTRIP)," in *A Window on the Future of Geodesy*. Springer-Verlag, 2005, pp. 60–64.

[9] S. Pullen, T. Walter, and P. Enge, "System overview, recent developments, and future outlook for WAAS and LAAS," in *Proc. Tokyo Univ. Mercantile Marine GPS Symp.*, 2002, pp. 45–56.

[10] N. Alam, A. T. Balaei, and A. G. Dempster, "Relative positioning enhancement in VANETs: A tight integration approach," *IEEE Trans. Intell. Transp. Syst.*, vol. 14, no. 1, pp. 47–55, 2013. doi: 10.1109/TITS.2012.2205381.

[11] F. de Ponte Müller, E. M. Diaz, B. Kloiber, and T. Strang, "Bayesian cooperative relative vehicle positioning using pseudorange differences," in *Proc. IEEE PLANS*, 2014, pp. 434–444. doi: 10.1109/PLANS.2014.6851401.

[12] K. lassoued, P. Bonnifait, and I. Fantoni, "Cooperative localization with reliable confidence domains between vehicles sharing GNSS pseudoranges errors with no base station," *IEEE Intell. Transp. Syst. Mag.*, vol. 9, no. 1, pp. 22–34, Spring 2017. doi: 10.1109/MITS.2016.2630586.

[13] P. D. Groves, Z. Jiang, L. Wang, and M. K. Ziebart, "Intelligent urban positioning using multi-constellation GNSS with 3D mapping and NLOS signal detection," in *Proc. ION GNSS*, September 2012, pp. 458–472.

[14] J. Farrell, "Real-time differential carrier phase GPS-aided INS," *IEEE Trans. Control Syst. Technol.*, vol. 8, no. 4, pp. 709–721, 2000. doi: 10.1109/87.852915.

[15] K. A. Redmill, T. Kitajima, and U. Ozguner, "DGPS/INS integrated positioning for control of automated vehicle," in *Proc. IEEE Intell. Transport. Syst.*, 2001, pp. 172–178. doi: 10.1109/ITSC.2001.948650.

[16] S. Rezaei and R. Sengupta, "Kalman filter-based integration of DGPS and vehicle sensors for localization," *IEEE Trans. Control Syst. Technol.*, vol. 15, no. 6, pp. 1080–1088, 2007. doi: 10.1109/TCST.2006.886439.

[17] J. Greenfeld, "Matching GPS observations to locations on a digital map," presented at 81st Annu. Meeting Transportation Research Board, Washington, D.C., 2002.

[18] A. H. Sakr and G. Bansal, "Cooperative localization via DSRC and multi-sensor multi-target track association," in *Proc. IEEE ITSC*, 2016, pp. 66–71. doi: 10.1109/ITSC.2016.7795533.

[19] J.A. Farrell, M. Todd, and M. Barth, "Best practices for surveying and mapping roadways and intersections for connected vehicle applications," Connected Vehicle Pooled Fund Study, 2016.

[20] E. Ward and J. Folkesson, "Vehicle localization with low cost radar sensors," in *Proc. IEEE Intell. Veh. Symp.*, 2016, pp. 864–870. doi: 10.1109/IVS.2016.7535489.

[21] V. Kogan, I. Shimshoni, and D. Levi, "Lane-level positioning with sparse visual cues," in *Proc. IEEE Intell. Veh. Symp.*, 2016, pp. 889–895. doi: 10.1109/IVS.2016.7535493.

[22] F. Bai, D. D. Stancil, and H. Krishnan, "Toward understanding characteristics of dedicated short range communications (DSRC) from a perspective of vehicular network engineers," in *Proc. 16th Annu. Int. Conf. Mobile Computing and Networking*, 2010, pp. 329–340. doi: 10.1145/1859995.1860033.

[23] S. Worrall, J. Ward, A. Bender, and E. Nebot, "GPS/GNSS consistency in a multi-path environment and during signal outages," in *Proc. IEEE ITSC*, pp. 2505–2511.

[24] R. Toledo-Moreo, D. Bétaille, and F. Peyret, "Lane-level integrity provision for navigation and map matching with GNSS, dead reckoning, and enhanced maps," *IEEE Trans. Intell. Transp. Syst.*, vol. 11, no. 1, pp. 100–112, 2010. doi: 10.1109/TITS.2009.2031625.

[25] N. Drawil, H. Amar, and O. Basir, "GPS localization accuracy classification: A context-based approach," *IEEE Trans. Intell. Transp. Syst.*, vol. 14, no. 1, pp. 262–273, 2013. doi: 10.1109/TITS.2012.2213815.

[26] J. Richardson and D. Kavner, "Method and apparatus for generating infrastructure-based basic safety message data." U.S. Patent 8 878 927, Nov. 4, 2014.

[27] J. Fischer, A. Menon, A. Gorjestani, C. Shankwitz, and M. Donath, "Range sensor evaluation for use in cooperative intersection collision avoidance systems," in *Proc. IEEE Vehicular Networking Conf.*, 2009, pp. 1–8. doi: 10.1109/VNC.2009.5416389.

[28] T. Kitazato, M. Tsukada, H. Ochiai, and H. Esaki, "Proxy cooperative awareness message: An infrastructure-assisted V2V messaging," in *Proc. IEEE Int. Conf. Mobile Computing and Ubiquitous Networking*, 2016, pp. 1–6. doi: 10.1109/ICMU.2016.7742092.

[29] J. Wang, D. Ni, and K. Li, "RFID-based vehicle positioning and its applications in connected vehicles," *Sensors*, vol. 14, no. 3, pp. 4225–4238, 2014. doi: 10.3390/s140304225.

[30] J. Wang and P. Ober, "On the availability of fault detection and exclusion in gnss receiver autonomous integrity monitoring," *J. Navigation*, vol. 62, no. 2, pp. 251–261, 2009. doi: 10.1017/S0373463308005158.

[31] M. Spangenberg, V. Calmettes, O. Julien, J.-Y. Tourneret, and G. Duchâteau, "Detection of variance changes and mean value jumps in measurement noise for multipath mitigation in urban navigation," *Navigation*, vol. 57, no. 1, pp. 35–52, 2010. doi: 10.1002/j.2161-4296.2010.tb01766.x.

[32] N. Zhu, J. Marais, D. Bétaille, and M. Berbineau, "GNSS position integrity in urban environments: A review of literature," *IEEE Trans. Intell. Transp. Syst.*, vol. 19, no. 9, pp. 1–17, doi: 10.1109/TITS.2017.2766768.

[33] D. Hohman et al., "GPS roadside integrated precision positioning system," in *Proc. IEEE PLANS*, 2000, pp. 221–230. doi: 10.1109/PLANS.2000.838306.

[34] M. Ergen, "Critical penetration for vehicular networks," *IEEE Commun. Lett.*, vol. 14, no. 5, pp. 414–416, 2010. doi: 10.1109/LCOMM.2010.05.100296.

[35] E.-H. Choi, "Crash factors in intersection-related crashes: An on-scene perspective," National Highway Traffic Safety Administration, Tech. Rep. DOT HS 811 366, 2010.

[36] M. F. Rachmadi et al., "Adaptive traffic signal control system using camera sensor and embedded system," in *Proc. TENCON 2011 – IEEE Region 10 Conf.*, Bali, 2011, pp. 1261–1265. doi: 10.1109/TENCON.2011.6129009.

[37] S. Shladover and S. Tam, "Analysis of vehicle positioning accuracy requirements for communication-based cooperative collision warning," *J. Intell. Transp. Syst.*, vol. 10, no. 3, pp. 131–140, 2006. doi: 10.1080/15472450600793610.

[38] "2017 Federal radionavigation plan." Accessed on: Oct. 2018. [Online]. Available: https://www.navcen.uscg.gov/pdf/FederalRadioNavigationPlan2017.pdf

[39] M. A. Quddus, "High integrity map matching algorithms for advanced transport telematics applications," Ph.D. thesis, Centre for Transport Studies, Imperial College London, 2006.

[40] W. Y. Ochieng, P. J. Shardlow, and G. Johnston, "Advanced transport telematics positioning requirements: An assessment of GPS performance in Greater London," *J. Navigation*, vol. 52, no. 3, pp. 342–355, 1999. doi: 10.1017/S0373463399008486.

[41] Y. P. Fallah and M. K. Khandani, "Context and network aware communication strategies for connected vehicle safety applications," *IEEE Intell. Transp. Syst. Mag.*, vol. 8, no. 4, pp. 92–101, Winter 2016. doi: 10.1109/MITS.2016.2593672.

[42] F. V. Diggelen, "System design & test: GNSS accuracy – Lies, damn lies, and statistics," *GPS World*, vol. 18, no. 1, pp. 26–33, 2007.

[43] *Dedicated Short Range Communications (DSRC) Message Set Dictionary.* Warrendale, PA: SAE, 2009.

[44] M. Uradzinski, D. Kim, and R. Langley, "The usefulness of Internet-based (NTrip) RTK for navigation and intelligent transportation systems," in *Proc. ION GNSS*, 2008, pp. 6–19.

[45] D. Odijk, P. Teunissen, and L. Huisman, "First results of mixed GPS+GIOVE single-frequency RTK in Australia," *J. Spatial Sci.*, vol. 57, no. 1, pp. 3–18, 2012. doi: 10.1080/14498596.2012.679247.

[46] J. Breßler, P. Reisdorf, M. Obst, and G. Wanielik, "GNSS positioning in non-line-of-sight context: A survey," in *Proc. IEEE ITSC*, 2016, pp. 1147–1154. doi: 10.1109/ITSC.2016.7795701.

[47] Y. Suh and R. Shibasaki, "Evaluation of satellite-based navigation services in complex urban environments using a three-dimensional GIS," *IEICE Trans. Commun.*, vol. E-90(B), no. 7, pp. 1816–1825, 2007. doi: 10.1093/ietcom/e90-b.7.1816.

[48] D. Asavasuthirakul and H. Karimi, "Integrated GNSS QoS prediction for navigation services," in *Proc. 6th ACM SIGSPATIAL Int. Workshop on Computational Transportation Science*, 2013, p. 73. doi: 10.1145/2533828.2533830.

[49] S. Miura, L. Hsu, F. Chen, and S. Kamijo, "GPS error correction with pseudorange evaluation using three-dimensional maps," *IEEE Trans. Intell. Transp. Syst.*, vol. 16, no. 6, pp. 3104–3115, 2015. doi: 10.1109/TITS.2015.2432122.

ITS